Original papers

The spatial variability of soil resources following long-term disturbance

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Abstract. The spatial distributions of selected soil properties in two adjacent sites in southwest Michigan were examined to evaluate the potential effects of chronic disturbance on resource heterogeneity. One site was a cultivated field that had been cleared, plowed, and cropped annually for decades prior to sampling while the other, uncultivated field was cleared of original forest in 1980 after which it was allowed annually but never plowed or cropped. We took replicate samples from a 330-point unaligned grid across the sites for soil pH, gravimetric moisture, inorganic phosphorus, total carbon, and net nitrification and nitrogen mineralization potentials. Soils in the cultivated site contained less than half as much carbon as in the uncultivated site, but had higher levels of inorganic phosphorus and moisture, and higher soil pH. Potential net nitrogen mineralization and nitrification rates did not differ between sites. Geostatistical analysis showed that almost all properties examined were strongly autocorrelated within each site; structural variance as a proportion of sample variance ranged from 30-95% for all properties, and for any given property differed little between sites. The distance over which this dependence was expressed, however, was for all properties but pH substantially less in the uncultivated site (7-26 m) as compared to the tilled site (48-108 m), especially for total C and net nitrification and N mineralization. These results suggest that the spatial pattern and scale of soil variability can differ markedly among edaphically identical sites and that these differences can be related to disturbance history.

Key words: Soil nutrients – Spatial variability – Geostatistics – Disturbance – Nitrogen cycling

Spatial heterogeneity is an inherent feature of virtually all plant communities, and the scale and degree to which this heterogeneity is expressed belowground can have important consequences for both community structure (Tilman 1983) and ecosystem-level processes (Robertson and Goss 1994). In recent years substantial effort has been directed towards explicitly quantifying field-scale (1-100 m) variability for biologically important soil properties, most notably in agricultural sites (see, e.g. reviews by Trangmar et al. 1983; Warrick et al. 1986; Webster and Olver 1986). For our data are available for nonagricultural sites, but existing studies (e.g. Snyodon 1982; Robertson et al. 1985; Allen and Aiken 1990; Hook et al. 1991; Jackson and Caldwell 1993) tell us that in the plant communities examined, many soil properties vary in statistically predictable ways at scales that might influence (and eventually reflect) vegetation dynamics.

Unclear, however, are the specific factors that appear to underlie soil variability in most sites, e.g. whether variability is more related to environmental factors such as prevailing weather patterns or differential distributions of soil parent material than to the accumulated effects of individual plants. Also unclear is the likely persistence of the patterns described: how and to what extent patterns of variability will change in time, particularly in response to site disturbance. This latter question may be especially important for understanding vegetation dynamics in early succession, since disturbances that affect the heterogeneity of soil resources may have a major impact on the distribution of successful individual colonizers.

In the present paper we describe an initial attempt to understand the role of chronic soil disturbance on the spatial structuring of several soil properties important to plants. On a single sample date we quantified the spatial distribution of soil nitrogen mineralization potentials, carbon, phosphorus, moisture, and pH at two adjacent sites: one site had been subjected to long-term soil and vegetation disturbance — annual plowing and monoculture cropping for > 30 years — and the other undisturbed but for annual mowing following tree removal > 30 years prior to sampling. The nature of this study is largely descriptive; the patterns described, however, suggest that
the spatial pattern and scale of soil variability can differ markedly among edaphically identical sites and that these differences can be related to disturbance history.

Site description

This study was conducted at the W. Kellogg Biological Station (KBBS) in southwest Michigan (42° 24' W longitude, 42° 24' latitude). KBBS is located in the priced outwash plain of the morainic system left by the last retreat of the Wisconsin glaciation, ca. 14,000 B.P. Soils in the KBBS are developed on glacial outwash materials at ever site are Typic Hapludults either fine-loamy, mixed, mesic (Kalamazoo series) or fine-loamy, mixed (Osborne series; Whitehead et al. 1959). Mean annual temperature is 9°C; precipitation (ca. 86 cm yr⁻¹) is evenly distributed throughout the year.

The 2.2 ha cultivated site was cleared of its original vegetation (oak-hickory, Quercus-Carya spp., forest) prior to 1930 and plowed and planted every spring at least since 1930. In the fall prior to sampling for this study the site had been plowed (withoutillage) to a winter cover of annual grasses (Lolium sp.). The adjacent 0.6 ha uncultivated site was— togethers with a larger area— cleared of the original oak-hickory forest in 1960 and has been mowed once every fall since then. The vegetation at this site is dominated by heterocenous perennial dicots and grasses, including Trifolium pratense, Rosa spp., Medicago lupulina, Achillea millefolium, Bromus spp. and Poa spp. Both sites occur in a landscape matrix that is essentially cropland with adjacent patches of forest.

Materials and methods

In early May, prior to plowing the cropped site, we established 216 sample locations on the historically tilled site and 63 locations on the smaller uncultivated site. Sample locations were chosen on the basis of a stratified unplugged sampling strategy (Webster and Oliver 1990) designed to provide both a representative number of samples separated by small (<15 m) sample intervals and coverage of each site sufficient to allow confident mapping. Each site was sampled at the same density (ca. 110 sample locations/ha).

On a single sample date in May we took 2.5 cm diameter × 20 cm deep soil cores from a 9.07 m² area (11.5 cm radius) at each of the sample locations in each site. The cores were composited by location, refrigerated on site, and taken to a laboratory where each composite was mixed, put through a 4 mm sieve, and subsampled for replicates individual analyses. Three 10 g subsamples of each of the 312 composites were then analyzed for soil pH in a 2:1 water:soil suspension. Three additional 10 g subsamples of each composite were extracted in 100 ml of 0.5 M NaCl for later determination of NH₄ and NO₃ by flow injection analysis (Ruggiero and Henion 1981). One 10 g subsample from each composite was placed at 10°C for 30 min in gravimetric water determination; this dried soil was then crushed and further subsampled for carbon and phosphorus analysis. Three subsamples were analyzed for carbon via the Walkley-Black wet combustion technique (Nelson and Sommers 1982). For phosphorus analysis, three 5 g subsamples were each extracted in 10 ml Brön-Böhr's P-3 extractant (Olson and Sommer 1983) and analyzed by flow injection analysis.

The remainder of the triplicated undisturbed soil samples (3 to 8 per sample location) was placed in a 2 L polyethylene bag and incubated in the dark at 15°C. After 10 days, three 10 g subsamples from each of the composites were extracted in 2 M NaCl and analyzed for inorganic N as described above. The net increase in inorganic N over the incubation interval was used to indicate net nitification potential. Net N mineralization was defined as the net increase in NH₄-N + NO₃-N over this interval. For all soils, but moisture the analytical coefficient of variation (n = 2 replicate samples per sample location or composite except n = 1 for moisture) was 5% or less (samples outside this range were re-analyzed). Analytical means were used for subsequent statistical analysis.

Geostatistical analyses (Webster 1985; Robinson 1987; Rossi et al. 1992) were performed using GS* (Gamma Design 1992). All variograms were estimated using a spherical model weighted least-squares analysis (c u f Riese 1991). Semivariances were plotted into 15 separation distance (lag) classes for spatial fitting; the separation distances between each lag class (step size) was 0.0 m, with pairs of points in the first lag separated by an average distance of 1.2 (lag 1) or 1.9 (lag 2) cm. For the uncultivated site the number of samples in pairs in the first through third distance classes (ca. 2, 4, and 16, respectively) were 16, 16, and 14 pairs; for the cultivated site corresponding values were 75, 75, and 77 pairs.

For variogram models the semivariance data were fit to either spherical or exponential functions (Webster 1985; Isaaks and Srivastava 1989) depending on the better reduced sums of squares fit. For comparative purposes all models but one were fit across a range of 0-120 m, although in cases examined because semivariances tended to become erratic at longer lag intervals—a fit to a smaller lag would have better minimized model variance. One exception to this was moisture, which was fit across a smaller (0-80 m) range due to very erratic semivariances at greater lags. In almost all cases the model chosen appeared to describe semivariances at small lag intervals very well. Maps of properties were also produced with GS* (Gamma Design 1992); following a ordinary block kriging with a block size of 0.5 x 0.5 m both with and without standardization grid within each block. All data but pH were logtransformed prior to analysis and analysis backtransformed to original units prior to mapping. backtransformations followed Krig (1981).

We use the proportion of model sample variance [C - C̃] explained by structural variance C (the relative nugget effect vary (and Srivastava 1989) as a normalized measure of spatial determination for a particular soil property, i.e., where the value of C/C = C̃) approaches 1 because of a small nugget variance term C̃, spatial dependency is high over the range of separation distances modeled: where this value is close to 0 for a large nugget variance term C̃, spatial dependency is low. In terms of model sample variance [C - C̃] is less than total sample variance V, indicating potential spatial dependency outside the range of separation distances modeled (Barnes 1991); in which instance a property’s spatial dependency may be scale-dependent, i.e. different levels of dependence may occur across different scales within the spatial domain sampled (Robson and Gross 1994).

Results

All six of the sampled soil properties (pH, moisture, total carbon, inorganic P, and net mineralization potential) varied markedly within each of the sites, with ranges for all properties but moisture spanning an order of magnitude or more in one or both sites (Fig. 1). Coefficients of variation (calculated as standard deviation divided by mean) correspondingly varied from 135% for soil moisture in the uncultivated site to almost 90% for H⁺ activity in both sites, though for most properties coefficients were within the orders of magnitude Table 1).

Between-site differences were generally distinct. Soils in the uncultivated site had a lower pH and about half the
amount of inorganic P than did soils in the cultivated site, and had about twice the total carbon and (on the date sampled) soil moisture. Net nitrification and N mineralization rates between sites were essentially identical (Table 1).

Variograms for each of the variances (Fig. 2) showed strong spatial dependence for almost all variances at both sites. The sole exception was moisture in the uncultivated site, which exhibited little if any spatial dependence at the scales examined (1-120 m). All other variances - including moisture in the cultivated sites - exhibited stronger to strong spatial dependence, with structural variance [C] as a proportion of modeled sample variance [C' + C], ranging from 67 to 95% for H+ activity, moisture, and inorganic P (Table 2). For total carbon, net nitrification, and net N mineralization, this proportion ranged from 30-42% in both sites. With the exception of soil moisture, the degree of spatial dependence was strikingly similar between sites for any given variance: the rate of structural/model sample variance [C: C + C] for any individual variance differed by more than about ±10% between sites.

Unlike spatial dependence per se, however, the distance over which this dependence was expressed varied markedly between sites. For every variance but pH, semivariogram ranges were substantially greater in the cultivated than in the uncultivated sites (Table 2), often by a factor of >3. Total soil carbon, for example, was spatially autocorrelated to ca. 50 m in the cultivated site but to only about 7 m in the uncultivated site. Net nitrification and N mineralization were spatially dependent to >100 m in the cultivated site but to only about 11 m in the tilled site.

**Discussion**

The cultivated and uncultivated sites differed substantially in both the magnitudes and the spatial scales over which soil properties varied. For the most part differences were consistent with what might be an expected consequence of tillage and cultivation (Stevenson 1982; Mann 1985; Webster and Nyborg 1986): total carbon was substantially lower on the cultivated site and soil pH and inorganic P levels were substantially higher. These effects likely result from tillage-induced depletion of soil organic matter and cultural practices such as liming and
P fertilization that are designed to maintain high soil pH and inorganic P. The higher soil moisture in the uncultivated site in early spring likely reflects the greater water holding capacity of these higher-C soils (Reznick and Pierce 1992). It is remarkable that nitrogen mineralization and nitrification potentials were similar for both sites; this suggests that available nitrogen did not differ much between sites on this early spring sample date despite differences between sites in total carbon.

Spatial dependence

Each of the soil properties we examined exhibited different levels of spatial dependence that appeared to be surprisingly little affected by disturbance. For example 95% of the model sample variance \( C + C_u \) for inorganic P can be attributed to spatial autocorrelation in the cultivated site vs. 84% in the uncultivated site (Table 2). For net N-mineralization, 38% of model sample variance appears spatially dependent in the cultivated site vs. 42% in the uncultivated site. Only for soil moisture do inter-site differences in the proportion of sample variance that is spatially dependent exceed 12%.

Nevertheless, while the degree of spatial dependence for most properties appears to be little affected by disturbance history, the distance over which this spatial dependence is expressed differs substantially and consistently between sites for most properties. Except for soil pH, the distance over which we could detect dependence is much greater in the cultivated than in the uncultivated sites. For total carbon, net nitrification, and net N mineralization, for example, we detected spatial autocorrelation among points as distant as 49–109 m in the cultivated site; this contrasts to maximum ranges in the uncultivated site of only 7–11 m (Table 2).

In geostatistical analysis the proportion of sample variance not directly attributable to spatial autocorrelation — i.e. the nugget variance of \( C_u \) — is due to random field and laboratory sampling error and autocorrelation at scales smaller than the smallest interval separating sampled points (1.4 m in this study). We attempted to minimize field sampling error by compositing mixing

<table>
<thead>
<tr>
<th>Variate</th>
<th>Site</th>
<th>Model Type</th>
<th>Model Parameters</th>
<th>Range (m)</th>
<th>( \sigma^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>Cultivated</td>
<td>Exponential</td>
<td>0.023, 0.07</td>
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<tr>
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<td>0.0086, 0.45</td>
<td>21.9, 0.228</td>
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<tr>
<td>PO4-P</td>
<td>Cultivated</td>
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<td>0.065, 0.95</td>
<td>63.9, 0.936</td>
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<tr>
<td></td>
<td>Uncultivated,</td>
<td>Spherical</td>
<td>0.051, 0.84</td>
<td>36.4, 0.843</td>
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<tr>
<td>Total Carbon</td>
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<td>0.032, 0.34</td>
<td>7.4, 0.465</td>
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<tr>
<td>Net N-Mineralization</td>
<td>Cultivated</td>
<td>Spherical</td>
<td>0.040, 0.41</td>
<td>108.6, 0.598</td>
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<td>Spherical</td>
<td>0.056, 0.42</td>
<td>10.7, 0.43</td>
<td></td>
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</tbody>
</table>

\[ \gamma(h) = C_u + (C - C_u) \left( \frac{1}{1 + \frac{h}{\sigma}} \right) \] range = 3\( \sigma \)

\[ \delta = \text{range} \] for \( \gamma(h): \text{range} = \text{range}\]

\[ \gamma(h) = C_u + (C - C_u) \left( \frac{1}{1 + \frac{h}{\sigma}} \right) \] range = 3\( \sigma \)

\[ \delta = \text{range} \] for \( \gamma(h): \text{range} = \text{range}\]

\( \delta \) values are provided for comparative purposes only; model parameters were chosen by least-squares criteria...
several soil cores per sample location and attempted to minimize analytical error by uplogging soil extractions and analyse sufficient to maintain analytical variability to ±5% CV. If these measures did, in fact, keep random sampling error small, then the nugget variance we estimate for most variates is predominately due to autocorrelation at scales of < 1.4 m. This implies that for many of the properties we examined (notably soil carbon, nitrogen, net N mineralization, and moisture), greater than 50% of its variability is occurring at the scale of individual plants or smaller.

For all properties in both sites-model sample variabilities [C + C0] coincided almost exactly with overall within-site sample variabilities (Table 3). This suggests that within these sites there are no additional levels of spatial dependence beyond the 120 m for which we could confidently model semivariance. Were such levels present—e.g. if a nested structure were present but not detected within 120 m—within-site sample variiances would significantly exceed model sample variance (Burns, 1991).

A short range over which spatial dependence is expressed together with a nonuniform frequency distribution for the given variate suggests a "hot-spot" distribution pattern for that variate. For such variates, a small number of dispersed locations in a site can contribute disproportionately to total site mean. Frequency distributions and variograms for our data suggest that, in general, high values should be more spatially aggregated in the uncultivated site than in the cultivated site. Figure 3 illustrates this patchiness for net N mineralization; other properties (not illustrated) were dispersed similarly. Note that net N mineralization rates differed between sites only in their patchiness—mean rates did not differ between sites (0.87 vs. 0.89 mg g⁻¹ d⁻¹ N; Table 1).

This pattern probably reflects the long-term influence of tillage on soils of the cultivated site. Although the primary action of plowing is to inves the soil profile to a depth of 20-30 cm, increased humus and erosion as a consequence of plowing ought, over decades, to result in the gradual dispersion of soil properties now evident on the cultivated site. In Fig. 3, e.g., net N mineralization appears variably in homogenous patches in the cultivated than in the uncultivated site; this pattern is also evident for other properties (not shown). The imposition of a plow monoculture on the site may additionally affect variability by removing—or at least homogenizing—the potential for different individual plant species to affect soil heterogeneity. In contrast, a major portion of long-term spatial variability in the never tilled site likely remains plant-induced—both sites developed on well-sorted glacial outwash deposited ca. 12,000 B.P.; parent (C-horizon) material is uniform sand, shorter term variability is also likely affected by individual plants—especially by longer-lived perennial (e.g., Wedin and Tilman, 1999). In the tillled site, however, the influence of individual plants will have been diminished as monocultured annuals replaced the original polyculture; although even monocultured plants in this site may strongly affect the small-scale spatial structuring of some soil processes such as carbon and nitrogen availability (e.g. Jackson and Caldwell, 1993), most of these effects will persist only until the next plowing.

The degree and scale of spatial dependence found in this study is similar to that found in a previous study by Robertson et al. (1988). Using a similar sampling regime in a 0.25 ha field 40-year post-abandonment from agriculture, they found that structural variabilities were ca. 40-65% of modeled sample variances for most soil properties examined, including net nitrification and net N mineralization. The distances over which dependence were expressed—1 to 40 m—were similar to those found in the present study's uncultivated site. Suggesting that plowing's apparent effect on spatial patterning may persist for decades following abandonment. Also consistent with our finding of smaller-scale patterning in our uncultivated site.