Catena 111 (2013) 98–103

Contents lists available at ScienceDirect

Catena

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

Sources of spatial complexity in two coastal plain soil landscapes

Jonathan D. Phillips *

Department of Geography, University of Kentucky, Lexington, KY 40506-0027, USA

ARTICLE INFO

Article history:
Received 29 April 2013
Received in revised form 8 July 2013
Accepted 11 July 2013

Keywords:
Soil spatial heterogeneity
Soil-forming factors
Soil factor sequences
Adjacency matrix
Spectral radius
Soil landscape complexity

ABSTRACT

The spatial pattern of soils and soil properties in soil landscapes is considered here as a function of (1) systematic variation along catenas or associated with spatial patterns of soil-forming factors; and (2) local pseudo-random variations associated with local disturbances or small, unobserved variations in soil-forming factors. The problem is approached at two study sites in the U.S. Atlantic Coastal Plain using algebraic graph theory and the spectral radius of the soil adjacency matrix as a measure of complexity. The matrix is constructed based on the observed spatial contiguity of soil taxa, and soil factor sequences (SFS) are defined for each site based on systematic soil variation associated with variations in parent material, topography, sandy surface thicknesses, and secondary podzolization. The spectral radii of the networks described by the adjacency graphs are compared to those associated with the maximum for a graph of the same size, and the maximum associated with control entirely by variations in soil forming factors. At the Clayroot study site, which is entirely cropland, complexity of the adjacency matrix is less than Λ, the maximum that could be accounted for by the four identified SFS, due to redundant information in the SFS. The Littlefield site, by contrast, has a spectral radius greater than Λ. Here, where about half the site is forested, the contingent variation is likely associated with effects of individual trees on soil morphology. The utility of the adjacency analysis is in identifying whether soil heterogeneity is likely associated with SFS or with contingent factors not captured in SFS.

1. Introduction

The spatial variability of soils and soil properties is well known to any field pedologist, and has been the subject of intensive research over the last three decades (e.g. Burrough, 1983; Campbell, 1979; Culling, 1986; Oliver and Webster, 1986; Trudgill, 1983). Soil variability is traditionally attributed to a systematic, predictable component, and an apparently random noise component (Burrough, 1983), with the apparent noise in many cases actually attributable to deterministic complexity associated with dynamical instability and chaos (e.g. Borujeni et al., 2010; Culling, 1988; Ibáñez et al., 1990, 1994; Liebens and Schaetzl, 1997; Milan et al., 2009; Phillips, 1993, 2000, 2001a, 2001b; Phillips and Marion, 2005; Phillips et al., 1996; Toomanian et al., 2006; Webster, 2000). The "noise" component is referred to here as contingent factors, as instability, local disturbances, and other deviations from systematic patterns are geographically and/or historically contingent. This recognizes that rather than randomness, the irregular variations are associated with local geographical variations in environmental controls and/or specific local (chains of) events.

The purpose of this study is to analyze the structure of soil spatial heterogeneity at the landscape level to determine the relative importance of pedological variability related to variation in soil forming factors (SFF) versus that associated with local disturbances and dynamically unstable magnification of minor initial differences, referred here collectively as contingent factors. The focus is on soil types rather than individual soil properties; the importance of and rationale for this type of analysis are discussed by, e.g., Campbell (1979), Phillips and Marion (2005, 2007), Toomanian et al. (2006); Bockheim and Haus (2013) and Ibáñez et al. (2013). The analysis is based on the pattern of spatial adjacency of soil types, rather than a spatially explicit analysis. The advantage of this approach is that it is unaffected by locally unmeasured or unobserved variation in SFF, as long as the state factors relevant to the area are identified.

A high degree of soil heterogeneity over short distances and small areas is common. This variation is sometimes, but not always, related to readily observed variations in SFF. Even when heterogeneity is related to (for instance) microtopography or localized bioturbation, which are included in the standard suite of SFF, variation may occur at a spatial scale too fine for relationships to be apparent at typical measurement and mapping resolutions. The multiple interrelated environmental factors that influence soils are not independent (of each other, or of soils themselves) and may include relic or inherited properties unrelated to contemporary environmental controls. Further, pedogenesis may sometimes be divergent, exaggerating the effects of minor initial variations or disturbances. Thus, notwithstanding technical and practical problems of measurement and observation of environmental heterogeneity, linking soil heterogeneity to variations in SFF is often no simple matter.

Soil landscape complexity is a function of the number of different soil types, the density of links or connections between them (here

* Fax: +1 859 323 1969.
E-mail address: jdp@uky.edu.

0341-8162/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.catena.2013.07.003

defined as spatial adjacency), and the (ir)regularity of the adjacency relationships. Soil forming factors are those environmental controls that are known to, or can potentially, result in variations in soil properties and soil types. These include the classic state factors of climate, biota, topography, parent material, and time or surface age, as well as any other locally or regionally significant factors such as land use, aeolian or other non-topographically driven soil redistribution, disturbance regimes, sea-level change, etc. Pedology and soil geography, as well as practical soil surveying and mapping, are based on the notion of sequences of soil variation based on SFF. Thus, for example, climo-, bio-, litho-, and toposequences represent systematic variation of soil properties along gradients of climate, biotic communities, lithology or parent material properties, and topography, respectively. Catenas, defined as sequences of soils developed from similar parent material under similar climatic conditions but whose characteristics differ because of variations in relief and drainage, are one example. Many are associated with spatial gradients—a climosequence, for instance, may occur along gradients of temperature or moisture. However, some sequences of SFF may be associated with categorical variations, which may involve multiple SFF. In a coastal landscape, for instance, fundamentally different suites of soils may be associated with tidal marsh, dune swale, and sand dune settings related to differences in parent material, topography, and drainage, which may or may not vary along a spatial gradient. All of these systematic sequences—catenas, factor sequences, soil-landform relationships, etc.—will be referred to here as soil factor sequences (SFS). SFS may include soil-forming factors such as parent material and topography, landscape elements such as landforms or geomorphic surfaces used to differentiate soil types, or catenary relationships reflected in soil properties themselves, such as horizon types and thicknesses, and redoximorphic features.

2. Theory

If soil heterogeneity is wholly explained by associations with SFS, then spatial adjacency should be entirely determined by catenas, gradients, and factor sequences. In a spatially explicit examination of, say, soil variation in relation to parent material texture, an unobserved patch of sandy material in otherwise fine-textured parent materials might yield an apparently anomalous soil type. However, as long as the relationship between parent texture and soil type is recognized in a SFS for the study area, the relationship between the apparently anomalous soil and its neighbors will be shown correctly in an adjacency matrix indicating soil contiguity. The analysis is based on algebraic graph theory. The latter has not been applied much in pedology, but a few exceptions exist (Jeon et al., 2010; Phillips, 2011a, 2013).

A soil adjacency matrix for a soil landscape with N identified soil types is an $N \times N$ matrix with cell entries of *1* if the row and column soil types are spatially contiguous (i.e., share boundaries on a soil map or occur within the same mapping unit), and *0* otherwise (by convention, the entry is zero when the row and column are the same soil). The matrix can be thought of as representing a mathematical graph with N nodes or vertices (soil types) and m edges (adjacency links between soil types).

The largest eigenvalue (λ_1) of the adjacency matrix is called the spectral radius of the graph. The spectral radius is a critical indicator of many network properties, and is a general indicator of graph complexity (Logofet, 2013; Restrepo et al., 2006, 2007; Tinkler, 1972). Spectral radius is closely related to more familiar graph properties such as connectivity, but is a more robust indicator of complexity. For a graph with a given number of nodes, λ_1 reaches a maximum value of $N - 1$ for a fully connected graph (in this case, each soil may occur adjacent to every other), and its minimum value (for a connected graph) occurs when $m = N - 1$. Among other things, λ_1 is directly related to the intensity of cycling in the graph, where cycles are defined as sequences of edges that begin and end at the same node. The spectral radius is also inversely related to critical coupling strength at which a graph undergoes a transition from incoherent to coherent behavior (Restrepo et al., 2006, 2007). In the temporal domain coherence implies a fixed phase relationship; its approximate spatial analog would be a recurring spatial sequence. While coherence is not directly relevant to soil spatial heterogeneity, this property indicates that spectral radius is an indicator of the complexity of the interrelationships represented in the graph (see, e.g., Fath, 2007; Phillips, 2011a, 2011b).

The upper bound for the spectral radius of any graph is

$$\lambda_1(\max) = [2m(N-1)/N]^{0.5}. \tag{1}$$

Thus $\lambda_1(\max)$ can be determined for any graph or adjacency matrix where N and m are known.

A SFS can be thought of as a (sub) graph with a linear sequential or chain structure. Suppose, for instance, that in a given landscape different suites of soils are associated with topographically controlled drainage classes (Fig. 1). The adjacency network of this spatial structure represents a graph with $N = 6$, $m = 5$. If a soil landscape represented by an adjacency matrix has p SFS influencing soil heterogeneity, we can define

$$\Lambda = \sum_{q=1}^{p} \lambda_{1,q} \tag{2}$$

where $\lambda_{1,q}$ is the spectral radius of the q^{th} SFS, $q = 1,2,\ldots,p$.

If the calculated spectral radius for the soil adjacency matrix is greater than Λ (the maximum spectral radius that can be accounted for by the SFS) this indicates soil landscape complexity greater than can be explained by the applicable SFS. This indicates either the presence of undiscovered SFS or of dynamical instability and chaos in pedogenesis, whereby minor variations in or disturbances to SFS grow disproportionately large over time. In this case the proportion of the maximum possible complexity associated with contingent factors for the N, m adjacency matrix (ψ) given a baseline of Λ, is

$$\psi = (\lambda_1 - \Lambda)/(\lambda_1(\max) - \Lambda). \tag{4}$$

For example, if $\psi = 0.6$, this indicates that contingent factors result in complexity (as indicated by the spectral radius) of 60% of the maximum possible above the baseline associated with the SFS.

On the other hand, if $\lambda_1 < \Lambda$, actual soil landscape complexity is less than the maximum associated with SFS. This could occur due to overlapping of SFS, where different sequences imply the same pattern of adjacency and provide redundant information. This is not uncommon, due to covariation of environmental factors. In mountainous terrain, for instance, a microclimate SFS and a vegetation SFS might both reflect differences in slope aspect. In this case, the reduction in complexity from Λ is given by $1 - [\lambda_1/\lambda_1(\max)]$.

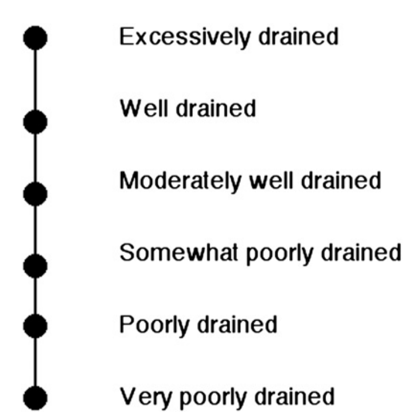

Fig. 1. Hypothetical soil drainage factor sequence represented as a simple chain or linear sequential graph.