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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 1960 after which it was mown 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 1988) and ecosystem-level processes (Robertson and Gross 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. 1985; Warrick et al. 1986; Webster and Oliver 1990). Fewer data are available for nonagricultural sites, but existing studies (e.g. Snaydon 1962; Robertson et al. 1988; Allen and Allen 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 site 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

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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.K. Kellogg Biological Station (KBS) in southwest Michigan (85° 24′W longitude, 42° 24′ latitude). KBS is located on the pitted outwash plain of the morainic system left by the last retreat of the Wisconsin glaciation, ca. 14 500 years B.P. Soils in the area developed on glacial outwash; soils at our site are Typic Hapludalfs either fine-loamy, mixed, mesic (Kalamazoo series) or coarse-loamy, mixed, mesic (Oshtemo series; Whiteside 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 1950. In the fall prior to sampling for this study the site had been planted (without tillage) to a winter cover of annual ryegrass (*Lolium* sp.). The adjacent 0.6 ha uncultivated site was – together 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 herbaceous perennial dicots and grasses, including *Trifolium pratense*, *Rosa* spp., *Medicago lupilina*, *Achillea millefolium*, *Bromus* spp. and *Poa* spp. Both sites occur in a landscape matrix that is primarily cropland with adjacent patches of forest.

Materials and methods

In early May, prior to plowing the cropped site, we established 256 sample locations on the historically tilled site and 65 locations on the smaller uncultivated site. Sample locations were chosen on the basis of a stratified unaligned sampling strategy (Webster and Oliver 1990) designed to provide both a reasonable 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 five 2.5 cm diameter × 20 cm depth soil cores from a 0.07 m^2 area (15 cm radius) at each of the sample locations in each site. The five 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 replicated individual analyses. Three 10 g subsamples of each of the 321 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 2 M NaCl for later determination of NH_4^+ and NO_3^- by flow injection analysis (Ruzicka and Hansen 1981). One 80 g subsample from each composite was dried at 105° C for gravimetric water determination; this dried soil was then crushed and further subsampled for carbon and phosphorus analyses. Triplicate subsamples were analyzed for carbon via the Walkley-Black wet combustion technique (Nelson and Sommers 1982). For phosphorus analyses, three 5 g subsamples were each extracted in 50 ml Bray's P-1 extractant (Olsen and Sommers 1982) and then analyzed by flow injection analysis.

The remainder of the original undried soil composite (> 80 g per sample location) was placed in a 2L polyethylene bag and incubated in the dark at 25° 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 NO_3^--N over the incubation interval was used to indicate net nitrification potentials. Net N mineralization was defined as the net increase in NH_4^+-N + NO_3^--N over this interval. For all soil analyses but moisture the analytical coefficient of variation ($n \geq 3$ 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 geostatistical analysis.

Geostatistical analyses (Webster 1985; Robertson 1987; Rossi et al. 1992) were performed using GS^+ (Gamma Design 1992), including variogram model fitting, which was performed via unweighted least-squares analysis (*cf* Cressie 1991). Semivariances were grouped into 15 separation distance (lag) classes for model fitting; the separation distance between each class (step size) was 0.8 m, with pairs of points in the first class separated by an average distance of 1.2 (cultivated) or 1.9 (uncultivated) m. For the uncultivated site the number of pairs in the first through third distance classes (ca. 2, 8, and 16 m respectively) were 16, 146, and 147 pairs; for the cultivated site corresponding values were 37, 587, and 727 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 many cases – because semivariograms 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 models chosen appeared to describe semivariances at small lag intervals very well. Maps of properties were also produced with GS^+ (Gamma Design 1992), following ordinary block kriging with a block size of 0.5 × 0.5 m across each site and a 2 × 2 discretization grid within each block. All data but pH were lognormally transformed prior to analysis and backtransformed to original units prior to mapping; backtransformations followed Krige (1981).

We use the proportion of model sample variance $[C + C_0]$ explained by structural variance C (the relative nugget effect *sensu* Isaaks and Srivastava 1989) as a normalized measure of spatial dependence for a particular soil property. I.E., where the value of $[C/(C + C_0)]$ approaches 1 (because of a small nugget variance term C_0), spatial dependence is high over the range of separation distances modeled: where this value is close to 0 (due to a large nugget term), apparent spatial dependence is low. In some cases model sample variance $[C + C_0]$ is less than total sample variance s^2, indicating potential spatial dependence outside the range of separation distances modeled (Barnes 1991); in such instances a property's spatial dependence may be scale-related, i.e. different levels of dependence may be occurring at different scales within the spatial domain sampled (Robertson and Gross 1994).

Results

All six of the sampled soil properties (pH, moisture, total carbon, inorganic P, and net nitrification and N mineralization potentials) 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]/[mean]) correspondingly varied from 13% for soil moisture in the uncultivated site to almost 90% for H^+ activity in both sites, though for most properties coefficients were on the order of 30–70% (Table 1).

Between-site differences were equally distinct. Soils in the uncultivated site had a lower pH and about half the

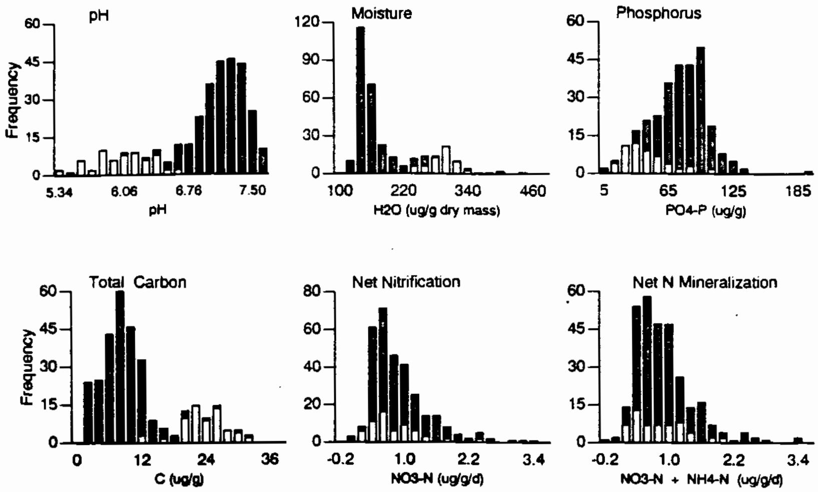

Fig. 1. Frequency distributions for soil properties in each site. Shaded bars represent historically tilled samples, unshaded bars represent never tilled. ■ cultivated; □ uncultivated

Table 1. Soil properties examined in both cultivated (4 ha) and uncultivated (1 ha) sites. Values are untransformed means (n = 240–256 sample locations) for the entire site followed by standard deviations (SD), coefficients of variation (CV), and number of sample locations (n) for each untransformed variate. Analytical replicates (n = 3) were used to estimate values at each sample location. All values but H^+ activity are on a dry soil mass basis

Property	Units	Cultivated Site				Uncultivated Site			
		mean	SD	%CV	n	mean	SD	%CV	n
H^+ Activity	$[H^+] \times 10^{-6}$	0.085	0.075	88.2	256	1.16	1.00	86.2	65
	pH	7.16	0.26	3.6	256	6.08	0.37	6.1	65
Moisture	mg/g	162.0	34.0	21.0	255	297.0	38.0	12.8	65
Inorganic P	ug/g	80.4	20.7	25.7	228	49.5	31.4	63.4	58
Total C	ug/g	8.45	4.37	51.7	251	23.2	4.6	19.8	65
Nitrification N[a]	$ug\ g^{-1}\ d^{-1}$	0.89	0.53	59.6	245	0.81	0.58	71.6	63
N Mineralization[a]	$ug\ g^{-1}\ d^{-1}$	0.89	0.52	58.4	240	0.87	0.65	74.7	61

[a] Net rates, based on 10-day laboratory incubations at 25 °C with soil moistures maintained at existing field values

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 variates (Fig. 2) showed strong spatial dependence for almost all variates 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 variates – including moisture in the cultivated sites – exhibited moderate to strong spatial dependence, with structural variance [C] as a proportion of model sample variance $[C+C_0]$ 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 variate: the ratio of structural : model sample variance $[C:C+C_0]$ for any individual variate differed no more than about $\pm 10\%$ between sites.

Unlike spatial dependence *per se*, however, the distance over which this dependence was expressed varied markedly between sites. For every variate 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 are consistent with what might be an expected consequence of tillage and cultivation (Stevenson 1982; Mann 1986; 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

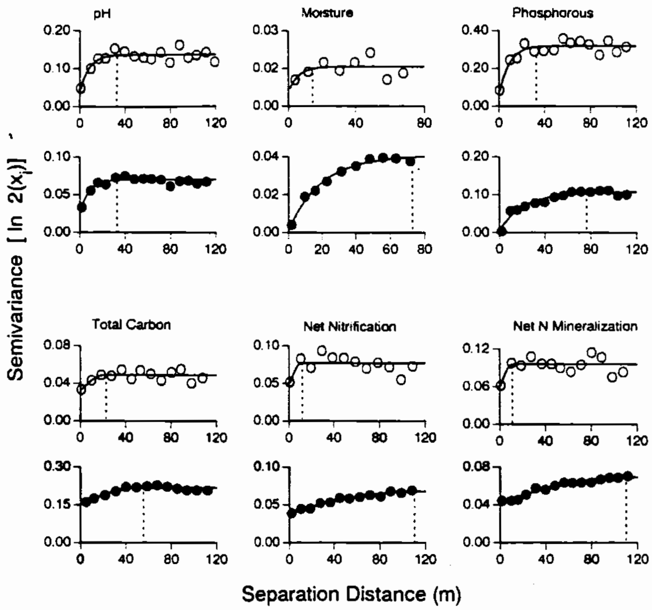

Fig. 2. Variograms for soil properties in the uncultivated and cultivated sites. Shaded symbols represent the cultivated site (the lower figure in each variate pair), open symbols represent the uncultivated site (the upper figure in each pair). Vertical dashed lines indicate variogram ranges on the x-axis; note that except for pH, ranges are always more distant in culva sites. *Symbols:* ● cultivated; ○ uncultivated

P fertilization that are designed to maintain high soil pH and inorganic P. The higher soil moisture on the uncultivated site in early spring likely reflects the greater water holding capacity of these higher-C soils (Reinert 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 $[C+C_0]$ 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 or C_0 – 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 and mixing

Table 2. Variogram model parameters for soil properties across each site. C_0 = nugget variance. $C/(C_0+C)$ = structural variance C as a proportion of model sample variance $[C_0+C]$; range = distance (m) over which structural variance expressed. See Fig. 2 for Variograms

Variate	Site	Model Type	Model Parameters			
			C_0	$C/(C_0+C)$	Range (m)	r^{2d}
pH	Cultivated	Exponential[a]	0.023	0.67	22.8	0.920
	Uncultivated	Exponential	0.035	0.75	24.6	0.772
Moisture[c]	Cultivated	Spherical[b]	0.0052	0.87	48.4	0.973
	Uncultivated	Spherical	0.0086	0.45	21.9	0.238
PO_4-P	Cultivated	Exponential[a]	0.005	0.95	63.9	0.936
	Uncultivated	Exponential	0.052	0.84	26.4	0.843
Total Carbon	Cultivated	Spherical[b]	0.152	0.30	49.1	0.885
	Uncultivated	Spherical	0.032	0.34	7.4	0.485
Net Nitrification	Cultivated	Spherical[b]	0.040	0.41	108.6	0.958
	Uncultivated	Spherical	0.047	0.39	10.9	0.356
Net N-Mineralization	Cultivated	Spherical[b]	0.043	0.38	103.8	0.958
	Uncultivated	Spherical	0.056	0.42	10.7	0.43

[a] $\gamma(h)=C_0+(C-C_0)\cdot(1-e^{-h/a})$; range = 3(a)
[b] for h ≥ range, $\gamma(h)=C_0+(C-C_0)\cdot(1.5\cdot h/\text{range})-0.5\cdot(h/\text{range})^3$; for h < range, $\gamma(h)=C$
[c] maximum lag = 80 m rather than 120 m as for others (see Fig. 2)
[d] r^2 values are provided for comparative purposes only; model parameters were chosen by least-squares criteria

Table 3. Sample variance (s^2) and model variance (C_0+C) for the transformed soil properties noted in Tables 1 and 2

Property	Cultivated Site		Uncultivated Site	
	s^2	$C+C_0$	s^2	$C+C_0$
pH	0.070	0.070	0.135	0.138
Moisture	0.032	0.039	0.015	0.016
Inorganic P	0.101	0.108	0.322	0.321
Total C	0.212	0.218	0.049	0.049
Nitrification N[a]	0.062	0.068	0.078	0.077
N Mineralization[a]	0.063	0.069	0.096	0.096

[a] See footnote Table 1

several soil cores per sample location and attempted to minimize analytical error by replicating soil extractions and analyse sufficient to maintain analytical variability to $\leq 5\%$ CV. If these measures did, in fact, keep random sampling error small, then the nugget variance we estimate for most variates is predominantly due to autocorrelation at scales of <1.4 m. This implies that for many of the properties we examined (notably soil carbon, net nitrification, net N mineralization, and moisture), greater than 50% of in situ variability is occurring at the scale of individual plants or smaller.

For all properties in both sites model sample variances [C + Co] coincided almost exactly with overall within-site sample variances (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 variances would significantly exceed model sample variance (Barnes 1991).

A short range over which spatial dependence is expressed together with a nonuniform frequency distribution for any 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 means. Frequency distributions and variograms for our data suggest that, in general, high values should be more spatially aggregrated 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 patterning probably reflects the long-term influence of tillage on soils of the cultivated site. Although the primary action of plowing is to invert the soil profile to a depth of 20–30 cm, increased runoff 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 visually to be much less patchy in the cultivated than in the uncultivated site; this pattern is also evident for other properties (not shown). The imposition of a plant monoculture on the site may additionally affect variability by removing – or at least homogenizing – the

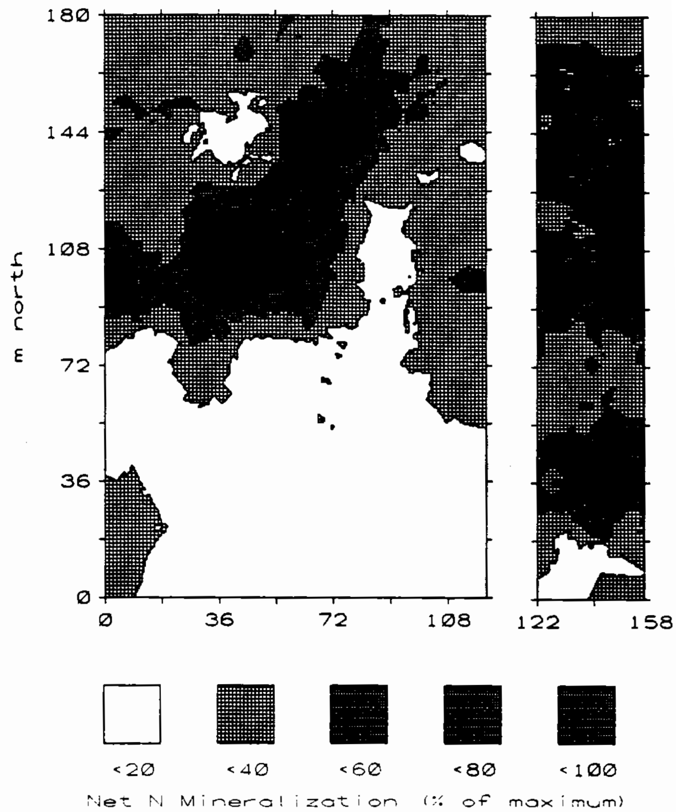

Fig. 3. Isarithms for soil net N-mineralization across the study sites. Maximum rate for the historically tilled site is 2.0 ug g^{-1} d^{-1} N; for the never tilled site maximum rate is 1.6 ug g^{-1} d^{-1} N

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 y B.P.; parent (C-horizon) material is uniform sand. Shorter term variability is also likely affected by individual plants – especially by longer-lived perennials (e.g. Wedin and Tilman 1990). In the tilled 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-years post-abandonment from agriculture, they found that structural variances were ca. 40–60% 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 cultivated 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 are results from Jackson and Caldwell (1993), who found most spatial dependence for nutrient pools in a native sagebrush-steppe community occurring at scales of < 1 m.

Patterns of spatial dependence and thus the scale of spatial heterogeneity of soil properties in terrestrial plant communities can have important implications for both community composition (e.g. Caldwell and Pearcy 1994) and for estimates of biogeochemical fluxes at landscape and larger scales (e.g. Matson et al. 1989). A better understanding of this heterogeneity – and of the factors that can affect it – may significantly improve our understanding of controls on community and ecosystem-level processes.

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