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Spatial Variability of Soil Properties in a Floodplain Forest in Northwest Spain

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ABSTRACT

Floodplain forests are generally areas of high plant diversity compared with upland forests. Higher environmental heterogeneity, especially variation in belowground properties may help explain this high diversity. However, there is little information available on the spatial scale and pattern of belowground resources in floodplain forests. Geostatistics and coefficient of variation (CV) were used to describe the spatial variability of 20 soil properties ranging from essential plant nutrients, such as NH_4^+–N or PO_4^{3}–P, to nonessential elements like Ti or V. The spatial variation of Si-to-(Al + Fe) ratio, an index of soil development, was also analyzed. Semivariograms and maps of selected properties were used to discriminate between the effect of flooding (and other mechanisms that may contribute to large scale trends in data) and local heterogeneity. The hypothesis that elements mainly cycled through biological processes (such as N) show different spatial properties than elements cycled through both biological and geological processes (such as P) or elements under strict geological control (such as Ti or V) is also presented. Redox potential was the most variable property (CV = 1.35) followed by mineral N, phosphate, organic matter, and carbon. Nonessential elements for organisms such as Si, Al, Ti, Rh, or V were less variable, supporting the hypothesis that biological control on soil properties leads to higher spatial variability. The range (the average distance within which the samples correlate spatially) varied between 3.89 m for water content to 18.5 m for the Si-to-(Al + Fe) ratio. The proportion of the total variance that can be modeled as spatial dependence (structural variance) was very variable, ranging between 0.34 for Fe and 0.96 for K. The addition of the large trend had a strong influence on the CV of most soil variables and created a gradient in C accumulation and the mineral weathering rate. Our results suggest that flooding and other processes that are responsible for large spatial trends in the floodplain forest differentially affect biologically and geologically controlled variables and at different turnover rates, thus providing a heterogeneous edaphic environment.

Key words: flooding effect; floodplain forest; spatial scale; semivariograms; kriging; redox potential; organic matter; soil nutrients; geostatistics.

INTRODUCTION

Environmental heterogeneity is often essential for the coexistence of species. Numerous researchers have proposed a positive correlation between environmental variability and species richness (for example, Jeltsch and others 1998; Ettema and Wardle 2002). In plant communities, this correlation may be explained, at least partially, by variation in belowground resources. Variation of soil resources at the individual scale is likely to affect the local distribution and abundance of plant species and the performance of individual organisms and, therefore, to have important consequences for both community structure and ecosystem-level processes (Tilman 1988; Schlesinger and others 1990). Changes in the magnitude and scale of spatial de-

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pendence in soil nutrients may reflect changes in the cover, composition, or size of plants over the succession (Gross and others 1995).

Although the importance of spatial heterogeneity is well recognized, the scale or extent to which it occurs and how it might differ among communities are poorly understood (Robertson and Gross 1994). Characterizing site heterogeneity is difficult because a sufficient number of samples is needed to characterize the site. Consequently, information about soil spatial variability is available from only a very few sites worldwide and is usually limited to a single set of physicochemical soil characteristics. Riparian forests are likely to be a particularly difficult challenge in terms of spatial heterogeneity compared with agricultural or forested upland ecosystems. Differences in slope and drainage in the transition between riparian and upland areas occur at scales of meters to tens of meters. This physical heterogeneity results in small-scale variability in plant communities, and, not surprisingly, these areas are usually high in plant diversity (Kirkman and Sharitz 1993; Sharitz and Mitsch 1993).

Flooding could be particularly important in determining the spatial variability of soil nutrients in forested floodplains by altering biological and geochemical reactions. Temperate wetlands have strong seasonal hydrological cycles in which comparatively dry summers alternate with occasional periods of flooding. This process may alter the decomposition rate of organic matter by increasing soil anaerobic conditions as well as the weathering rate and soil development. Flooding also influences the oxidation state of soil elements and consequently its availability to microbes and plants.

The present study was designed to address the general need for basic information about soil resource heterogeneity and specifically to gain information about heterogeneity in floodplain forests. Geostatistics were used to quantify the scale and pattern of soil variability and to discriminate between large trends in the data (because of the directional effect of flooding) and finer-scale structure (Robertson 1987; Legendre and Fortin 1989; Rossi and others 1992). I hypothesize that elements that mainly cycle through biological processes (such as N) might show different spatial properties than elements cycled through both biological and geological processes (such as P) and elements that are primarily under geological control (such as Al or Ti). To test this hypothesis, the spatial variation of essential plant and microbe elements (both biologically and geochemically controlled) and nonessential elements were analyzed in a floodplain forest of northwest Spain.

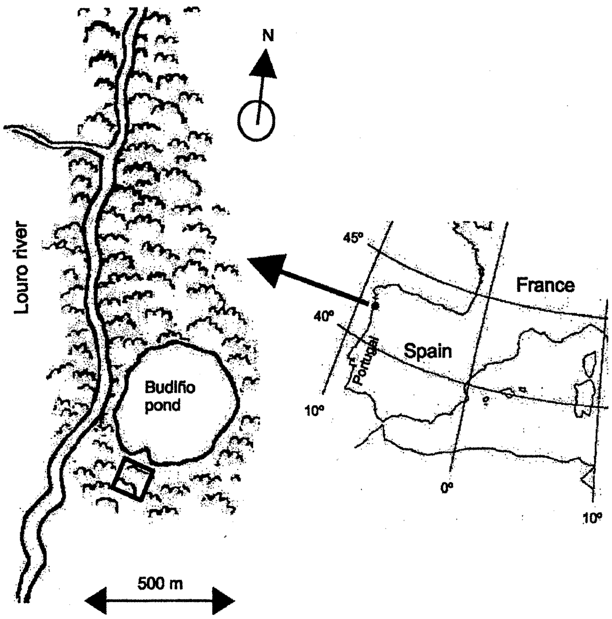

Figure 1. Location of the study area.

METHODS

Study Site

The study area forms part of the Louro river watershed in Galicia, northwest Spain (42°06'42" N, 8°37'45" W; Figure 1). Mean annual precipitation is 1715 mm and mean annual temperature is 14°C (12 y mean). The climate is warm– temperate with a slight Mediterranean influence that decreases the chance of precipitation during the summer months.

The floodplain forest is located on the lower terrace of the Louro river (0–10 m), formed in the late Pleistocene (Riss–würm interglacial). The top of this terrace is characterized by a silty clay horizon with dispersed siliceous boulders, derived from rock weathering within the watershed (IGME 1981). Three major rock types were identified in the watershed: coarse grain granite, biotite gneiss, and plagioclase and biotite paragneiss. Chemical composition of these three rock types is presented in Table 1. Soils ranged from umbric cambisols in the higher terrace to histosols in the lower ones.

Plant communities in the area and their relation with the topography have been described by Silva–Pando and others (1988). The chosen area has an overall mean slope of 1.0%. The forest at lower elevations is dominated by *Alnus glutinosa* L. Gaertner and *Salix atrocinerea* Brotero. This community is rapidly replaced by a forest dominated by *Quercus robur* L. at higher elevations, with few other tree species. In permanent aerobic

Table 1. Chemical Composition of Rocks and Soils at the Louro River Watershed[a]

	Coarse Grain Granite	Biotite Gneiss	Plagioclase and Biotite Paragneiss	Mean Rock	Mean Soil	Mean Soil (Organic Matter-Free Basis)
SiO_2	73.8	76.6	72.5	74.3	31.5	45.1
TiO_2	0.19	0.08	0.63	0.30	0.51	0.73
Al_2O_3	13.5	11.9	13.9	13.1	12.6	18.02
Fe_2O_3	2.04	1.05	4.56	2.55	6.39	9.14
MgO	0.24	0.20	1.71	0.72	0.32	0.46
MnO	0.04	0.02	0.04	0.03	0.03	0.04
CaO	0.92	0.40	0.67	0.66	0.38	0.5
Na_2O	3.04	3.18	1.57	2.60	0.39	0.6
K_2O	5.07	4.84	2.13	4.01	1.23	1.76
P_2O_5	0.15	0.07	0.2	0.14	0.22	0.31
$SiO_2/(Al_2O_3 + Fe_2O_3)$	4.75	5.91	3.91	4.74	1.72	2.47

[a] *Units in %. Soil data corresponds to the top 10-cm of the soil profile.*

soils, *Pinus pinaster* Sol. is the dominant tree species.

Sampling Design

In January 2000, an area of 1 ha was selected at the southern edge of a permanent pond for an assessment of variability in soil resources (Figure 1). This ground water-fed pond is the major source of flooding in the adjacent floodplain forest, separated from the river by about 200 m. The pond normally drains into the river, but on occasion, during times of heavy rainfall, the river overflows its banks and water flows from the river into the pond via a narrow connecting channel (Silva–Pando and others 1988).

The sampling design was based on Gross and others (1995). Inside the selected area, ten parallel 40-m transects were randomly placed perpendicular to the pond (NE–SW direction), and base points were marked at 4-m intervals along the entire length of each parallel. A 2-m transect was drawn through each base point along different cardinal directions (N, E, SE, S, W, NW). This 2-m transect was marked at 0.5 m, 1 m, and at 2 m. This gave a total of 400 sampling points. Four additional transects were placed to cover large nonsampled areas. A total of 541 soil samples were taken from the field (Figure 2).

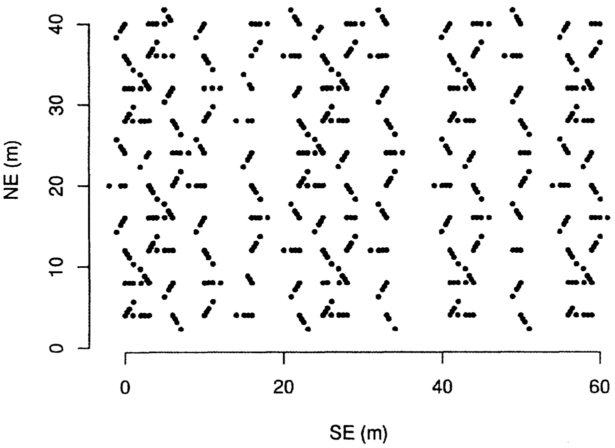

Figure 2. Diagram of point locations sampled in the floodplain forest (see text for details).

Field Sampling

To avoid interference with soil sampling, field measurements of relative water content and soil redox potential were made in an adjacent plot with the same sampling scheme. Water content was measured using an Aquaterr Moisture meter (model EC- 200, Aquaterr Instruments, Fremont, CA), previously calibrated in a nearby spring. This moisture meter is a capacitance probe which measures the dielectric constant of the soil–air–water combination. Designed for rapid and coarse measurement of water content in agricultural fields, we used it to establish a threshold (readings of 85% of relative water content) to measure the soil redox potential. Well-drained soils were avoided because of the narrow range and poor reproducibility of their redox potentials thereby limiting their value as a tool for characterizing aeration (Patrick and others 1996).

To measure soil redox potential, three platinum electrodes were simultaneously used in field conditions (Orion Research Inc., Beverly, MA, USA, and Metrohm AG, Herisau, Switzerland). The electrodes were previously calibrated in the lab with a 468-mV standard solution. Any electrode differing by more than 5 mV from the former value or showing slow drift was cleaned by scribbing the exposed surface of the platinum wire with a paste of a commercial scouring powder. After cleaning, the electrodes were placed in distilled water overnight prior to testing (Patrick and others 1996). In each measurement, the electrodes were inserted in the soil and a mark was placed 5 cm from each electrodes is edge. Because of the high variability in redox potential measurements and to decrease the nugget variance (see Data analysis subsection below) additional samples were randomly selected to ensure sufficient numbers of distances between 0.10 and 0.5 m. In each 40-m transect, one new base point was randomly selected and a 50-cm transect was drawn through this base point along a different cardinal direction (as described above). Redox potentials were measured overy 10 cm along these new 50-cm transects. A total of 473 redox potentials were measured during three weeks in January 2000.

In the other plot, soil samples from the top 10 cm of the soil profile were taken using a 5-cm-diameter cylinder. The litter layer, when present, was carefully removed before sampling. The samples were immediately placed in an ice-filled cooler and transported to the lab where they were sieved through a 2-mm screen mesh and maintained at 4°C prior to analysis. The approximate position and size of major lower elevations were recorded during sampling.

Laboratory Analysis

Organic matter was estimated using the loss-on-ignition method by placing the soil subsamples in a muffle furnace at 450°C for 4 h. Total C and total N were determined by combustion in a CHNS elemental autoanalyzer, and total P, Si, Al, Fe, Ti, K, Mg, Ca, Mn, Rb, and V were analyzed by X-ray fluorescence following Buhrke and others (1997). To extract the mineral N, soil subsamples (4 g) were shaken with 80 ml of 1M KCl and filtered through 0.45-μm Millipore filters. NH_4^+–N and NO_3^-–N were determined by colorimetry with a microplate reader (Sims and others 1995). To determine the PO_4^3–P, 2-g soil subsamples were extracted with 80 ml of 2.5% acetic acid and filtered through 0.45-μm Millipore filters, then the extract was colorimetrically measured by the molybdenum blue method in a microplate reader (Allen and others 1986; Sims and others 1995).

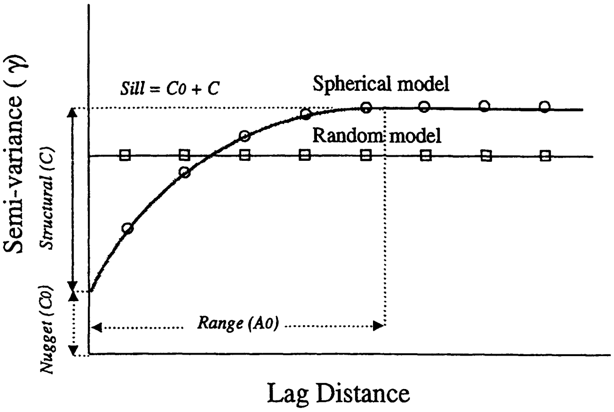

Figure 3. Schematic diagram of a semivariogram showing the proportion of variance (semivariance) found at increasing distances of paired soil samples (lag distances). The random model is expected when soil properties are randomly distributed. The spherical model is expected when soil properties show spatial autocorrelation over a range (A_0) and independence beyond that distance. Total variance is the sum of the variation explained by the spatial model (C) and the variation found at a scale finer than the field sampling (nugget variance C_0).

Data Analysis

Geostatistics were used to describe the spatial variation of each of the soil properties measured in the floodplain forest. We calculated a semivariogram (Figure 3) that shows the average variance found in comparisons of samples taken at an increasing distance from one another, the lag interval. For randomly distributed data, there is little change in the semivariance encountered with increasing distance and the variogram is essentially flat (Robertson 1987; Rossi and others 1992). For spatially patterned data, the semivariogram first rises from comparisons of neighboring samples that are similar and autocorrelated and then levels off at the sill, indicating the distance (A_0) beyond which samples are spatially independent (Figure 3). Variance that exists at a scale finer than the field sampling is found at zero lag distance and is known as nugget variance (C_0). A high nugget variance can occur because (a) there is spatial structure at smaller scales, (b) there is sampling or analytical error, or (c) there is a lack of structure at this scale. A high ratio of structural variance (C) to sill variance ($C_0 + C$) is an indication of a spatial pattern among the data (Trangmar and others 1985). By common convention, the analysis is restricted to distances of half the dimension of the study area.

The interpolation of points using semivariograms requires the stationarity assumption, that is, the mean and variance of the data are the same in the various parts of the area under study (Legendre and

Fortin 1989). A large spatial trend in the data across the site violates the stationarity assumption. Trend can be thought of as a pattern whose dimensions are larger than the sampling space and/or the significant lag classes. Because of the trends, the local mean and variance will be different with location and direction (Rossi and others 1992). The directional effects of flooding or groundwater depth on soil disturbance may cause a large-scale trend in some soil properties because the effects of these processes should decrease with increasing distance from the water body. This large-scale trend, if reflected in the semivariogram, may mask small-scale structures in the data. Thus, the presence of a large-scale trend is typically seen as a confounding factor in spatial analysis and is removed by detrending (Legendre and Fortin 1989). Detrending can be accomplished by fitting a regression to the trend and using only the residuals for semivariance analysis. The residuals reflect the local spatial dependency. When interpolation of the variables is performed based on the semivariograms (kriging), the trend is added at the end of the numerical analysis. In this article, the trend, rather than being a confounding factor for spatial analysis, is an essential part of it.

The soil properties were log-transformed when the Shapiro–Wilk test indicated lack of normality. Detrended analysis and the corresponding semivariograms for the residuals were performed for each variable. Once the trend was taken into account, the directional lag-to-lag spatial continuity was isotropic. To facilitate comparisons, all the empirical semivariograms were fitted to a spherical model. Kriging was performed based on these theoretical semivariograms, either adding or ignoring the trend to describe the effect of the environmental gradient on the spatial pattern. When the trend (distance to the pond) was removed, the resulting map was drawn based just on the local spatial dependency. Coefficients of variation of the kriged values were used to compare the effect of the trend on overall heterogeneity of the soil properties.

Geostatistical analysis was performed using the statistical package R version 1.4.1 (modules geoR and sgeostat, http://www.r-project.org) on a Linux platform. R is a free clone of S-plus, and modules written for S-plus are usually written for R. The results were compared with those from the geostatistical package GSTAT version 2.3.3 for Linux (http://www.gstat.org).

RESULTS

Mean concentrations of total Si, K, Ca, Na, and Mg were lower in the soil than in the underlying rock (net changes due to rock weathering rate). However, the concentration of Al, Fe, P, and Ti was higher than in rock, indicating their retention in the soil top profile (Table 1).

The 20 sampled soil properties varied considerably across the study area (Table 2). Soil redox potential was the most variable of all the soil properties (CV = 1.35). Redox potential varied between −314 and 493 mV, indicating biochemical reactions ranging from aerobic metabolism to methane production in the area. Mineral N content was also very variable (CV = 1.33 for NO_3 and 0.91 for NH_4), and higher than that of total N (CV = 0.39). Similarly, extractable PO_4 was more variable (CV = 0.59) than total P (CV = 0.24). In contrast, nonessential plant elements such as Rb and V had low variability (CV = 0.12). The overall CV of variables cycled primarily through biological processes in the ecosystem, such as organic matter, C, N, NH_4 and NO_3, was higher (CV = 0.74) than that observed for P, PO_4, K, Mg, Ca, Mn, and Fe, elements that are cycled through both biological and geochemical processes (CV = 0.38). The overall CV of nonessential plant elements (influenced only by geochemical processes), such as Si, Al, Ti, Rh, and V, was only 0.16.

A significant relationship between several soil variables and the distance to the source of flooding was detected (Figure 4), suggesting an anisotropic trend of these properties. In this article, the trend indicates a floodplain process such as the effect of a natural disturbance, such as flooding, or gradual changes in the depth of groundwater (drainage class), elevation, or vegetation changes along a catena.

A spherical model provides a significant fit (based on r^2) to the semivariogram for all soil constituents (Table 3 and Figure 5). The range (the average distance within which the samples remain (spatially) correlated varied between 3.89 m for water content and 18.5 m for the Si-to-(Al + Fe) ratio. Several variables, including redox potential, organic matter, total C, total N, total P, NH_4, PO_4, Si, Al, and Fe, showed a range between 7.7 and 10.7 m. Lower values were found for K, Mg, Ca, Mn, and NO_3, ranging between 3.86 and 6.46 m.

The proportion of the total variance that was spatially dependent varied between 0.34 for Fe and 0.96 for K (Table 3). Soil-extractable nutrients (NH_4, NO_3, and PO_4 and water content showed much weaker spatial autocorrelation (lower structural variance) than total components of soil, with a degree of spatial dependence between 42% and 44%.

The addition of the large trend (distance to the pond) had a minor influence on the kriged mean of

Table 2. Univariate Statistics for Soil Properties in the Floodplain Forest[a]

	Units	Mean	Min.	Max.	CV	n
Redox potential	mV	169.7	−314	493	1.35	473
Water content[b]	(%)	73.2	6.23	99.8	0.21	188
Organic matter	(%)	30.1	3.65	75.1	0.52	541
Total C	(%)	13.26	0.85	32.68	0.54	541
Total N	(%)	1.12	0.38	2.69	0.39	541
Total P[c]	(%)	0.22	0.12	0.37	0.24	220
C:N ratio	—	11.03	2.25	18.65	0.22	541
NH_4^+-N	$\mu g\ g^{-1}$ soil	361	2.49	1798	0.91	541
NO_3^--N	$\mu g\ g^{-1}$ soil	172.9	0.1	1523	1.33	541
PO_4^{3}–P	$\mu g\ g^{-1}$ soil	4.33	0.01	39.4	0.59	527
K[c]	(%)	1.23	0.86	1.71	0.16	220
Mg[c]	(%)	0.39	0.14	0.6	0.33	220
Ca[c]	(%)	0.38	0.13	0.92	0.44	220
Mn[c]	$\mu g\ g^{-1}$ soil	301.7	160.5	795.3	0.42	220
Si[c]	(%)	31.52	20.9	40	0.14	220
Al[c]	(%)	12.59	6.64	20.2	0.23	220
Fe[a]	(%)	6.39	3.27	20.3	0.48	220
Si/(Al + Fe)	—	1.72	0.85	2.54	0.2	220
Ti[c]	(%)	0.51	0.3	0.7	0.19	220
Rb	$\mu g\ g^{-1}$ soil	121.89	84	157	0.12	220
V	$\mu g\ g^{-1}$ soil	93.72	74.1	120.9	0.12	220

[a] *The values shown are untransformed means for the entire site followed by the minimum values (Min.), the maximum values (Max.), coefficients of variation (CV), and number of sample locations (n) for each untransformed variate. All soil concentrations are on a dry soil mass basis.*

[b] *Percent of maximum reading (obtained by calibration with free water).*

[c] *Total P was measured as P_2O_5, K as K_2O, Mg as MgO, Ca as CaO, Fe as Fe_2O_3, Mn as MnO, Si as SiO_2, Al as Al_2O_3, and Ti as TiO_2.*

most soil properties. Only the mean values of soil redox potential and water content were modified when the trend was included in the estimate of the values (Table 4). However, the coefficient of variation of the kriged values increased for most variables when the trend effect was added to the map, suggesting an important effect of the environmental gradient in determining overall soil heterogeneity. The CV of most biologically important elements increased between 2 and 3 times when the trend effect was included. Remarkably, the increase in CV with flooding for PO_4 was lower than the observed increase for NH_4 and NO_3 as was expected because of the poor correlation between PO_4 and the distance to the pond (Figure 4). However, the CV of Ti, Rh, and V, nonessential elements for organisms, was unaffected by the large-scale trend. The CV of Si, Al, and Fe, the major components of soil minerals, increased between 4 and 4.8 times when the trend was added to the map. Not surprisingly, water content showed the greatest increase in CV when the trend was included in its estimate, up to 16.7 times the CV of the kriged values based on the local spatial dependency (local heterogeneity). In contrast, the CV for soil redox potential increased only slightly (1.39 times), but the large-scale trend had a marked effect on the mapping of this property (Figure 6). The four areas with negative redox potentials shown on the map of local dependency coincided with four local areas of lower elevation recorded during the sampling period. As in the case of soil redox potential, mapping without the large trend of C, N, NH_4, NO_3, cations, and the Si-to-(Al + Fe) ratio detected major topographic discontinuities in the sampled area [only total C and the Si-to-(Al + Fe) ratio are shown, Figures 7 and 8]. This local heterogeneity had a major influence in the estimate of the variable when the large trend was included (Figures 6, 7, and 8).

DISCUSSION

A high degree of soil variability was observed in the sampled area. This study showed that redox potential was the most variable property in the floodplain forest (CV = 1.35). A similar value (CV = 1.33) was found by Amador and others (1997) for phosphatase activity in poorly drained soil from a riparian forest. This high variability may reflect the fact that redox potential is the result of a variety of microbial reactions continuously varying in time and space (Schlesinger 1997). Distinct patterns of redox po-

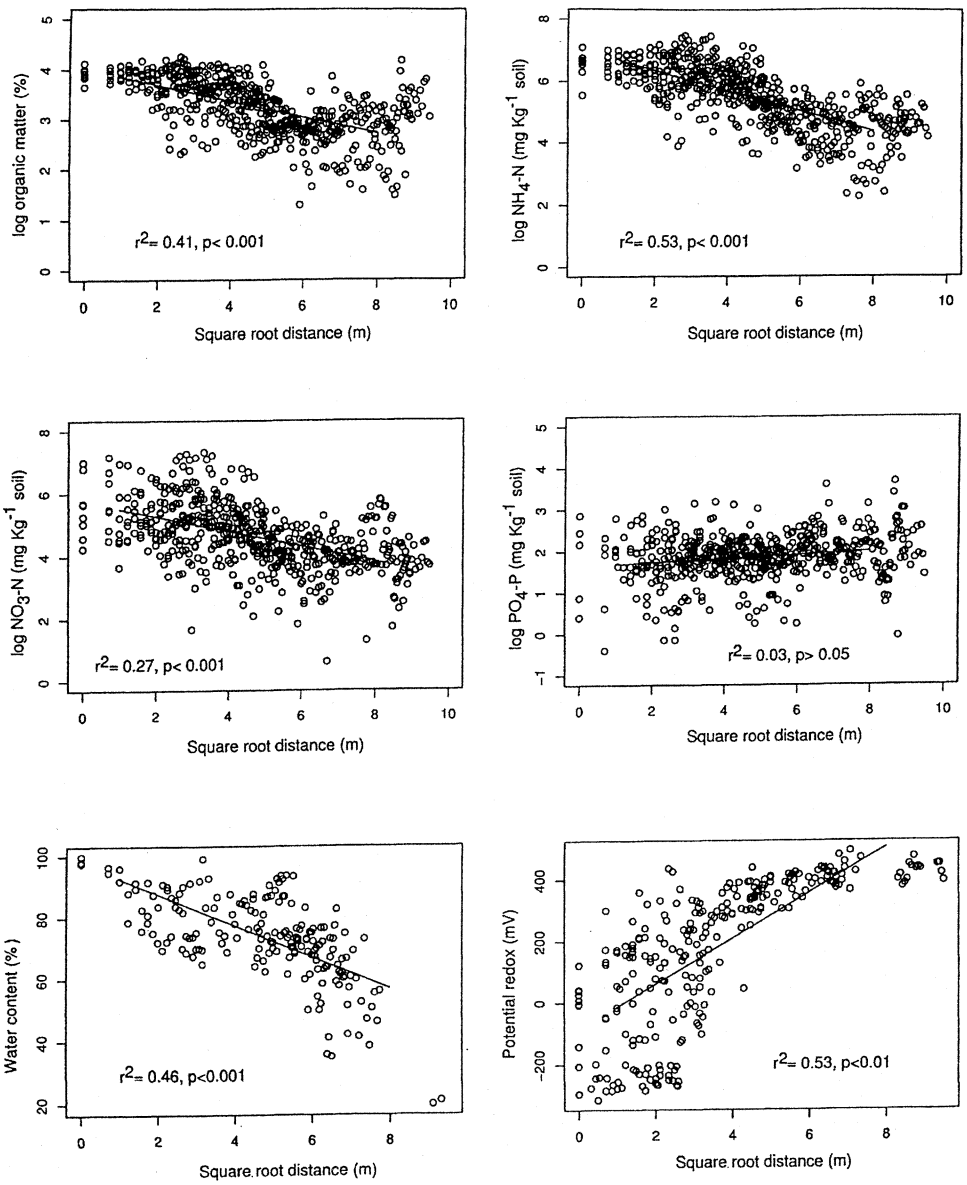

Figure 4. Relationship between organic matter, ammonium, nitrate, phosphate, water content, and redox potential of the top 10 cm of soil profile and the square root distance to the edge of the pond (source of flooding).

tentials have been observed in nonwetland, transitional, and wetland habitats (Faulkner and others 1989; Megonigal and others 1993), making this property particularly diagnostic for determining whether an area is functioning as a wetland.

Nitrate was the second most variable property in the sampled area. Nitrate concentration directly depends on microbial reactions, such as nitrification and denitrification as well as plant uptake and soil leaching, that may be operating simultaneously in this floodplain forest. Ammonium concentration in soil was less variable than NO_3, perhaps because of its lesser mobility in soils and its tendency to be retained at the cation exchange sites. Ettema and others (1998) also found NO_3 much more spatially variable than NH_4 in a restored riparian wetland. The concentration of extractable PO_4 had a lower CV than both forms of mineral N. Noticeably, total P also showed lower CV than total N. Biogeochemical processes may explain the differences found between these two essential elements. First, PO_4 concentration was very low (Table 2) when compared with NO_3 and NH_4, which could indicate low P availability and that P may control primary production in this forest. Extensive uptake and immobilization of inorganic P by plants and microbes may make PO_4 less spatially variable than inorganic N. Secondly, inorganic P easily reacted with Al and Fe oxides in the soil profile forming secondary minerals. Inorganic P may be buffered by this geochemical process, thereby decreasing the spatial variability. Data in Table 1 showed that total P and Al and Fe oxides were retained in the top soil profile during the weathering reactions, suggesting that Al and

Table 3. Parameters for the Spherical Variogram Model of Soil Properties across the Floodplain Forest[a]

	Units	Sill ($C_0 + C$)	Nugget (C_0)	Range (m)	$C/(C_0 + C)$	r^2
Redox potential	mV	31838	3953	9.14	0.88	0.70
Water content	(%)	69.15	40.12	3.89	0.42	0.80
Organic matter	(%)	0.16	0.06	9.76	0.60	0.95
Total C	(%)	0.20	0.08	9.68	0.60	0.95
Total N	(%)	0.10	0.05	7.74	0.52	0.92
Total P	(%)	0.0018	0.00047	10.7	0.79	0.61
C:N ratio	—	0.03	0.01	12.66	0.60	0.88
NH_4^+–N	$\mu g\ g^{-1}$ soil	0.42	0.24	9.86	0.43	0.84
NO_3^-–N	$\mu g\ g^{-1}$ soil	0.78	0.44	4.55	0.44	0.86
PO_4^{3-}–P	$\mu g\ g^{-1}$ soil	0.24	0.14	7.99	0.44	0.78
K	(%)	0.02	0.0008	3.86	0.96	0.89
Mg	(%)	0.12	0.03	5.71	0.73	0.93
Ca	(%)	0.16	0.09	6.46	0.42	0.87
Mn	$\mu g\ g^{-1}$ soil	0.14	0.01	4.54	0.92	0.85
Si	(%)	0.03	0.01	8.09	0.68	0.92
Al	(%)	5.52	1.58	9.33	0.71	0.65
Fe	(%)	2.74	1.81	9.78	0.34	0.86
Si/(Al + Fe)	—	0.11	0.05	18.51	0.59	0.94
Ti	(%)	0.01	0.002	6.32	0.82	0.98
Rb	$\mu g\ g^{-1}$ soil	191.97	74.79	12.68	0.61	0.93
V	$\mu g\ g^{-1}$ soil	115.94	55.43	7.45	0.52	0.52

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[a] *Values are log-transformed except for water content, redox potential, Ti, and V.*
[b] *$C/(C_0 + C)$= structural variance C as a proportion of model sample variance ($C_0 + C$).*

Fe oxides may play an important role in P retention (Darke and others 1997; Darke and Walbridge 2000). Thus, elements implied in geochemical reactions (P) might show less spatial variability than elements cycled primarily through biological reactions (N). Supporting this hypothesis, the overall variation of organic matter (C, N, NH_4, and NO_3) was higher than the overall variation of elements (P, K, Mg, Fe, and Mn) cycled through both biological and geochemical processes. Similarly, all these elements were more variable than the nonessential plant elements (Si, Al, Ti, Rh, and V), again supporting the hypothesis that biological control on soil properties leads to a high spatial variability.

Inorganic N and PO_4 were more variable than total N and P, again suggesting that high variability may correspond to a rapid turnover rate of elements in soils.

The distance at which samples remain correlated spatially (range) varied from approximately 4 m for water content to 18.5 m for the Si-to-(Al + Fe) ratio. The range (equivalent to the fractal dimension) is an important parameter because it expresses the grained pattern of spatial heterogeneity and indicates the extent at which plants can exploit the variability of soil resources or are influencing these patterns (Schlesinger and others 1996). Relatively few workers have provided high-resolution analyses of the spatial dependence of soil properties in soils. Palmer (1990) found that most elements showed spatial autocorrelation within 5 m in forest soils of North Carolina, with P showing spatial dependence within 1 m. Lechowicz and Bell (1991) reported that soil pH, K, and NO_3 were autocorrelated within a distance of 2 m in a forest in southern Quebec. Variation at similar scales was found by Farley and Fitter (1999) in a deciduous woodland, and Gross and others (1995) found that the range for several indexes of N availability oscillated between 2.5 and 10 m in a second-growth hardwood forest in southwestern Michigan. Higher ranges of variation were found in Robertson (1987) and Robertson and others (1988) where mineral N, soil NO_3, and microbial processes were autocorrelated over distances between 8 and 30 m in an old- field community in Michigan. The highest range values were found in agricultural fields (but see Gross and others 1995). For example, semivariograms for NO_3^-–N and mineral N showed ranges of 90 m on a cultivated site in Michigan (Robertson and others 1997).

In contrast, the lowest distances of spatial patterning were found in grassland and shrubland communities of arid or semiarid ecosystems. Jack-

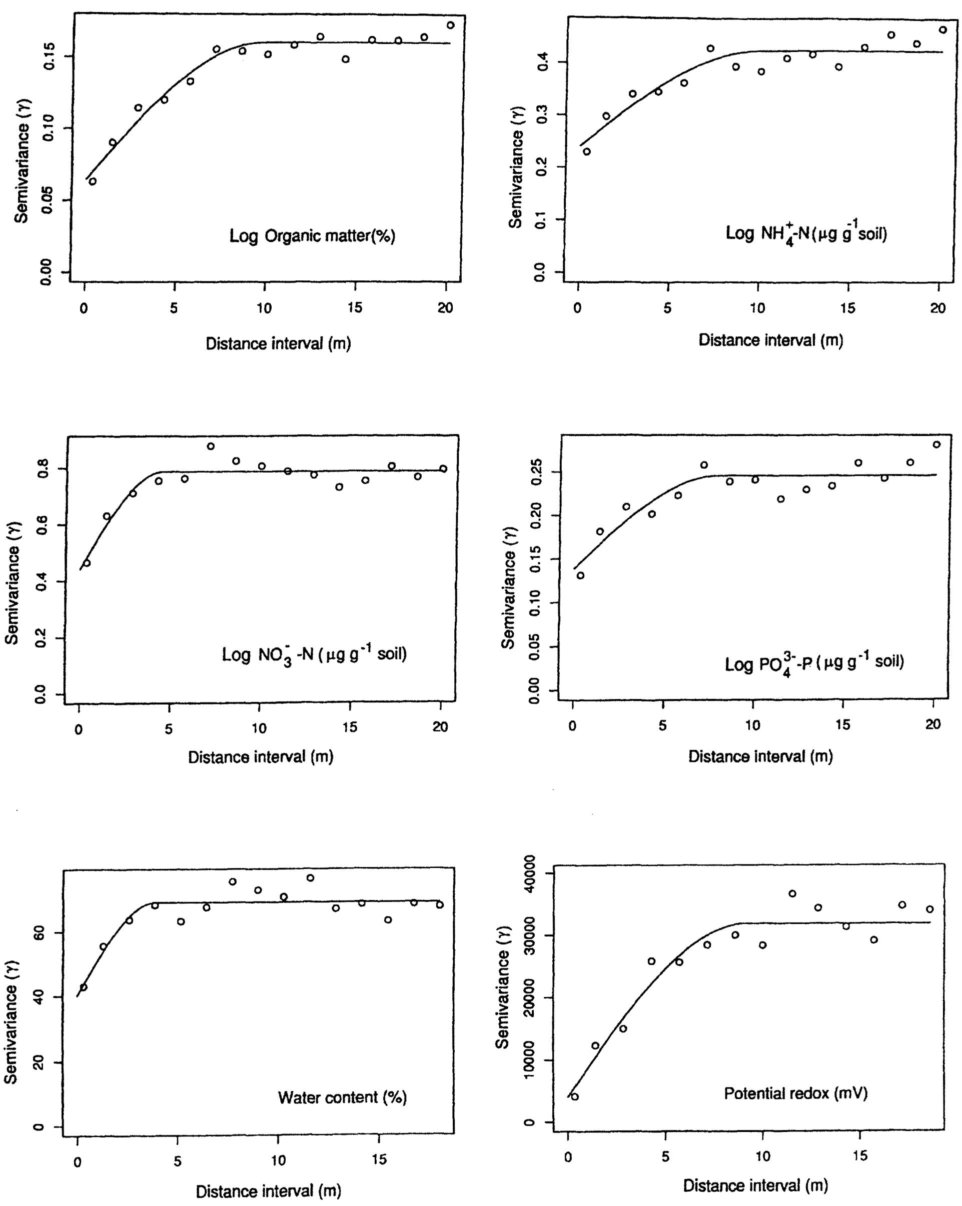

Figure 5. Semivariograms for soil organic matter, ammonium, nitrate, phosphate, water content, and redox potential in the top 10 cm of a floodplain forest.

son and Caldwell (1993a, 1993b) reported that most spatial variability of the soil properties studied was expressed at distances of less than 1 m, while Schlesinger and others (1996) found essential nutrients autocorrelated over distances of 1–2, close to the mean size of *Larrea tridentata*, the dominant shrub, suggesting that the spatial distribution of these elements may be associated with biotic processes operating at the scale of shrub islands. Similarly, Gallardo and others (2000) found ranges between 9 and 10 m matching the canopy diameter of large trees in a Dehesa ecosystem (savanna-like ecosystem) in southwest Spain. In general, the observed range of essential and nonessential nutrients in the floodplain forest soil was somewhat higher than the ranges found in forest or shrublands but lower than ranges found in agricultural or abandoned field soils, even though the different scales of heterogeneity detected by the authors may have been influenced by the sampling scale. Flooding is a periodic physical disturbance that may, in the long-term, increase the distance over which the spatial dependence is expressed. Increased range values of most soil properties, as a consequence of physical disturbance in cultivated sites, were reported by Robertson and others (1993).

The size of dominant individuals in the community can influence the distance at which autocorrelation is expressed (Jackson and Caldwell 1993b; Schlesinger and others 1996; Gallardo and others 2000). In the floodplain forest in northwest Spain, groups of trees and areas without trees conform to

Table 4. Mean and Coefficient of Variation of the Kriged Values with and without the Large Trend[a]

	Local Heterogeneity		Local Heterogeneity + Large Trend[a]			
Units	Mean	CV_1	Mean	CV_2	CV_2/CV_1[b]	
Redox potential	mV	88.0	0.94	139.0	1.31	1.39
Water content	(%)	75.1	0.02	69.0	0.25	16.67
Organic matter	(%)	25.6	0.20	23.9	0.54	2.70
Total C	(%)	11.1	0.22	10.3	0.61	2.77
Total N	(%)	1.0	0.13	0.9	0.37	2.85
Total P[b]	(%)	0.2	0.08	0.2	0.26	3.25
C:N ratio	—	10.4	0.10	9.8	0.23	2.30
NH_4^+–N	μg g^{-1} soil	233.1	0.38	250.7	1.13	2.97
NO_3^-–N	μg g^{-1} soil	131.6	0.23	120.3	0.73	3.17
PO_4^{3-}–P	μg g^{-1} soil	7.6	0.07	8.0	0.12	1.71
K[c]	(%)	1.2	0.02	1.2	0.05	2.50
Mg[c]	(%)	0.3	0.06	0.3	0.12	2.00
Ca[c]	(%)	0.3	0.06	0.4	0.56	9.33
Mn[c]	μg g^{-1} soil	312.5	0.06	325.4	0.17	2.83
Si[c]	(%)	30.7	0.03	30.6	0.12	4.00
Al[c]	(%)	11.9	0.07	11.8	0.31	4.43
Si/(Al+Fe)	(%)	1.9	0.07	1.9	0.21	3.00
Fe[c]	—	5.4	0.05	5.3	0.24	4.80
Ti[c]	(%)	0.5	0.03	0.5	0.03	1.00
Rb	μg g^{-1} soil	125.9	0.03	125.8	0.03	1.11
V	μg g^{-1} soil	95.4	0.02	95.3	0.02	1.05

[a] *The large trend was the effect of the square root distance to the edge of the pond.*
[b] *Total P was measured as P_2O_5, K as K_2O, Mg as MgO, Ca as CaO, Fe as Fe_2O_3, Mn as MnO, Si as SiO_2, Al as Al_2O_3, and Ti as TiO_2.*
[c] *Ratio of the CV of the kriged samples with the large-trend effect to the CV of the kriged samples without the large-trend effect.*

an apparent source of heterogeneity. This heterogeneity is equivalent to the lower elevation characterized by more frequent flooding (swale) and a higher elevation with shorter hydroperiod (ridge) microsites cited by Darke and Walbridge (2000). This heterogeneity coincides with the local dependency detected when the large trend was removed and may explain larger ranges of soil nutrients than those found in upland forests.

The structural variance (C) as a proportion of model sample variance ($C_0 + C$) of soil properties in the floodplain forest reached similar intervals as in other ecosystems. For example, Robertson and others (1993), sampling at a scale greater than 1 m, found values of structural variance between 30% and 95% of model sample variance in agricultural and abandoned fields, with strikingly similar values between these sites for any given variate. Schlesinger and Coworkers (1996) sampling at a finer scale, reported that 35%–76% of the variance was found at a scale of less than 20 cm in desert grasslands. These authors argued that this high nugget variance may be due to local accumulations of soil constituents under a perennial bunchgrass. Jackson and Caldwell (1993b), using a minimum pair distance of 12.5 cm, found spatial dependence lower than 50% for soil ammonium, soil nitrate, and water content in a sagebrush steppe. In the floodplain forest, one of the most variable attributes was redox potential. By lowering the scale of sampling from 50 to 10 cm, the structural variance increased from 40% (data not shown) to 88% (Table 3 and Figure 5). Similarly, Robertson and others (1997), sampling every 2.5 cm, found minimal nugget variance for soil respiration. The studied area showed the lowest structural variance (highest nugget variance) for Fe, NH_4, NO_3, and PO_4, indicating high variability at scales less than 0.5 m. All of these elements are involved in microbial reactions that may be restricted to favorable microsites at very small spatial scales.

Geostatistical analysis of detrended data allows one to overcome the nonstationary assumption and to differentiate two sources of spatial variation: a local variation and a large-scale-trend variation. A violation of the stationary assumption would imply that the semivariogram would gather the large trend, ignoring the local heterogeneity of data. In-

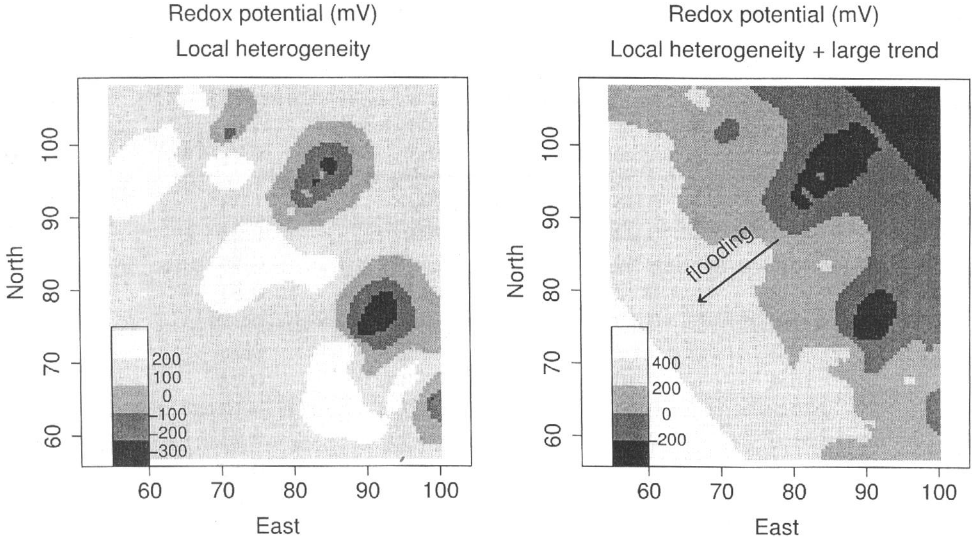

Figure 6. Kriged map of redox potential with the large trend (distance to the pond) removed (left) and added (right). Note that the left map is an estimated map representing the values of the variable if the large trend did not exist (local heterogeneity only).

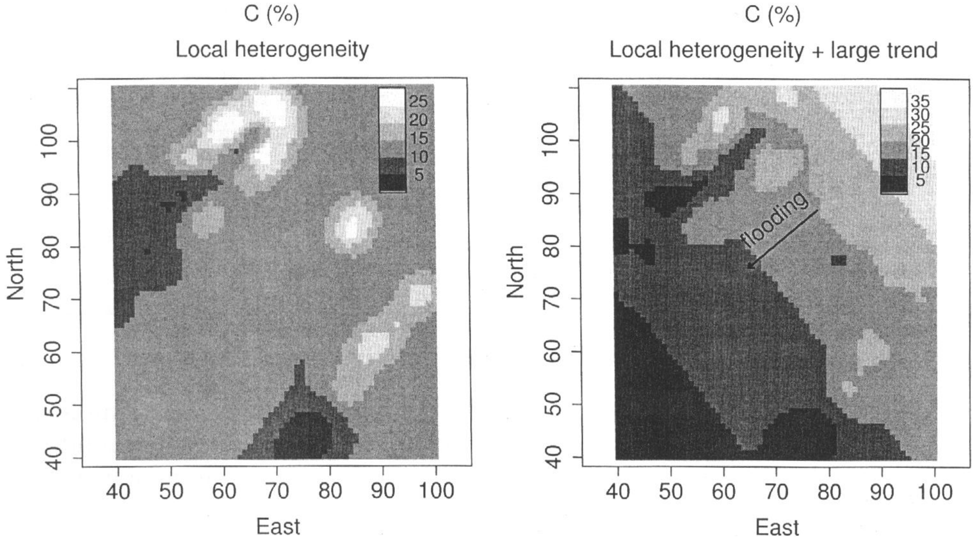

Figure 7. Kriged map of total C (top 10 cm of soil profile) with the large trend (distance to the pond) removed (left) and added (right). Note that the left map is an estimated map representing the values of the variables when the large trend is removed (local heterogeneity only).

terpolation (kriging) with and without the large trend allows one to compare the global effect of the large trend on soil heterogeneity. Because an external large trend (distance to the pond) was used in the analysis, any differences between maps with and without large trends may be equivalent to differences due to the long-term effect of flooding or any variable interacting with it, such as slope or drainage class. This interpretation is supported by the fact that the greatest increase in variability of soil water content ocurred when the large trend was used in the estimate of these values. Local variability may be related to local topography (as mentioned earlier), and the effect of flooding may cause a redistribution of soil resources and accelerate or modify chemical and biological reactions. Floodplain processes such as flooding or differences in drainage classes could create a gradient of anaerobic conditions in the soil. The decomposition process is less efficient in anaerobic conditions, leading to an accumulation gradient of organic matter and of the elements held within it, and potentially explaining the overall increase in CV of essential elements for organisms when the large trend is taken into account. However, the spatial distribution of Ti, Rh, or V were not affected by the large trend. These elements are not essential for plants and microbes and have no known interaction with organic matter. The large trend affected the variability of PO_4 less than that of NH_4 and NO_3. To the extent that this environmental gradient is influenced only by periodic flooding, it may suggest that P is less sensitive to this disturbance than N. Different sensitivities to disturbance between N and P were proposed

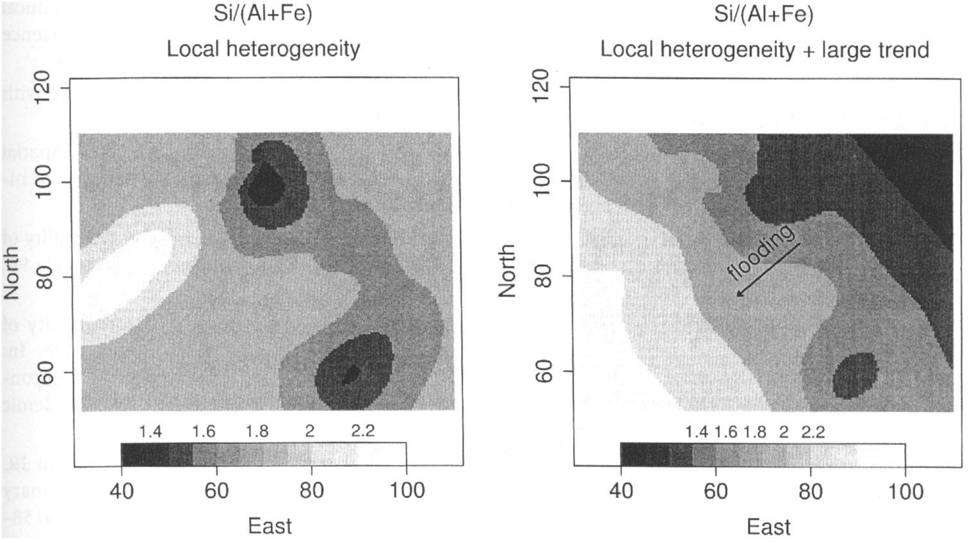

Figure 8. Kriged map of the ratio Si-to-(Fe + Al) in the top 10 cm of the soil profile with the large trend (distance to the pond) removed (left) and added (right). Note that the left map is an estimated map representing the values of the variable when the large trend is removed (local heterogeneity only).

by Vitousek and Howarth (1991) as a mechanism to explain the common N limitation found in earlier successional stages. Again, PO_4 appears to be better buffered and less sensitive to environmental gradients than inorganic N. The large trend had less effect on variation of soil redox potential than other soil variables probably because of local depressions with higher hydroperiods fed by precipitation, which are local sources of soil heterogeneity. The spatial variation of Si, Al, and Fe, the major components of soil minerals, was more affected by the large trend than biological elements such as C, N, P, or cations. This result suggests a gradient of mineral weathering created by the effects of flooding or some other environmental gradient related to different hydroperiods in soils. The observed changes in the Si-to-(Al + Fe) ratio, a comparative index of soil development and weathering rate, support this hypothesis. This ratio increased with increased distance to the pond (Figure 8), as expected, because Si is relatively mobile compared with Al and Fe hydroxides that tend to accumulate in well-weathered soils (Markewich and Pavich 1991; Schlesinger 1997).

The spatial distribution of soil properties was the sum of an underlying local heterogeneity, likely related to microtopography and vegetation, plus the directional effect of an environmental gradient related to flooding. These results also suggest that this environmental gradient differentially affects the spatial distribution of variables that are under biological or geological control, thereby creating a heterogeneous edaphic environment. This high variability found in this floodplain forest soil may explain the fact that these types of forests generally have high plant diversity compared with upland forests. For example, in the studied area, Silva-Pando and others (1988) described 18 plant associations in the flooded environment versus 6 plant associations in the surrounded upland soils.

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