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Biomechanical effects, lithological variations, and local pedodiversity in some forest soils of Arkansas

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Abstract

A high degree of soil variability over short distances and small areas is common, particularly in forest soils. This variability is sometimes, but not always, related to readily apparent variations in the environmental factors that control soil formation. This study examines the potential role of biomechanical effects of trees and of lithological variations within the parent material in explaining soil diversity in the Ouachita Mountains of Arkansas. The diversity of soils on Ouachita sideslopes is high, and the soil series vary primarily with respect to morphological properties such as soil thickness and rock fragment content. Soils vary considerably within small more-or-less homogeneous areas, and richness–area analysis shows that the overall pattern of pedodiversity is dominated by local, intrinsic (within-plot) variability as opposed to between-plot variability. This is consistent with variation controlled mainly by individual trees and local lithological variations. Given the criteria used to distinguish among soil types, biomechanical as opposed to chemical and hydrological effects of trees are indicated. Results also suggest divergent evolution whereby the pedologic effects of trees are large and long-lived relative to the magnitude of the initial effects and lifespan of the plants.

Keywords: Pedodiversity; Spatial variability; Ouachita Mountains; Biomechanical effects; Richness–area analysis

1. Introduction

Spatial variability of soils has long been recognized as a crucial issue in a variety of practical contexts and is emerging as a key concern in the geosciences. Because soils reflect the interacting influences of geology, climate, hydrology, geomorphic processes, and the biosphere, the understanding and interpretation of soil patterns and variability is of concern in the use of paleosols to reconstruct environmental change, and in comprehending contemporary earth surface systems. The value of spatial analysis of the soil cover in relation to environmental constraints on soil formation, soil processes and evolution, and the architecture of the environment has been amply demonstrated (Fridland, 1976; Grzebyk and Dubrucq, 1994; Hole and Campbell, 1985;

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Ibañez, 1994; Ibañez et al., 1990, 1995, 1998; McBratney, 1992, 1998).

A high degree of soil variability over short distances and small areas is common. This variability is sometimes, but not always, related to readily observed variations in soil-forming factors. Even when variability is related to (for instance) microtopography or tree throw, which are incorporated in the factors of soil formation conceptual framework, it may occur at a spatial scale which is too fine for typical applications of the soil-landscape model and the soil survey paradigm. While variation in individual soil chemical and physical properties is increasingly measured at very detailed spatial scales, variation in soils themselves (pedodiversity) is primarily treated at the scale of 1:10,000 or smaller soil maps.

Soils are influenced by multiple interrelated environmental factors. They may also include relic or inherited properties unrelated to contemporary environmental controls. Further, pedogenesis may sometimes be convergent, so that variations in environmental factors are reduced and obscured, and sometimes divergent, exaggerating the effects of minor initial variations or disturbances. Thus, even without consideration of the technical and practical problems of measurement and observation of environmental variability, linking soil variability to variations in vegetation, topography, hydrology, etc.—and vice versa—is no simple matter.

The purpose of this paper is to investigate the potential role of several factors, including biomechanical effects of trees, lithological variations in parent material, and microtopography in determining soil spatial variability in the Ouachita Mountains of Arkansas. This arose as a consequence of our observations of a great deal of soil variability at our study sites over small areas, which seemed to suggest a potential role for the effects of individual trees and microtopography. The criteria used to distinguish among the soils in the study area are morphological properties that would be influenced primarily by biomechanical (rather than biochemical or hydrological) effects of trees, thus we focus on this possibility. The importance of lithological variations emerged as the study progressed.

We were also interested in the relative importance of readily observable and measurable variations in soil-forming factors (for example, differences in topographic setting or parent material) in determining soil spatial variability, versus variations attributable to the unstable persistence and growth of minor variations in initial conditions or small disturbances. Several studies have suggested or demonstrated that dynamical instability and deterministic chaos can contribute to local-scale soil variability (Culling, 1988; Ibañez, 1994; Liebens and Schaetzl, 1997; Minasny and McBratney, 1999; Phillips, 1998, 1999, 2001; Phillips et al., 1996; Webster, 2000). Instability and chaos leads to divergent soil development whereby small variations and perturbations persist and become exaggerated over time, rather than convergent development characterized by the muting of variations. The latter is an issue because, if effects of individual trees are invoked as a cause of the observed spatial pattern of soils, then the pedologic impacts of the trees must persist much longer than the trees themselves. Likewise, centimeter-scale microtopographic variation must involve some divergence from initial conditions to lead to morphologically distinct soil profiles at scales an order of magnitude or more broader.

The concern here is with soil morphology and soil stratigraphy rather than soil characteristics which tend to be fast-reacting and transient, such as nutrient status, organic matter, carbon, or pH. The latter are quite important, but this study is concerned with soil changes which would be relevant to soil mapping, the evolution of soils and regolith covers, and efforts to detect or reconstruct past vegetation boundaries based on soil properties. Thus the focus is on characteristics such as soil thickness, presence and thickness of master horizons, drainage status as indicated by redox features, the content and distribution of rock fragments, and the presence or absence of specific pedogenic features. Differences in these factors give rise to variation in soil taxa within the study area. Accordingly, the primary concern is pedodiversity—that is, the richness and variability of soils—as opposed to the variability of specific soil attributes.

While classification of soils, mapping of soil types, and analysis of the spatial patterns thereof is quite routine in practical applications of pedology and soil geography, and among many researchers, it must be acknowledged that not all soil scientists are comfortable with the basic idea that there exist qualitatively, categorically different types of soil that can be so identified and classified in a way analagous to biological taxonomy. In this view analysis of soil maps or of data on spatial distributions of soil types is of little value; rather the analysis should be based on specific soil features and characteristics such as nitrogen content, pH, or depth. This study is based on the premise that it is reasonable to identify qualitatively different types of soil, and that the analysis of the variability of these entities provides insight not obtainable from the analysis of separate soil properties. This is based on three assertions. First, soil classifications integrate the effects of a number of specific soil properties and are thus more comprehensive indicators of soil variability. Second, soil classification, while clearly imperfect and sometimes arbitrary, is a systematic, rule-based technique for grouping similar and distinguishing among dissimilar soils in a way that numerical values of soil properties cannot. Third, we believe the record and tradition of this type of analysis has produced scientifically useful and practically relevant results that clearly legitimize it (e.g., Beckett and Bie, 1978; Bregt et al., 1992; Fridland, 1976; Grzebyk and Dubrucq, 1994; Guo et al., 2003; Hole and Campbell, 1985; Ibañez et al., 1995, 1998). We also believe this reasoning applies more generally to factors such as lithologies and vegetation communities, which may be similarly imperfectly and sometimes arbitrarily classified. In short, this work is based on the premise that there is value in studying the spatial structure of the soil cover.

2. Background

2.1. Forest soil variability

It is not unusual for detailed mapping and measurements to reveal extensive variability of soils over small areas and short distances (e.g., Campbell, 1979; Campbell and Edmonds, 1984; Culling, 1986, 1988; Oliver and Webster, 1986; Phillips, 1997; Webster, 2000). Variability of forest soils may be even greater than that of otherwise similar non-forest soil. For example, a high degree of local variability in soil chemistry (pH, Ca, Mg, and N contents, and litter mass) was documented by Boettcher and Kalisz (1990) at 135 sites in an eastern Kentucky research forest. In eastern North Carolina, variability in A and E horizon thickness and water table elevations were found to be high in cultivated soils, but higher in adjacent forested soils on the same landforms and formed from the same parent material (Phillips et al., 1999a). At the same site, studies of effects of row crop agriculture showed that whereas human agency created new soil types and pedologic changes, the soil landscape is simplified as compared to the adjacent forest soil landscape in the sense of lower entropy in the spatial pattern (Phillips et al., 1999b).

Vegetation influences soils via litter input, throughfall, moisture and temperature regimes, microtopography, and other effects. Pedological effects of trees can be conveniently divided into three overlapping and interrelated categories. First, there are biochemical effects related to changes and variations in pH and organic chemistry of soil and soil water. Changes in vegetation cover (forest/non-forest, or changes in dominant tree or community types) at the stand, ecosystem, or landscape scale, and individual trees at the patch or local scale have been shown to have significant impacts on soil chemistry and biology (e.g., Barrett, 1997; Boettcher and Kalisz, 1990; Certini et al., 1998; Harrison et al., 1995; Islam et al., 2001; Leth and Breuning-Madsen, 1992; Richter et al., 1995; Wilson et al., 1997).

Second, trees have hydrological effects. Individual trees or patches may have important hydrological influences which in turn affect soils via moisture storage and flux, eluviation–illuviation, leaching, and erosion–deposition. Trees may collect and concentrate precipitation delivery to the surface, sometimes having important implications for soil detachment and rainsplash erosion (Morgan, 1986). Tree trunks, roots, and root channels may also facilitate infiltration, subsurface water flow, and serve to concentrate moisture flux in the immediate vicinity. The pedologic outcomes of these processes are discussed by, e.g., Boettcher and Kalisz (1990), Crampton (1982), Herwitz (1993), and Zinke (1962).

Finally, trees may have mechanical influences on soils. Other than the influences of vegetation cover on soil erosion and deposition, the best-known biomechanical effects of trees are associated with tree throw. These events themselves have three different types of effects. First is the physical disruption, redistribution, and mixing of the soil as tree rootwads are ripped from the ground. Second are effects associated with the local topographic variation created by the tree throw (typically a mound-and-pit pair). Third are variations in microclimate, moisture flux, and chemistry associated with the resultant topography. Excellent reviews of biomechanical effects on soils in general have been produced by Johnson (1990, 1993), and of tree throw effects by Schaetzl et al. (1990) and Vasenev and Targul'yan (1998).

Trees may have other mechanical effects as well, such as displacement of soil by subsurface growth, and the creation of local pits by stump rot. The pedologic effects of these processes have received little attention, however, despite the fact that Lutz and Griswold (1939) identified their importance 65 years ago. Previous work has shown that pedologic effects of trees are often manifested over substantially longer time scales than the trees themselves or their remnants (Huggett, 1995; Mossa and Schumacher, 1993; Phillips, 1999; Retallack, 1990; Stephens, 1956; Vasenev and Targul'yan, 1998).

Pedological effects of trees are a major potential source of local variability within the forested study area. While trees may have a variety of physical, chemical, and biological effects on soils, we are specifically interested in biomechanical effects. This is because, as described below, the criteria for distinguishing among soil taxa at the study sites are morphological properties likely to be influenced chiefly by tree throw, root penetration and displacement, and stump holes as opposed to other effects mentioned above.

Sites are small, and were specifically selected to minimize within-plot variations in topography, lithology, vegetation communities, aspect and microclimate, and other influences. Thus, the most likely sources of variability within the study plots are effects of individual trees, microtopography (itself potentially related to tree effects), and lithological impurities (that is, variations in chemical or physical characteristics within facies of a single formation). Assessing the effect of geological variations within facies of mapped formations on soil variation can be problematic. Geological characteristics that cannot be observed via maps, in nearby outcrops, or within sampling pits cannot be determined, and thus represent an essentially unobservable (and unexplained) source of soil variability. While we were able to directly observe or sample underlying bedrock for each pedon, there was no way to definitively determine whether sandstone within an otherwise shale-dominated location (for instance) was related to an unmapped boundary between formations, a local lens or bedding plane of sandstone within shale, or a buried boulder transported from upslope.

2.2. Study area

The study area is in the Ouachita Mountains of western Arkansas, on Ouachita National Forest land (Fig. 1). The Ouachitas are a geologically complex structure representing a continental collision zone, believed by many geologists to be an extension of the Appalachians. The geologic formations of the study area are predominantly characterized as either shale or sandstone. They are all interbedded shales and sandstones, differing in the relative abundance and thickness of the two rock types. There is considerable lithological variation in both the shale and sandstone facies, and there are significant, sometimes major, contents of metamorphic rocks.

The Ouachita Mountains are parallel folded ridges oriented generally east–west. Many of the strata are strongly tilted, some to nearly vertical. There are also overturned folds, thrust faults, and local pressure-induced metamorphic features associated with those stresses. An overview of the regional geology is given by McFarland (1998) and Stone et al. (1980). The ridge tops are typically hard sandstones and quartzites. The side slopes, where all study plots were located, are underlain by shales and sandstones.

The climate is humid subtropical, with a mean annual precipitation of 1245 mm. Ice storms occur several times a decade, and National Forest personnel indicate that it is primarily ice storms rather than wind that is responsible for most of the tree throw in the area.

At present, there are four general dominant types of upland forest communities within the national forest. The pine–bluestem savanna, characterized by a shortleaf pine (*Pinus echinata*)-dominated overstory and *Andropogon gerardii*-dominated herb layer, is represented by relatively few areas now, but was apparently the dominant community on well-drained south-facing slopes at the time of European settlement (Burkenhofer and Hedrick, 1997). Fire suppression (and possibly the reduction or cessation of periodic con-

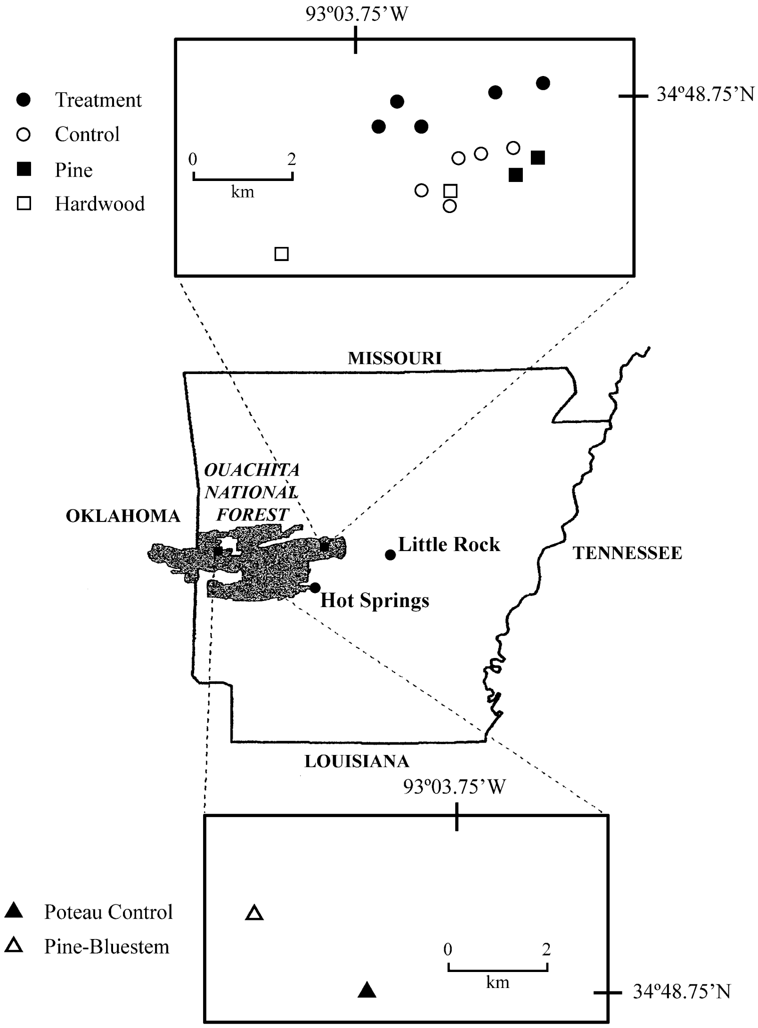

Fig. 1. Study area, showing general locations of sample plots.

trolled burns by native Americans) and logging has resulted in most of these ecosystems being transformed into mixed pine–hardwood communities. The latter include shortleaf pine and numerous hardwoods, particularly oaks (*Quercus* spp.). The pine–bluestem and pine–hardwood community types are prevalent on southern aspects, and the pine–hardwood occurs on northerly exposures as well. On generally north-facing slopes pine-dominated (closed canopy rather than pine–bluestem) or hardwood (oak)-dominated stands occur.

The mixed pine–hardwood community type is by far the most common on Ouachita National Forest land. The U.S. Forest Service is attempting to restore pine–bluestem communities at some sites by selective cutting of hardwoods and a regimen of controlled understory burns.

The best-developed upland soils are predominantly Hapludults, characterized by low base saturation and argillic horizons. Rock outcrops and thin, poorly developed soils (Dystrudepts and Udorthents) are common on the side slope study sites.

3. Methods

3.1. Field methods

The sample design was hierarchical, and partly dictated by a broader study of the silvicultural, ecological, and pedological effects of forest management and ecosystem restoration practices. Two areas were delineated, representing treatment and untreated control areas where the Forest Service is seeking to restore the shortleaf pine–bluestem communities, though all were of the mixed pine–hardwood community type at the time of sampling, which occurred prior to prescribed burns. Five circular plots each were established within the treatment and control areas. The plots have a 66-ft (21 m) radius from center points along previously established vegetation transects. All are on generally southern aspects, and on sideslopes (e.g., both ridgetops and valley bottoms were avoided). An additional six plots were established to represent other forest types. Two pine-dominated and two hardwood-dominated plots were established. A pine–bluestem plot was identified, but was located considerably west of most other sample plots due to the current paucity of these communities. A pine-dominated site near the pine–bluestem site was also analyzed because it has been identified by the Forest Service as a site that has never been logged, burned, or otherwise disturbed.

Within each plot 10 pairs of samples (20 pits per plot) were identified. Each pair included one pit directly beneath coarse woody debris (CWD) of some type, and a nearby pit with no evident CWD. The samples were mainly <1 m apart, but occasionally farther away to avoid surface rock outcrops or trees. The sampling scheme was originally intended to investigate the effects of CWD on soil morphology. These turned out to be insignificant, so in this paper the pits are treated as paired samples, the location of which was determined by the location of CWD at the time of sampling. Once the CWD point was selected its sample pair was chosen so as to be identical in slope gradient, curvature, and aspect.

Sampling was primarily accomplished using approximately circular pits about 30 cm in diameter. Most of the pits extended to bedrock or a lithic or paralithic contact, but in some cases additional augering was necessary to sample the entire soil thickness. Field descriptions followed standard methods as described by Schoeneberger et al. (1998). For each pit, the depth and sequences of horizons were recorded, along with the texture and Munsell color of the A and upper B horizons, rock fragment content of the B horizon, and depth to bedrock or a lithic or paralithic contact. Color was determined in the field in natural light with moist samples. Rock fragment contents were determined in the field with strike tests using a small metal rod or the tip of a soil knife. Fragment percentages less than 35% (the threshold for identifying skeletal soil families) and greater than 70% were sometimes simply recorded as $<35\%$ or $>70\%$ when B horizons were thin or otherwise difficult to sample. Pedogenic features which were recorded if encountered included stone lines and stone zones, redox features (based on Munsell chroma <3), and buried organic matter. The latter was included only if it was clearly and unambiguously identifiable as being buried (for example intact leaves). Stone lines and zones were identified if the rock fragment content was at least 70%, and at least 20% higher than layers above and below. The general lithology of rock fragments from each pit was also recorded by breaking at least five fragments per pit with a geological hammer. Aspect and slope were measured for each pit pair along the axis of greatest downhill slope with a prismatic compass and clinometer, respectively.

Field identification of E horizons was based on a texture no finer than the A horizon, along with a lighter color. Bt horizons were recognized based on a textural class of sandy clay loam or finer and at least two textural classes finer than overlying horizons, and the presence of blocky structures. The B horizons were also characterized by obvious color differences from A and E horizons. Bt and C horizons were often the same texture; they were distinguished in the field based on massive structures, and the presence of observable sedimentary bedding and/or unweathered or poorly weathered rock fragments from the underlying bedrock. Identification of other types of horizons followed standard U.S. Department of Agriculture guidelines (Schoeneberger et al., 1998).

A soil key based on U.S. Soil Taxonomy was constructed by first identifying all the soil series likely to be encountered at the study sites. This potential population was based on 39 fully described and classified soil pits in the study area described by

Ouachita National Forest Soil Scientist Ken Luckow (personal communication) shortly before commencement of this study; published soil surveys for Saline, Garland, and Perry Counties, Arkansas (Haley, 1979; Laurent et al., 1989; Townsend and William, 1998); and the Official Series Descriptions database (Soil Survey Division, 2001) maintained by the U.S. Natural Resources Conservation Service, utilizing the entries for "geographically associated soils." Once this population of candidate soils was identified, a key was developed based on discriminators that can be determined from the information collected at each sample pit (Table 1). The main discriminators are soil thickness (depth to rock or a contact), rock fragment content of the B horizon (e.g., skeletal control sections), the presence or absence of a Bt horizon, and surface texture. Soil mapping in the region often relies on the dip of underlying strata as one criterion, but this was not always evident at the sampling plots. Further, outcrops in the study area show extensive local variation in dip of strata and degree of folding and contortion. This criterion was thus excluded in the key used here, making it possible for soils normally mapped on steeply dipping and level-bedded strata to be keyed out at the same plot.

Tree throws, stumps, and standing dead trees were also inventoried for each plot. Sawn stumps and trees obviously pushed over by logging operations were excluded from the inventory. This inventory is described in more detail elsewhere (Phillips and Marion, 2004).

3.2. Richness–area analysis

Pedodiversity has several different aspects; the concern here is with soil richness, the number of different soils. Relationships between species richness and area have long been used in biogeography and biodiversity studies; this approach has been adapted to soils (Beckett and Bie, 1978; Ibañez et al., 1995, 1998; Guo et al., 2003; Phillips, 2001). Richness is defined in this case on the basis of the series level of U.S. soil taxonomy; richness–area relationships are likely to vary according to different taxonomic schemes and hierarchical levels (Ibañez et al., 1995, 1998; Guo et al., 2003). In this study the criteria used to distinguish among series, though characterized by arbitrary divisions (for example, soil depths of < 50,

Table 1
Soil key for the study area

Depth to bedrock or paralithic contact < 50 cm
- B horizon rock fragment content < 35%
  - B horizon silty clay loam or finer; low chroma (< 3) present: *Tuskahoma*
  - B horizon coarser than SiCl; low chroma absent: *Tuskahoma taxadjunct*[a]
- B horizon rock fragment content >35%
  - Dominantly shale parent material
    - Bt horizon absent (Bw only): *Bismarck*
    - Bt horizon present: *Bismarck-Bt*[a]
  - Dominantly sandstone parent material
    - >70% rock fragment content; no B horizon: Udorthents[a]
    - B horizon present
      - Bt horizon absent (Bw only): *Clebit*
      - Bt horizon present: *Clebit-Bt*[a]

Depth to bedrock or paralithic contact 50–100 cm
- Dominantly sandstone parent material
  - B horizon rock fragment content < 35%: *Pirum*
  - B horizon rock fragment content >35%: *Nashoba*
- Dominantly shale parent material
  - Colluvial; 2Bt horizon; texture contrast of loam or coarser to silty clay loam or finer: *Bengal*
  - Not colluvial, no 2Bt horizon
    - B horizon rock fragment content < 35%
      - B horizon clay loam or coarser: *Sherless*
      - B horizon silty clay loam or finer: *Townley*
    - B horizon rock fragment content >35%: *Honobia*

Depth to bedrock or paralithic contact 100–150 cm
- Dominantly sandstone parent material
  - < 35% rock fragments in B horizon: *Zafra*[b]
  - >35% rock fragments in B horizon: *Sherwood*
- Dominantly shale parent material
  - Iron depletions present in B horizon
    - Depletions present only in lower Bt: *Stapp*
    - Oxyaquic; depletions present throughout Bt: *Littlefir*
  - No iron depletions
    - Colluvial; 2Bt horizon; texture contrast of loam or coarser to silty clay loam or finer: *Endsaw*
    - Not colluvial, no 2Bt horizon
      - Irregular B/C boundary: *Carnasaw*
      - B/C boundary not irregular: *Enders*

Depth to bedrock or paralithic contact > 150 cm
- Upper B horizon sandy clay loam or coarser; >35% rock fragments: *Panama*[b]
- Upper B horizon clay loam or finer; < 35% rock fragments: *Octavia*[b]

The key was designed to allow identification of soils in the field, based on a known population of soils.

[a] Ad hoc soil type identified during fieldwork.

[b] Not found in field samples.

50–100, 100–150, or >150 cm), are related to distinctions which are quite significant in geomorphic interpretations of soils such as depth to lithic or paralithic contacts, rock fragment contents, parent material lithology, and presence or absence of colluvial deposits.

The richness–area analysis is designed to determine the relative importance of within-plot versus between-plot contrasts in soils. Further, because the plots are small and selected to represent (to the extent possible) a uniform set of climate, biotic, topographic, parent material, and time/age controls, within-plot variation should be related to divergent pedogenesis and the unstable exagerration of the effects of minor variations in initial conditions or of small disturbances (Phillips, 2001).

The <0.13 ha sample plots in this study can be characterized as "elementary areas" in the sense of Phillips (2001)—that is, spatial units that are essentially uniform relative to the scale or resolution of soil mapping and resource management. Variability within elementary units can be considered intrinsic in that it must derive from local irregularities or complexities. Thus an elementary unit is defined operationally as having uniform common properties. Any region of interest can be divided into n elementary units i (=1, 2,…,n), each with a total or cumulative area A_i. The elementary units may be, but are not necessarily, contiguous. Here the region of interest is represented by the 16 study plots. The number of soil types in each unit is S_i. Then, with an obvious analog to biological species–area relationships.

$$S_i = c_i A_i^{bi} \tag{1}$$

The general applicability of richness–area relations to soils, and the applicability of the power function form of Eq. (1) in pedology has been demonstrated by Beckett and Bie (1978), Ibañez et al. (1995, 1998), and Guo et al. (2003).

Let S be defined as the number of soil types and A the area at any broader resolution, such that $A = \Sigma A_i$.

$$S = cA^b \tag{2}$$

The coefficient c represents the intrinsic, baseline number of soils which are present regardless of area. If there is a one-to-one correspondence between S_i and the elementary units—that is, each unit consists of a single soil—$c_i = 1$ and $b_i = 0$. This would be the case, for instance, for an elementary unit based on a "pure" soil map unit comprised of a single series, with no inclusions. Where the elementary unit contains $S_i > 1$ soil types regardless of the size, area, or number of samples, $b_i = 0$ and $S_i = c_i$. Because any sample must contain at least one soil, c, $c_i \geq 1$, though statistically estimated values may be slightly lower.

The exponent b indicates the rate at which richness increases (i.e., more soils are found) as area increases, and takes values of $0 \leq b \leq 1$. Higher values indicate greater pedodiversity. The curve produced by Eqs. (1) and (2) indicates a relatively rapid increase in soil richness with area as sample size is increased initially, which flattens out at larger areas.

Variations in S_i must, by definition, be attributable to intrinsic factors. Then c_i can be interpreted as a reflection of the inherent diversity associated with unit i, and b_i as a reflection of the tendency for larger areas of unit i to show increasing soil diversity independent of environmental heterogeneity.

The entire region of interest and the subareas are related by

$$S = \sum (c_i A_i^{bi} - k_i) \tag{3a}$$

where k_i is the number of taxa in i already counted previously, or

$$S = m \sum (c_i A_i^{bi}) \tag{3b}$$

where m ($m < 1$) is an adjustment factor for taxa counted in more than one i; $m = S/\Sigma S_i$. Then

$$S = \overline{c_i A_i b_i} mn \tag{4}$$

The overbars indicate mean values.

The ratio b_i/b provides an indication of the importance of intrinsic variability related to deterministic uncertainty relative to that associated with increasing environmental heterogeneity as area increases.

The number of samples (N) can replace A in Eqs. 1–4 in situations where additional samples represent sampling of larger areas. Then

$$S = cN^b \text{ and} \tag{5}$$

$$S_i = c_i N_i^{bi} \tag{6}$$

In Eq. (6), theory indicates $c_i = 1$, since the first sample can record only one soil, though in estimating parameters from regression equations the intercept many deviate from unity. If Eq. (5) is based on aggregate data for the elementary areas, then $c \geq 1$. For instance, if the first plot has 20 sample points and four soil series, then the first pair of data points in developing the relationship would be $S = 4$ and $N = 20$. If the second area has 15 samples and one additional soil not found in the first area, the second pair of points in Eq. (5) would be $S = 5$, $N = 35$, and so forth.

The ratios b_i/b and c_i/c provide a quantitative indication of the relative importance of intrinsic and extrinsic sources of pedodiversity. Ratios greater than unity indicate that intrinsic or within-plot variability contributes more to the aggregate pattern of pedodiversity than the between-plot variations.

A regression equation of the form

$$\log S_i = c_i + b_i \log N_i \tag{7}$$

was developed for each plot. From this, the parameters of the equation $S_i = c_i N_i^{bi}$ were determined. The richness–area relationship for the entire site was developed from the aggregate data.

3.3. Analysis of variance and entropy

The richness–area analysis is the core tool for determining the relative importance of intrinsic, within-plot versus between-plot variability of soils as indicated by soil richness. It is useful, however, to see whether some specific soil and site properties exhibit generally similar patterns with respect to variability within or between plots.

Within-plot versus between-plot variability for quantitative, interval or ratio level data is readily accomplished using a two-way analysis of variance (ANOVA). This approach, based on the general linear model, apportions variance to that between categories (plots) and within plots. Use of ANOVA in soil science and geography is discussed in detail by Chorley et al. (1966), Nortcliff (1978), Moellering and Tobler (1972), Wright (1996), Webster (1977), and Griffith and Amrhein (1991), among others. ANOVA was applied to data on thickness of surface litter layers, total soil thickness (depth to bedrock or lithic contact), depth to the top of the B horizon (where present), aspect, and slope. Aspect values were converted to a vector mean direction (θ) to account for the fact that circular data such as compass bearings have the same beginning and end point:

$$\theta_{\mathrm{vm}} = \arctan\left[\left(\sum \sin\theta\right) \Big/ \left(\sum \cos\theta\right)\right] \tag{8}$$

where θ is the aspect in degrees.

A key soil property in classification is rock fragment content of the B horizon. However, some of these data are categorical (for example <35% or >70% rock fragments) and could not be analyzed with ANOVA. Instead, entropy was used to assess the variability by assigning each sample pit to one of three classes of rock fragment content in the B horizon—<35%, 35–70%, and >70%. Entropy (H) is then given by

$$H = -\sum [p(i) \ln(pi)] \tag{9}$$

where $p(i)$ is the proportion of samples in each of the three rock fragment classes.

The minimum entropy (0) is associated with a situation where all samples are in one class. Maximum entropy occurs where any class is equally probable and is equal to about 1.1 in this case. The probability of finding any given rock fragment class in this case would be 1/3 (more generally $1/n$, where n is the number of classes). The use of entropy statistics in the study of soil spatial variability is amply discussed and illustrated elsewhere (Ibañez et al., 1995; Ibañez and De Alba, 2000; Martin and Rey, 2000; Phillips et al., 1999b).

4. Results

4.1. Soil diversity

Of the 19 recognized soil series identified prior to fieldwork as possibly occurring at the study sites, 15 were observed in the sample pits. In addition, 4 variations were found that were morphologically distinct from the recognized series but taxonomically inconsistent with any of them. These were recorded as variations or taxadjuncts of recognized series or simply classified at higher levels of soil taxonomy (Table 2). Most of the soils are Hapludults. The typical study area soil is characterized as relatively thin (< 1 m) with a loam or sandy loam surface and a thick (>3 cm) litter layer and O horizon. Only a few have E horizons. Most have yellowish brown to red B horizons (the dominant Munsell hue is 7.5YR). Clay loam was the most common B texture, but textures ranged from sandy clay loam to clay. Some pedons have C horizons similar in texture and color to the B, but containing significant amounts of weathered and unweathered shale. These are general tendencies and there was significant variation in all properties.

Table 3 summarizes the taxonomic variability of the study plots. Within each 0.127 ha plot, 4–11 different series were found. Of the 10 paired pits at each plot, 3–7 pairs had different series in pits typically less than 1 m apart. On average, each of the 16 plots had 6.4 different soil types and 60% of the sample pairs differing in soil series. Given that the plots are considerably smaller than a typical soil mapping unit delineation, and chosen to minimize environmental variability, this demonstrates a high degree of variability over short distances and small areas.

Table 2
Soils mapped at the study sites

Series name or soil type	Taxonomy
Bengal	Typic Hapludults
Bismarck	Typic Dystrudepts
Bismarck-Bt[a]	Lithic Hapludults
Carnasaw	Typic Hapludults
Clebit	Lithic Dystrudepts
Clebit-Bt[b]	Lithic Hapludults
Enders	Typic Hapludults
Endsaw	Oxyaquic Hapludalfs
Honobia	Typic Hapludults
Littlefir	Oxyaquic Hapludults
Nashoba	Typic Dystrudepts
Pirum	Typic Hapludults
Sherless	Typic Hapludults
Sherwood	Typic Hapludults
Stapp	Aquic Hapludults
Townley	Typic Hapludults
Tuskahoma	Albaquic Hapludalfs
Tuskahoma taxadjunct[c]	Lithic Dystrudepts
Udorthents[d]	Typic, Thapto-Histic Udorthents

Taxonomy refers to the suborder level of U.S. Soil Taxonomy.

[a] Similar to the Bismarck series but with a Bt horizon, or similar to the Honobia series, but with a solum thickness less than 50 cm.

[b] Similar to the Clebit series but with a Bt horizon, or similar to the Pirum series, but with a solum thickness less than 50 cm.

[c] Similar to the Tuskahoma series, but lacking low chromas and/or clay texture in the B horizon.

[d] Soils with A–C profiles lacking B horizons. One pedon was thapto-histic.

The fact that 60% of the paired samples had different soil series also argues against topography or microtopography as a control of local spatial variability. This is because the sample pairs were chosen to be identical in slope gradient, curvature, shape, aspect, and elevation. There were 37 different pairs of soils at the 96 pairs with different soils. The single most common combination was Sherless/Honobia, which differ with respect to the rock fragment concentration in the B horizon (16 cases). Relating the criteria in the soil key (Table 1) to the sample pairs with different soils, in 47 cases (49%) the soils differed with respect to depth class (depth to lithic or paralithic contact). In 34 cases (35%), the paired soils varied with respect to rock fragment content of the B horizon, and in 10 cases the difference in taxonomy was related to presence or absence of a Bt horizon. Eight of the pairs differed with respect to presence/absence of colluvial deposits, and seven contrasted in terms of redox features or texture. Surprisingly, given the close proximity of the pairs, 22 pairs (23%) had different parent material (shale versus sandstone). Note that in some cases more than one of the above criteria was applicable.

Taxonomic distinctions are sometimes inevitably based on more-or-less arbitrary categories. Most significant in this context is soil thickness. Hypothetically, otherwise identical soils with depths to lithic or paralithic contacts of 50 and 51 cm could be classified in different series, while two soils 51 and 100 cm thick could be in the same class. The mean difference in soil thickness between the paired samples was 11.4 cm (standard deviation 10.9). For those pairs where soil depth/thickness figured into the soils being classified differently, the mean difference was 19.7 cm (standard deviation 14.1). Of these 47 pairs, 38 (81%) differed in thickness by at least 10 cm. There are inevitably a few cases where depths to parent material a few cm different happen to fall either side of a taxonomic threshold, resulting in different soils being identified. This is a minor factor, however, and is balanced by four pairs where soils differing in thickness by 20 cm or more are in the same series.

Table 3
Soil diversity by plot

Plot type	Plot code	Diff. pairs[a]	No. of soil types	Soils
Treatment	3200 P4	4	4	Sherless, Carnasaw, Littlefir, Honobia
Treatment	3826 P28	6	6	Pirum, Bismarck-Bt, Bengal, Honobia, Bismarck, Clebit
Treatment	4025 P40	7	7	Bengal, Sherless, Bismarck-Bt, Honobia, Pirum, Clebit-Bt, Bismarck
Treatment	3100 P1	6	6	Townley, Carnasaw, Honobia, Carnasaw, Sherless, Endsaw
Treatment	3000 P2	8	8	Bengal, Sherless, Honobia, Stapp, Carnasaw, Townley, Pirum, Clebit
Control	3428 P34	6	6	Sherless, Honobia, Nashoba, Bismarck, Tuskahoma taxadjunct, Clebit
Control	3514 P12	5	5	Sherless, Tuskahoma taxadjunct, Honobia, Bismarck-Bt, Clebit
Control	3514 P8	7	7	Sherless, Townley, Honobia, Pirum, Nashoba, Tuskahoma taxadjunct, Clebit
Control	3912 P10	5	5	Pirum, Clebit-Bt, Townley, Honobia, Sherless
Control	3627 P34	8	8	Honobia, Bismarck-Bt, Sherless, Townley, Bengal, Carnasaw, Nashoba, Pirum
Hardwood	HW1	6	6	Clebit, Clebit-Bt, Pirum, Honobia, Nashoba, Bismarck-Bt
Hardwood	HW2	6	6	Sherwood, Nashoba, Bengal, Sherless, Honobia, Udorthents
Pine	AC1	7	7	Tuskahoma taxadjunct, Sherless, Bismarck, Honobia, Pirum, Bismarck-Bt, Tuskahoma taxadjunct
Pine	Flattop	6	6	Sherless, Honobia, Tuskahoma taxadjunct, Bismarck, Udorthents, Bismarck-Bt
Pine–bluestem	pine–bluestem	4	4	Sherless, Honobia, Townley, Pirum
Undisturbed	Poteau control	10	10	Bismarck-Bt, Clebit, Honobia, Clebit-Bt, Thapto-Histic Udorthents, Bengal, Tuskahoma taxadjunct, Bismarck, Udorthents, Sherless
Mean		6.0	6.4	

Treatment and control sites are both mixed pine–hardwood. Soils were examined prior to treatments. Soil types are listed in the order they were encountered during field sampling.

[a] Number of the 10 sample pairs which differed in soil type.

The richness–area relationship for soil types is $S=1.05N^{0.53}$ for the study area as a whole. For the individual plots, the mean values are $S_i=1.1N^{0.61}$. As expected, c values are near unity, ranging from 0.88 to 1.36 for individual plots. The exponent values range from 0.40 to 0.76. This is higher than the values found for a similarly detailed study in an agricultural area of the southeastern coastal plain, where b values ranged from 0.39 to 0.72, with a mean of 0.53 (Phillips, 2001). The b_i/b ratio is 1.15, indicating local within-plot pedodiversity plays a greater role than between-plot variation.

4.2. Soil properties

ANOVA results are shown in Table 4. These results show more variability between plots than within plots. Thickness of surface litter, total soil thickness, and depth to the B horizon all differ significantly between plots with a significance level of less than 0.01. None of the within-plot variations is statistically significant. The same is true for the topographic variables, as slope and aspect both vary significantly between but not within the study plots. The characteristic aspect, slope, and geomorphic position or slope type for each plot is shown in Table 5.

Table 6 shows the results of entropy analysis for B horizon rock fragment classes. Entropy in general is quite high, ranging from 36% to 98% of the maximum (mean 80%). The mean entropy value of all plots is 0.87 with a range of 0.39–1.08. The overall entropy for all plots lumped together is 1.01. Because entropy is decomposable by scale or hierarchical level (see Batty, 1976; Phillips, 1987), this indicates that about 87% of the overall entropy is accounted for by within-plot entropy. The implications of these results are discussed in the next section.

4.3. Tree throw and stumps

The inventory of tree throws, stumps, and standing dead trees reported by Phillips and Marion (2004) is a

Table 4
Analysis of variance (ANOVA results)

Variation source	SS	MS	F	P-value	F crit
Surface litter thickness					
Intraplot	268.325	14.122	1.148	0.303	1.623
Between plots	1356.2	90.413	7.348	< 0.0001	1.702
Error	3506.675	285	12.304		
Total	5131.2				
Total soil thickness (depth to bedrock)					
Intraplot	3200.034	168.423	0.851	0.645	1.623
Between plots	49 511.517	3300.771	16.671	< 0.0001	1.702
Error	56 427.616	197.992			
Total	109 139.222				
Depth to B horizon					
Intraplot	512.659	26.982	0.694	0.825	1.623
Between plots	4392.547	292.836	7.528	< 0.0001	1.702
Error	11 085.891	197.992			
Total	15 991.097				
Aspect					
Intraplot	9438.306	1048.701	1.205	0.297	1.950
Between plots	82 594.594	5506.306	6.329	< 0.0001	1.741
Error	117 450.594	870.004			
Total	209 483.494				
Slope					
Intraplot	37.220	4.136	0.466	0.895	1.950
Between plots	1615.723	107.715	12.132	< 0.0001	1.741
Error	1198.605	8.878			
Total	2851.548				

Degrees of freedom for surface litter thickness, total soil thickness, and depth to B are 19 for intraplot, 15 for between plot, 319 for total, and 285 for error. For aspect and slope, degrees of freedom are 9 for intraplot, 15 for between plot, 159 for total, and 159 for error. SS = sum of squares, MS = mean square, F = F-ratio, P-value is the statistical significance level, and F crit is the value of F associated with $p = 0.05$.

highly contingent snapshot. Results of any such inventory are likely to vary with whether, or how recently, events such as storms, fires, pest infestations, logging, or other human impacts have occurred. Those results underestimate tree influences for two reasons. First, they do not include living trees. Second, stumps obviously attributable to logging activity were deliberately excluded.

Plots vary greatly in the incidence of tree throw, ranging from none to six throws with a total root wad surface area of more than 20 m^2. The mean was 1.3 per plot, with a mean surface area of disturbance of 2.4 m^2. All plots had tree throws nearby (i.e., visible from within the plot), even if none were found within the plot boundary. Examination of tree throw root wads and pits showed that in almost every case the depth of disturbance coincided with the lower limit of the soil, at a lithic or paralithic contact. The depth of disturbance, as measured from mean thickness of the root wad, ranged from 19 to 100 cm, with a mean of

Table 5
Mean aspect, slope, (both in degrees) and modal geomorphic position of study plots, based on measurements at 10 sample pairs of soil pits

Plot	Aspect	Slope	Modal geomorphic position
3200 p4	144	8.4	straight lower midslope
3826 p28	160	11.3	convex lower midslope
4025 p40	200	8.0	straight midslope
3100 p1	165	11.9	straight upper midslope
3000 p2	133	8.4	convex midslope
3428 p34	156	2.7	spur ridgetop and slope shoulder
3514 p12	100	4.3	straight midslope
3514 p8	133	3.4	concave midslope
3912 p10	205	7.8	concave midslope
3627 p34	209	10.9	straight midslope
HW1	121	9.2	convex interfluve
HW2	2[a]	11.8	convex midslope
AC1	358[a]	8.4	straight midslope
Flattop	329[a]	14.1	straight midslope
Pine–bluestem	120	6.3	concave midslope
Poteau control	169	12.0	concave midslope

[a] Calculation of mean adjusted for circular statistics.

Table 6
Entropy analysis of B horizon rock fragment classes

Plot	Entropy (H)	H/H_{max}
3200 p4	0.562	0.511
3826 p28	1.067	0.970
4025 p40	1.081	0.982
3100 p1	0.687	0.625
3000 p2	1.023	0.936
3428 p34	0.975	0.886
3514 p12	0.938	0.852
3514 p8	0.898	0.816
3912 p10	0.746	0.678
3627 p34	0.898	0.816
HW1	0.938	0.852
AC1	0.394	0.359
HW2	0.791	0.719
Flattop	0.999	0.908
Pine–bluestem	1.049	0.953
Poteau control	0.938	0.852
Total	1.005	0.914
Mean	0.874	0.802

45 cm. Details for individual plots are given by Phillips and Marion (2004).

Plots averaged about nine standing dead trees and stumps >5 cm in diameter (18 total), but basal areas were relatively small (mean of 0.14 and 0.43 m^2 for standing dead trees and stumps, respectively). Sample plots had 2–19 stumps and 3–14 standing dead trees. However, due to exclusion of sawn stumps the inventory is biased toward smaller trees (Phillips and Marion, 2004). In retrospect, the exclusion of sawn stumps was a mistake, as their potential pedological influences would not differ from those of naturally occurring stumps.

The pines at the sites are overwhelmingly shortleaf pine (*P. echinata*). This tree is capable of growing a deep taproot and is considered resistant to windthrow, but in the study area is vulnerable to uprooting from ice storms, apparently due to the relatively shallow soils. Most of the lateral roots occur within the upper 30 cm of soil, but the taproot penetrates to bedrock, and occasionally was observed to penetrate fractures or bedding planes therein. A wide variety of hardwood species may be associated with the mixed pine–hardwood stands, but the most common at the study sites are blackjack oak (*Quercus marilandica*), post oak (*Quercus stellata*) and mockernut hickory (*Carya tomentosa*). All three may develop taproots, and post oak in particular tends to have most of the lateral roots concentrated in the upper soil, above the B horizon. According to the U.S. Department of Agriculture's plants database (http://plants.usda.gov), minimum rooting depths are about 130 cm for mockernut hickory, 90 cm for post oak, and 60 cm for blackjack oak and shortleaf pine.

5. Discussion

There is a high degree of spatial variability of soil types in the Ouachita study sites. The richness–area analysis indicates that local, within-plot sources of pedodiversity are more important than broader-scale, between-plot sources. Differences among the 16 plots in general topography (slope and aspect), vegetation cover, site history, and parent material contribute less to soil diversity than variation within the plots. Given the overall general homogeneity within plots, the most likely local controls are associated with microtopography; the pedological effects of individual trees, which may be manifested via chemical, hydrological, or mechanical effects; and local variability within the parent material.

Microtopography does not appear to be the primary control of the local variability in soil morphology. ANOVA results show that aspect and slope are more variable between-plots than within-plots. More importantly, 60% of the sample pairs had different soils, even though the pairs were almost all within 1 m of each other, and were selected to have no observable differences in slope gradient, curvature and shape, elevation, and aspect.

Pedological influences of trees do appear to be important controls of local soil variability. These influences no doubt include a variety of chemical, biological, and hydrological effects on soil processes and properties, but in this case generally biomechanical effects are paramount, due to the way soils were differentiated, based on profile morphology. Rock fragment content of the B horizon is an important discriminator. The clasts are overwhelmingly sandstone, and were generally unrelated to the underlying parent material. In 238 of the 320 pits the parent material was shale, but even in the case of sandstone parent material there were often obvious differences in color and hardness between the soil fragments and the bedrock. The apparent source of the rock is transport from the ridgetops and upper slopes. Thus the presence of fragments well below the surface (typically throughout the solum) in predominantly residual soil implies vertical soil mixing or burial.

While faunalturbation is no doubt significant, and can result in the burial of surface clasts, we believe tree effects are more significant, for two reasons. First, we observed numerous cases of unburied sandstone fragments in tree throw pits, suggesting recent deposition, and in pits created by stump rot. Second, subsurface rock fragment concentrations tend to be highly localized. Subsurface stone lines or stone zones were identified in 57% of the 320 sample pits, defined on the basis of rock fragment percentages of at least 70%, and at least 20% higher than layers above and below. Recall that these sample pits are about 30 cm in diameter. In 49 full-size, fully described soil pits at the same plots (at least three per plot), no stone lines or stone zones were observed (data from Ken Luckow, soil scientist, Ouachita National Forest; 19 of the pits were also observed and described by the authors). In the sample, posthole-size pits, a stone concentration with a projected surface area of about 500–700 cm^2 would be sufficient to result in the identification of a stone line or zone. In a soil pit, a stone line or zone would have to be observed in two or three pit faces to be so identified in the descriptions, and would thus likely represent a projected surface area of at least 5000–10,000 cm^2. Stone lines or zones associated with faunal turbation would be expected to be more areally extensive than those associated with point-centered processes associated with tree throw or stump holes. The highly localized nature of the stone lines or zones suggests point-centered rather than spatially diffuse burial processes.

The variability of rock fragment classes, indicated by entropy statistics, is dominated by within-plot variations. This also points to biomechanical effects of trees, which may substantially influence rock fragment contents and distributions on a tree-by-tree basis. Tree throw may deplete subsoils of rock fragments as soil material is ripped out by rootwads. Pits associated with tree throw or stump rot may enrich the subsoil with sediments as mass wasting and bioporting (transport by biota) delivers stones to the pits, which are subsequently filled. The growth of trees may also displace near-surface rocks.

Soil depth varies primarily between rather than within plots, yet is an important determinant of local (within-pair) soil differences. Where this criterion results in taxonomic variation between members of a sample pair, the mean difference is about 20 cm. A number of factors could account for this, but we believe two are of particular importance. First, tree roots—especially pine tap roots—routinely penetrate into weathered parent material. Filling of associated cavities created by stump rot or tree throw can locally thicken soils. Second, in some cases strongly tilted parent strata creates local irregularities in the geometry of the top of C, Cr, and R horizons. In the 19 soil pits observed by the authors, 4 had irregular, 3 had wavy, and 1 had discontinuous horizon boundaries above, below, or within C or Cr horizons. Differences in soil thickness associated with vertical leaching and translocation are possible, but litter thickness and depth-to-B also vary more between plots, where the ANOVA shows highly significant *F*-ratios, than within plots (Table 4).

Parent material variation within plots and within sample pairs was surprisingly high. Given the size of the plots and the lack of any obvious surface expression of major lithological boundaries, it is unlikely that sample pits simply happened to be in the vicinity of boundaries between surficial formations. This leaves two general possibilities: the presence of localized veins, lenses, or bedding planes (for example of sandstone within dominantly shale bedrock); and soils formed on boulders or debris aprons transported from upper slopes. Given the interbedded shales and sandstones in the parent geology, the extensive and complex folding and tilting of strata, and the obvious evidence of material transport from ridgetops, both possibilities are likely.

The downslope transport of material accounts for some of the pedodiversity, via the identification of soils formed in colluvium. At the study plots this is predominantly in the form of mass wasting, but on the Ouachita side slopes more generally fluvial processes are also significant. Erosion and deposition can also contribute to local fluctuations in soil thickness, and to local variations in parent material. The data suggest that this is a minor factor in creating the short-range variability observed in the study plots, based on the assumption that such influences would be reflected in an important role for topography, which does not appear to be the case. Soils formed in colluvium were defined in the field on the basis of abrupt variations in texture and rock fragment lithology or burial of intact surface organic litter in suitable topographic positions. As the shedding of rock fragments from ridge tops to the side slopes appears to be ubiquitous, the gradual input of colluvial material (as opposed to large events or episodes that locally bury underlying regolith) appears to be a significant process that deserves further investigation.

At the outset of this study, the focus was on the potential role of individual trees and microtopography. The importance of geological variation within the parent material emerged as the study proceeded. We suggest that future work should address this issue further, perhaps making use of outcrops and trenches so that parent geology and stratigraphy can be more readily related to overlying soil and regolith properties.

It is unlikely that results in the Ouachita region can be applied uncritically to other forest areas, particularly where geology, climate, and vegetation communities differ appreciably. However, biomechanical effects of trees are likely to be common in forest soils, and have been shown to be related to local soil variability in a number of other forest settings (see Introduction). In areas of complex geology, such as the Ouachitas, it may also be expected that parent material variations may persist and perhaps be exaggerated over time in soil and regolith evolution, further contributing to local variability. The general phenomenon of forest soils that are quite variable even within relatively small areas of apparently uniform geology, topography, and vegetation is therefore likely to be very common.

Other studies which have shown that microtopographic influences, particularly associated with local convergence and divergence of infiltrating and percolated water, can have disproportionately large effects of soil morphology (Price, 1994, Phillips et al., 1996; Miller et al., 1999; Wright, 1996). The lack of such evidence in this study is likely attributable to microtopographic effects being overwhelmed by other factors. For example, it is possible that infiltration and percolation is controlled to such an extent by textural variations and macropores that microtopographic funneling is of little significance. Further, any highly localized topographic influences on soil morphology may be overwhelmed by effects of trees and/or lithological variations.

The role of individual trees in influencing soil morphology deserves further attention. If the relationships between tree throw, stump rot, and morphological effects of living trees and soil morphology can be worked out in greater detail than is now possible, pedologic and paleopedologic evidence can shed more light on forest ecosystem change. Climate changes that influence ice storm and wind events, for example, might be reflected in soil morphologies related to tree throw. Soil features related to tree throw versus stump rot or burning could reflect vegetation change (for example hardwoods versus pines, which often differ in their tendency to uproot) or vegetation management (for instance, harvesting of trees that might otherwise have a tendency to be uprooted). Features such as ‘‘basket podzols,’’ morphology related to tree throw mounds and pits, and fossil tree casts are already useful in paleoenvironmental interpretations (Retallack, 1990; Mossa and Schumacher, 1993; Schaetzl, 1990; Schaetzl et al., 1990; Stephens, 1956). The potential to expand those possibilities, and to predict impacts of vegetation change and forest management on soil morphology, is high.

6. Conclusions

Pedodiversity as reflected in soil richness is high on side slopes of the Ouachita Mountains, Arkansas, with contrasting soil series occurring in close proximity, and considerable variation over short distances and small areas. The spatial pattern of soil diversity initially suggested the possibility that effects of individual trees and microtopography could be the major controls of soil variation. Richness–area analysis shows that pedodiversity is dominated by local, intrinsic (within-plot) variability as opposed to between-plot variability. This is consistent with the unstable magnification of relatively small or short-lived influences such as trees or microtopography. Microtopography, however, does not have a major influence on the soil variability in the study area, probably because its effects are overwhelmed by those of trees and parent material variability.

The criteria used to identify soils in the field and the nature of the soil diversity point to a key role for biomechanical effects of trees, including vertical mixing via tree throw, root displacement, and filling of stump holes. The other major control of local variations in soil richness appears to be lithological variability associated with local veins, lenses or bedding planes in the sedimentary rock parent material, or with localized and buried boulder deposits.

Spatial variation in soil morphology at the study site is an outcome of a particular combination of the landscape setting and geological framework, so these results can be applied to other areas only with caution. However, two generalities are likely relevant in a wide variety of settings. First is the pedologic signature—that is, local spatial variation in soil morphology—of lithological impurities and biotic effects, which may be unstably magnified relative to the initial magnitude of the effects. Second, given the likelihood of biomechanical effects of trees in many forests, it is likely that local variability of forest soils, not necessarily related to controls or influences readily observable or measurable, is quite common.

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