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Variability in soil properties at different spatial scales (1 m–1 km) in a deciduous forest ecosystem ☆

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Abstract

The purpose of this research was to test the hypothesis that variability in 11 soil properties, related to soil texture and soil C and N, would increase from small (1 m) to large (1 km) spatial scales in a temperate, mixed-hardwood forest ecosystem in east Tennessee, USA. The results were somewhat surprising and indicated that a fundamental assumption in geospatial analysis, namely that variability increases with increasing spatial scale, did not apply for at least five of the 11 soil properties measured over a 0.5-km^2 area. Composite mineral soil samples (15 cm deep) were collected at 1, 5, 10, 50, 250, and 500 m distances from a center point along transects in a north, south, east, and westerly direction. A null hypothesis of equal variance at different spatial scales was rejected ($P \leqslant 0.05$) for mineral soil C concentration, silt content, and the C-to-N ratios in particulate organic matter (POM), mineral-associated organic matter (MOM), and whole surface soil. Results from different tests of spatial variation, based on coefficients of variation or a Mantel test, led to similar conclusions about measurement variability and geographic distance for eight of the 11 variables examined. Measurements of mineral soil C and N concentrations, C concentrations in MOM, extractable soil NH_4-N, and clay contents were just as variable at smaller scales (1–10 m) as they were at larger scales (50–500 m). On the other hand, measurement variation in mineral soil C-to-N ratios, MOM C-to-N ratios, and the fraction of soil C in POM clearly increased from smaller to larger spatial scales. With the exception of extractable soil NH_4-N, measured soil properties in the forest ecosystem could be estimated (with 95% confidence) to within 15% of their true mean with a relatively modest number of sampling points ($n \leqslant 25$). For some variables, scaling up variation from smaller to larger spatial domains within the ecosystem could be relatively easy because small-scale variation may be indicative of variation at larger scales.

Keywords: Spatial analysis; Soil C; Soil N; Soil C-to-N ratio; Particulate organic matter; Mineral-associated organic matter

1. Introduction

Like many other aspects of nature, soils are characterized by high spatial variation at multiple scales, ranging from point measurements (centimeters or less) to global scales. Other authors (Parkin, 1993; Heuvelink and Webster, 2001; Ettema and Wardle, 2002) have reviewed various aspects of spatial variation in soil properties and processes and soil biota. These reviews convey a general appreciation for the high degree of natural variation that can sometimes hamper or preclude the precise quantification and scaling of soils measurements to the resolution necessary for various analyses. For example, Lin et al. (2005) concluded that there can be substantial variation in soil properties, like depth of A-horizon and pH, over relatively short distances (meters). Other studies, over similar scales (centimeters to meters), indicate that spatial heterogeneity in soil properties affects variability in soil microbial community structure (Franklin and Mills, 2003).

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At even smaller scales (centimeters), there can still be considerable variability in soil measurements, like fungal and bacterial biomass (Morris, 1999), and microbial community structures (Mummey and Stahl, 2003). Microbial communities and activities have been found to be spatially variable even at a millimeter scale (Grundmann and Debouzie, 2000).

A better understanding of spatial variation in soils has both practical and theoretical ramifications. Practically, we need to understand spatial variation in order to more precisely quantify soil properties and processes at all scales. The natural variability associated with a measurement determines how precisely we can estimate its true value with a given set of soil samples. Theoretically, one of the more important and current research problems in landscape ecology involves understanding how to scale up soil properties and processes measured at small domains (e.g., plots) to larger spatial domains (e.g., ecosystems). This becomes increasingly important as we increase reliance on remote sensing technologies to monitor long-term changes in ecosystems. Remote sensing data are usually verified by on-the-ground measurements at scales appropriate to what satellite-based sensors "see" (i.e., meters to kilometers), however the degree of variability present within such scales could have dramatic effects on the measurement strategies applied when verifying such data.

Commonalities of parent material, vegetation, and micro-climate would lead to the common sense conclusion that soil samples collected in close proximity to one another are more similar in their soil properties and processes than those separated by greater distances. Indeed, one of the basic assumptions of geospatial approaches to describe spatial variation in soils is that "near points are more similar to one another on average than ones further apart" (Heuvelink and Webster, 2001). For example, Grigal et al. (1991) found that coefficients of variation for some forest floor and mineral soil properties, like loss on ignition and N concentrations, increased when samples were collected over five spatial scales ranging from 2.5 m to 1000 km. However, spatial variation in soils has not been given sufficient attention to determine if an assumption about greater variation with increasing spatial scale is universally valid and how often this premise might be violated.

The purpose of this research was to test the hypothesis that variability in 11 surface, mineral soil properties would increase from small (1 m) to large (1 km) spatial scales within a single ecosystem/forest stand, in this case a temperate, mixed-hardwood forest in east Tennessee, USA. The soil measurements were: (1) mineral soil C concentration, (2) N concentration, and (3) C-to-N ratio; (4) extractable soil NH_4-N; (5) C concentration in particulate organic matter (POM), and (6) mineral-associated organic matter (MOM); (7) fraction of soil C in POM; (8) POM C-to-N ratio; (9) MOM C-to-N ratio; (10) silt, and (11) clay content. The findings were somewhat surprising and indicated that increasing variability with increasing spatial scale, did not apply over a 0.5-km^2 area for at least five of the 11 soil properties measured in a deciduous forest ecosystem.

2. Methods and materials

2.1. Study site and sampling design

The study site was located in a deciduous, mixed-species forest on the Oak Ridge Reservation, near Oak Ridge, TN, USA. Oaks (*Quercus* spp.), maples (*Acer* spp.), yellow poplar (*Liriodendron tulipifera*), and hickory (*Carya* spp.) were commonly occurring canopy trees throughout the study area. Based on maps compiled by the USGS and the USDA Forest Service from remote sensing data,[1] the forest cover at this location is classified as "oak-hickory". Mean annual precipitation on the Oak Ridge Reservation, based on a 50-year record, is 135 cm and mean annual temperature is 14.2 °C (Hanson et al., 2003). The forest soils were primarily loam, with varying amounts of forest floor development based on aspect and slope position, and are predominantly acidic (pH = 4–5). The sampling design involved random selection of a center point (35.921 °N latitude and 84.264 °W longitude) in the forest. Soil sampling sites were then placed at 1, 5, 10, 50, 250, and 500 m distances from the center point along transects that extended in a north, east, south, and westerly direction. At the maximum distance from the center, samples in opposite directions were separated by 1 km. There was ≈80 m difference in elevation between the lowest (244 m) and highest (323 m) sampling sites. The total area defined by the sampling points was ≈0.5 km^2 (707 × 707 m).

2.2. Soil sampling

Four soil samples (15 cm deep) were collected with a bucket auger in the immediate vicinity of each sampling point after removing forest floor organic matter. In the field, fresh, mineral soil samples were pooled, sieved (6 mm), and thoroughly mixed in a plastic bag to yield a single, homogenous sample from each sampling point. All soil samples were taken on the same day (May 16, 2005) and transported to the laboratory in a cooler. Samples were refrigerated (≈10 °C) prior to sample processing, which commenced within 10 days of the field collections.

2.3. Soil measurements

Approximately 25% of each fresh soil sample was air dried (21 °C), in a room equipped with a dehumidifier, to determine the dry mass-to-fresh mass conversion factor. Representative subsamples from the air-dry soils were sieved to remove gravel and rocks and part of the <2 mm portion was ground and homogenized in a ball mill and

[1] http://www.nationalatlas.gov/mld/foresti.html