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RESEARCH ARTICLE

Spatial Impacts of Stream and Wetland Restoration on Riparian Soil Properties in the North Carolina Piedmont

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Abstract

Hydric soil development of riparian wetlands is primarily influenced by the hydrologic connection between the floodplains and the stream channel. Often, the goal of riparian restoration is to revitalize this connectivity through a restructuring of the stream channel and the floodplain; however, the effects of this restructuring on the physical and spatial characteristics of soil properties are rarely considered. The objective of this study was to quantify the impacts of restoration efforts on the spatial characteristics of soil properties by means of a pre- and post-restoration comparison. We determined that the spatial patterns of soil organic matter (SOM) and exchangeable phosphorus (P_{ex}) appeared less variable in the years following restoration than in the years before restoration. Mean SOM significantly decreased after restoration, whereas mean P_{ex} significantly increased. The spatial characteristics and mean concentrations of NO_2-NO_3 did not differ much between sampling dates. The loss of this spatial patterning in SOM and P_{ex} and the decrease in SOM pools may represent negative impacts of restoration on important ecosystem characteristics. This study demonstrates that soil properties and spatial patterns can be negatively affected by restoration activities potentially hindering ecosystem development and function.

Key words: floodplain, geostatistics, kriging, soil organic matter, spatial variability.

Introduction

The motivation behind restoration of streams and wetlands stems from recognition that these systems, which form the interface between terrestrial and aquatic environments, play a key role in buffering our freshwater and marine resources from degradation due to urban development (Groffman et al. 2003) and agricultural land use (Zedler 2003). Wetlands and riparian zones provide flood control, nutrient retention or removal, erosion control, water quality maintenance, carbon storage, open space, and wildlife habitat (Richardson 1994; Zedler 2003; Mitsch & Gosselink 2007). Restoration ecology, including stream and wetland restoration, is a relatively young field with methodologies and fundamentals which are still being developed based on evidence from field trials (Roberts et al. 2009). Research has indicated that wetlands vary in ecological characteristics and functions (Richardson 1994). Therefore, successfully restoring a diversity of wetlands that are functionally equivalent to their natural counterparts requires a more complex approach than simply adding water. Substantial efforts are being made to revitalize the natural ecosystem functions of degraded riparian and wetland systems; however, many are unsuccessful due to a lack of understanding of the complexities of these systems (Zedler 2000). One particularly important, and often overlooked, facet of restoration is the effect the physical activities of restoration may have on the soil and other ecological characteristics of the system. Impacts to the soil are of particular importance, because of the geologic timescale of pedogenesis, as well as the overarching influence that soils have on hydrology and the structure and distribution of plant communities and nutrient cycling (Ettema & Wardle 2002; Mitsch & Gosselink 2007).

Research has shown natural wetlands and riparian areas to be hotspots for biogeochemical function (Reddy & Patrick 1984; Groffman et al. 2002; McClain et al. 2003) as well as biodiversity (Naiman et al. 1993; Pollock et al. 1998). Therefore, incorporating physical characteristics which promote these factors is essential to the success of restoration. Many studies have shown that soil resources of natural wetlands exhibit unique spatial characteristics which undoubtedly influence the structure and functions of natural wetlands themselves (Gallardo 2003; Bruland & Richardson 2004, 2005; Bruland et al. 2006; Cohen et al. 2008). However, research documenting the effects of restoration activities on the spatial

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characteristics and distributions of soil properties in wetlands is sparse (Fennessy & Mitsch 2001; Bruland & Richardson 2005; Bruland et al. 2006). One study, with relevance to wetland restoration, determined that natural wetlands had much greater degrees of spatial structure than restored or constructed wetlands of the same region (Bruland & Richardson 2005). This study attributed the lack of spatial structure to the effects of soil homogenization resulting from heavy machinery and other construction activities that were part of the restoration. However, to the best of our knowledge, no study has examined the impacts of restoration activities on both the distribution and overall levels of soil resources. The purpose of this study was to examine changes in soil characteristics which result from the activities of stream and wetland restoration by (1) quantifying differences in the mean quantities in soil properties pre- and post-restoration and (2) modeling the spatial pattern and degree of spatial structure of the soil properties pre- and post-restoration. We hypothesized that restoration activities decreased the natural variability and spatial structuring of soil characteristics which could potentially affect the rate and trajectory of ecosystem development.

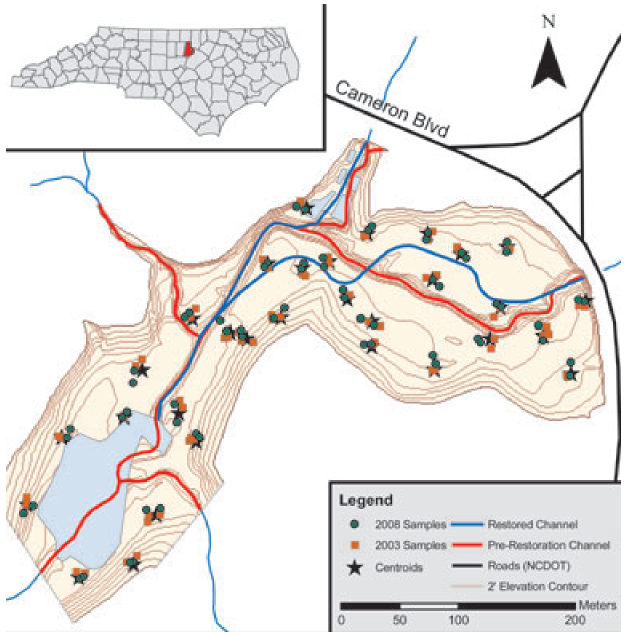

Figure 1. Sandy Creek and study site. Red channel indicates the location of the stream channel prior to restoration; blue represents the stream channel following restoration. The pond and rectangular cells are a product of the restoration. Durham County, North Carolina, is highlighted in red in the inset.

Methods

Site Description

The study area for this research is the Duke University Stream and Wetland Assessment Management Park (SWAMP), located in Durham, NC, U.S.A. (lat 35°59′27.78″N, long 78°56′31.09″W). Measuring approximately 8.47 ha in size, the study site includes the riparian areas of Sandy Creek, as well as some areas which are the fringe along the upland/lowland border (Fig. 1). Land use in the vicinity of Sandy Creek watershed is mostly residential, but contains portions of the Duke University Campus including several athletic fields. Partly due to these urban land uses, impervious cover in the Sandy Creek watershed has approached 20.6% (Elting 2003) resulting in more powerful stormwater discharges which have severely eroded the stream channel and disconnected it from its adjacent floodplain. In its degraded state, the ability of the stream and its floodplains to reduce nutrient and sediment loads are limited. To remedy this and improve the water quality, Sandy Creek has been restored by rerouting it to a new, more sinuous, channel which will dissipate the energy of storm flows and allow for overbank flooding, reconnecting the stream with the riparian wetlands. Restoration activities began in 2004 and were completed in the spring of 2005. Site elevations were not intentionally altered; however, over the course of redigging the new stream channel and filling the old using heavy machinery, all of the surface vegetation was scraped away, and surficial soils were likely mixed and redistributed.

The post-restoration floodplain of Sandy Creek regularly receives flood water during moderate to high rainfall events; however, the volume and frequency of overbank flooding can vary at different locations along the stream channel (Flanagan et al. 2008). In addition, well data indicates that areas adjacent to the stream channel exhibit a hydrologic budget similar to riverine wetlands characterized by periods of temporary soil saturation dependent on precipitation and the stage of the stream (Flanagan et al. 2008). Currently, the majority of the vegetation present is a young floodplain community consisting primarily of grasses, forbs, shrubs, and juvenile trees. Some older trees, which were left undisturbed during restoration activities, are also still present on the site. The topography of the study site is relatively constant on the floodplain, but becomes more variable approaching the upland border. A well-developed levee or terrace has yet to form on the floodplain likely because it has only been a few years since the stream channel and banks were altered as part of the restoration. According to soil maps (Kirby & Station 1976), the most widespread soils are Cartecay (coarse-loamy, mixed semiactive, nonacid, thermic Aquic Udifluvent)/Chewacla (fine-loamy, mixed, active, thermic Fluvaquentic Endoaquepts) soils. These loam soils are formed on floodplains through alluvial sedimentation and are considered to be hydric soils (National Resources Conservation Service 2009). Clay content of soils within the study area average 16.9% (±8.2%) (Sutton-Grier, unpublished data). Soil series on adjacent uplands include the clay-rich Mayodan and White Store, both of which are active or semiactive Hapludults, as well as the Pinkstone sandy loam, a ruptic-ultic Dystrudepts.

Sampling Design

In June and early July of 2003, and then again in June of 2008, the 8.47 ha area around Sandy Creek was assessed to quantify the variability of soil characteristics before and following stream restoration. A spatially discreet sampling design was used to account for both large-scale and fine-scale patterns of variation by randomly clustering sample points around centroids. Fourteen locations that were previously established hydraulic monitoring wells were selected as centroids. An additional 19 centroids were selected using randomly generated coordinates for a total of 33 centroids which were used in both the 2003 and 2008 sampling. Most of the 2003 centroid markers were located during the second round of sampling; however, the location of those which were destroyed during the restoration, had to be estimated using a Trimble GPS (GeoExplorer 2005). For each sampling year, two or three samples were randomly generated within a 10 m radius of each centroid. The coordinates for all centroid locations and all sample locations were acquired using the GPS. A total of 66 samples were collected in 2003 and 62 samples were collected in 2008.

Laboratory Analysis

Soil cores were collected at each sampling location by driving a 5.5 cm diameter steel sampling spoon to a depth of 10 cm below soil surface using a slide hammer. This depth was considered to be sufficient to capture developments of soil properties due to the influence of sedimentation and organic matter accrual occurring in the upper horizon (Mitsch et al. 2005). The steel spoon was lined with a plastic sleeve, which allowed for removal and storage of the soil core without disturbing it. Unincorporated duff and plant litter were brushed away from the soil surface prior to sampling so that only mineral soils were collected. After extracting a core of soil, the plastic sleeves were removed from the steel core and fitted with rubber caps and subsequently stored on ice in the field and then in a cold room in the laboratory until they could be processed.

Soil cores were evenly divided into two halves of equal weight by severing them longitudinally. Split plastic sleeves were weighed prior to sampling allowing the cores to be accurately separated into two evenly weighed half-cores with a minimal loss of soil. Half of the core (wet core) was stored at 4°C for later use in extractable phosphorus and nitrogen analysis. The soil of the other half-core (dry core) was weighed, passed through a 2 mm mesh sieve (# 10) to remove large rocks and roots, and dried at 100°C in order to obtain moisture content and bulk density. The sieved soil was then used to determine soil organic matter (SOM) by loss on ignition (Nelson & Sommers 1996).

Inorganic nutrients were measured using extraction techniques to measure inorganic nitrogen (NO_2–NO_3), and inorganic phosphorus (P_{ex}). Nitrate and nitrite nitrogen was extracted from 2 g of soil with 20 mL of 2M KCl solution (Maynard & Kalra 1993). Twenty milliliter of distilled water was used to extract inorganic phosphate from 2 g of soil (Kuo 1996). A Lachat "Quick-Chem" was used to measure NO_2–NO_3 by cadmium column reduction (method 10-107-04-1-B), NH_4 by the Bertholet reaction (method 10-107-06-1-J), and P_{ex} by the Murphy–Riley (method 10-115-01-1-F).

Statistical Analysis

Means and standard errors were calculated for each soil property from soils collected in 2003 pre-restoration ($n = 66$) and 2008 post-restoration ($n = 62$). The means were compared using Wilcoxon tests of significance (Gehan 1965). This test of significance was preferred over the standard t test, because it is a nonparametric test of significance which does not require assumptions of independence to be met. This is an important issue to address when analyzing samples taken from a clustered pattern which may be spatially correlated (Legendre & Fortin 1989; Cambardella et al. 1994). In our analysis we also quantified the changes in spatial characteristics of soil properties using semivariance analysis and kriging (see details below). All statistical analyses were completed using the R v2.8.1 core package (R Development Core Team 2008), RPART package (Therneau et al. 2008), and GSTAT package (Pebesma & Wesseling 1998).

Geostatistical Analysis

Prior to analysis, NO_2–NO_3 and P_{ex} were log transformed to conform to the assumptions of normality. Regression analysis was used to detrend all variables prior to semivariance analysis in order to remove the potentially confounding influence of large-scale patterns. By using the residuals of the soil property regression models as the inputs for our semivariance analysis, we had already accounted for the variability explained by relationships between soil properties. The residuals (i.e. the detrended data) then represented the remaining variability in the data which we examined for patterns of spatial variability.

The importance of spatial structure in SOM, inorganic NO_2–NO_3, and P_{ex} was evaluated by semivariance analysis using the GSTAT package in R v2.8.1 (Pebesma & Wesseling 1998). We created empirical semivariograms from 10 equal distance classes (20 m) from 0 to 200 m and fit them with spherical semivariogram models. Three characteristics of the semivariogram were most important in quantifying the degree to which the variable in question was spatially correlated: the nugget, the sill, and the range. The "nugget," the y-value at distance 0, indicates the background variance of the data. This could be due to intrinsic random variability, or insufficiently capturing the fine-scale-spatial variability. The "sill," the y-value at which the variogram flattens out, represents the total variance in the data. The "range" or lag distance, the x-value at which the variogram flattens out, represents the distance beyond which samples are spatially independent. The ratio of nugget to sill is generally representative of the degree of spatial dependency in the data (Cambardella et al. 1994), and was used as a means by which to compare spatial correlation between different properties and different years. Different classes of spatial dependency for the soil variables were grouped as follows: a ratio of 25% or less was considered strongly spatially correlated; between 25 and 75% was considered moderately spatially correlated; and greater than 75% was considered weakly spatially correlated (Cambardella et al. 1994). Universal kriging (Krige 1966) was used to interpolate soil properties across the entire study area for the purpose of visually representing the spatial patterns. The steps involved in universal kriging are similar to the process we described previously for semivariance analysis; however, the semivariogram model was derived from the residuals of a second-order-polynomial surface trend model which related soil properties to their x- and y-coordinate locations. Universal kriging uses the semivariogram model to estimate the fine-scale trends, and then refits the global trend surface to areas which fall outside the range of spatial correlation.

Results

Comparison of Mean Soil Properties

There were substantial differences between soil properties, pre- and post-restoration (Table 1). Mean soil properties were significantly different for both soil variables, SOM and P_{ex} (Table 1). SOM significantly decreased from a mean of 9.6% pre-restoration to an average of 6.9% following restoration. Conversely, P_{ex} concentrations showed a 3-fold increase following restoration from 0.615 µg/g in 2003 to 1.53 µg/g in 2008. No significant differences were found for the means of bulk density, percent moisture, or NO_2-NO_3. On average, the distance of sample locations to the stream decreased post-restoration resulting from the increased sinuosity of the channel (Table 1).

Spatial Analysis

Semivariance analysis showed a marked difference between spatial characteristics of pre- and post-restoration. SOM exhibited the strongest difference in spatial dependency class between pre- and post-restoration. Prior to restoration, SOM exhibited a moderate spatial structure and a range of 42 m. The "moderate" spatial structure was determined by the ratio of the nugget (5.289) to the sill (8.937) of approximately 59%. Strikingly, the semivariogram for SOM in 2008 did not show any evidence of spatial correlation as exhibited by the nugget (3.298) to sill (3.304) ratio of 99.8%. The range in 2008, although much larger than that of 2003, was meaningless because it lacked a sill indicating that soils were not spatially correlated at any distance in regards to SOM. This implies that SOM after restoration was not spatially structured, and was distributed either randomly or homogenously throughout the site without any distinct patterning or patchiness.

This difference in spatial characteristics is most clearly visualized in the maps of the kriged SOM concentrations (Fig. 2a & 2b). Figure 2a demonstrates the patchy distribution

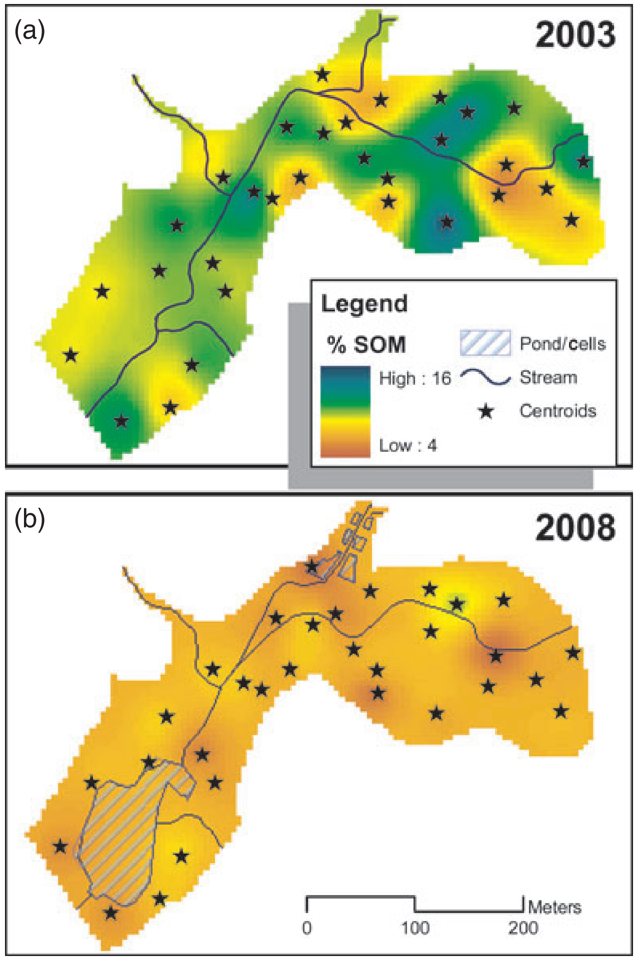

Figure 2. Kriged map of the percentage SOM for years. (a) 2003 and (b) 2008.

Table 1. Soil properties before and after restoration.

Parameter	*2003 (n = 66)* Mean	SE	*2008 (n = 62)* Mean	SE	*Wilcoxon Test p Value*
Moisture (%)	24.33	0.94	29.4	1.90	0.1320
Bulk density (g/cm^3)	1.037	0.02	1.044	0.03	0.3947
Soil organic matter (%)	9.619	0.46	6.892	0.30	<0.0001*
P_{ex} (µg/g)	0.615	0.10	1.532	0.12	<0.0001*
NO_2-NO_{3ex} (µg/g)	2.472	0.21	3.617	0.73	0.578
Distance (ft)	103.31	6.33	67.68	7.47	<0.0001*

* A statistically significant p value.

and the higher variability of SOM pre-restoration with a few patches of high and low SOM representing the "moderate" degree of spatial dependency. The post-restoration soils (Fig. 2b) kriged map suggests not only a reduced SOM content over the majority of the study area, but also a much more homogenous distribution of SOM with a lack of patches of high or low concentration.

The change in spatial structure of P_{ex} after restoration was similar to that of SOM although not as pronounced. Although exhibiting one of the shortest ranges, 29 m, the class of spatial dependency for P_{ex} before restoration was considered "strong" due to the relatively large difference between the nugget (0.189) and the sill (0.755), which yielded a ratio of 25%. In 2008, P_{ex} had a similar nugget value comparatively (0.186); however, the magnitude of the sill was much less (0.346), signifying a reduction in overall variability. Spatial structure in 2008 is thus weaker (53.7%) and is classified as a "moderate" degree of spatial dependency, with a range of 68 m. These differences in spatial dependency between the two sampling dates are driven largely by the differences in the sill values, given the nuggets are similar in both years. The lower value of the sill implies that there was less variability of soil P_{ex} in 2008. The kriged maps of the P_{ex} data visually demonstrate that the spatial characteristics of P_{ex} have been substantially altered by the process of restoration, leading to a more homogenous distribution of soil P_{ex} (i.e. "strong" spatial structure in 2003 with lots of patches [Fig. 3a] and greatly reduced spatial structure with less patchiness in 2008 [Fig. 3b]).

The spatial characteristics of NO_2-NO_3 did not appear to be affected by restoration in the same way as SOM and P_{ex}. The importance of spatial distribution for NO_2-NO_3 did not decrease after restoration as it did for SOM and P_{ex}, but instead increased as is evident from the change in the class of spatial dependency from "moderate" (30.3%) pre-restoration to "strong" (9.8%) post-restoration. This was determined from

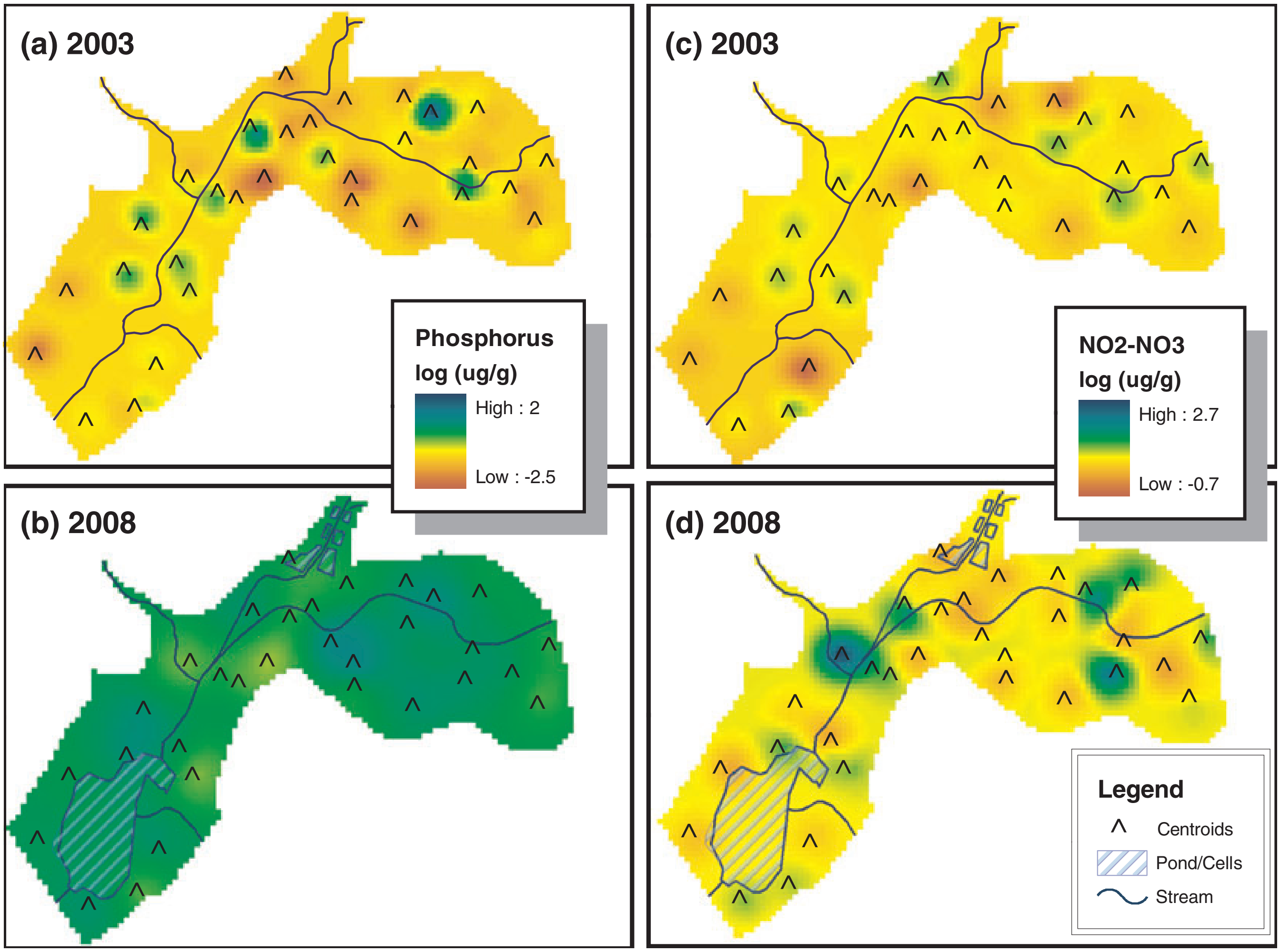

Figure 3. Kriged maps of the (a) log P_{ex} in 2003, (b) log P_{ex} in 2008, (c) log NO_2-NO_3 in 2003, and (d) log NO_2-NO_3 in 2008. The range of P_{ex} in original units is 0.07–4.77 μg/g (2003) and 0.038–5.71 μg/g (2008). The range of NO_2-NO_3 in original units is 0.65–35.84 μg/g (2003) and 0.04–8.35 μg/g (2008).

the larger difference between the pre-restoration nugget (0.290) and sill (0.954) as compared to the post-restoration nugget (0.064) and sill (0.695). Nitrite–nitrate nitrogen was the only one of three soil properties to increase in spatial dependency post-restoration. It is important to note, however, that although NO_2-NO_3 changed spatial dependency classes, the actual degree of change was less than all other soil variables. The small amount of change between sampling dates can also be seen when comparing the kriged models; although some distinct patches are present in the kriged map of NO_2-NO_3 post-restoration (Fig. 3d) which are not in the pre-restoration (Fig. 3c), the maps are generally similar. Also, the difference in the spatial distributions of NO_2-NO_3 between years is minimal in comparison to the changes we observed for SOM and P_{ex}.

Discussion

Only a handful of studies have examined the effects of restoration (Bruland & Richardson 2005) and creation (Fennessy & Mitsch 2001) on the spatial patterns of soil properties. Those studies that examined spatial structure of restored systems typically compared the restored sites to natural sites and consistently concluded that disturbance is a key factor influencing spatial patterns of soil properties. For example, Bruland and Richardson (2005) attributed the lack of spatial structure found in restored and constructed wetlands of their study to the use of heavy machinery during restoration which disturbed and homogenized the soil. Thus, the activities typically used to restore ecosystem structure may have negative impacts on soil properties, particularly the spatial patterns. To the best of our knowledge, this is the first study to examine differences in soil properties pre- and post-restoration at the same site.

The difference in the means and spatial structure of soil properties of our pre- and post-restoration analysis suggest that the processes of restoration can significantly alter the characteristics of soil resources. In our study, we determined that different aspects of soils can change post-restoration including the average levels of a resource and the spatial patterns of soil resources. We also determined that SOM and P_{ex} experienced the most alterations while NO_2-NO_3 was less altered.

The 33% decrease in the mean SOM along with the loss of spatial structure are perhaps our strongest evidence that the disturbance associated with restoration activities may have an effect on the function and development of the system. The loss of these characteristics is very clear when comparing the post-restoration kriged maps of SOM to the pre-restoration map. The majority of the post-restoration study area is of a lower percentage SOM than the pre-restoration study area. Furthermore, the distribution of SOM post-restoration does not occur as patches of high and low concentrations as it did prior to restoration and is much more homogenous. These results are similar to those of another study which found that SOM levels were much lower in created or restored wetlands when compared to natural wetlands and that spatial variability of SOM tended to be much more heterogenous in natural wetlands versus those that had been created or restored (Bruland et al. 2006). Post-restoration SOM at our site (6.8% average) fell within the range of what other studies of restored/created riverine wetlands with comparable bulk densities and time-since-restoration have found. An Ohio study found average SOM to be 3.97% (Broennum et al. 2000), while another study in the coastal plain of North Carolina found average SOM to vary from 2.43% in a restored mainstem riverine wetland to 8.73% in a restored headwater riverine wetland (Bruland & Richardson 2005). Furthermore, levels of SOM ranged from 4 to 16% in a restored riverine wetland in the piedmont of North Carolina which had undergone varying treatments of organic amendments (Sutton-Grier et al. 2009).

We believe the decrease in SOM and loss of spatial structure is a direct result of soil disturbance which accompanied the restoration activities. Levels of SOM were lowest in areas immediately adjacent to the stream channel in 2008, likely because these were the areas in which disturbance from restoration was most intense, and SOM loss was the greatest. With increasing distance from the channel disturbance was less significant and SOM was higher. The restoration activities could have changed soil properties through a variety of ways. The physical process of grading and contouring a new stream channel and floodplain required a high degree of earthmoving by heavy machinery which likely resulted in the mixing and homogenization of soils of the riparian area. During this physical process, SOM-rich-upper horizons may have been turned under or mixed with the underlying mineral soils thereby reducing the average SOM concentrations at the surface, as well as the unique patchiness which was present pre-restoration. Soil mixing may also have increased decomposition rates by exposing buried organic layers to aerobic conditions, reducing the average amount of SOM. Furthermore, prior to restoration the site existed under a forested canopy which contributed a large degree of organic matter to the soil in the form of leaf detrital matter. Much of this tree canopy around the stream channel has been replaced with an early floodplain grass and forb community with juvenile trees still in development. The amount and nature of detrital matter being contributed to the soil is therefore substantially different post-restoration compared to pre-restoration. Essentially, both SOM and the factors which influence it have been altered by restoration activities, therefore leading to a decrease in SOM pools and a loss of spatial heterogeneity.

This loss of SOM, as well as the loss of spatial heterogeneity, could have important consequences for the biogeochemistry of this site. Many microbes that perform nutrient transformations are heterotrophic meaning they require organic carbon, which comes from the breakdown of SOM, as a source of energy for biogeochemical reactions (Megonigal et al. 2004). It is therefore a concern that SOM levels decreased post-restoration because decreases in overall SOM levels may mean a decrease in microbial functioning and biogeochemical cycling. Also of concern are the changes in the spatial structure of SOM; soils across the site post-restoration are experiencing a more limited range of SOM levels suggesting that important hotspots of microbial activity associated with patches of SOM (Groffman et al. 2009) were likely destroyed. This homogenization of soil conditions is likely to be accompanied by decreases in the associated biogeochemical transformations (Bruland et al. 2006). To mitigate problems with low SOM, additions of topsoil or organic matter have been suggested to improve soil quality and biogeochemical cycling in created or restored wetlands (Bruland & Richardson 2004; Sutton-Grier et al. 2009). Practitioners could also consider stockpiling topsoil from the site and replacing it once restoration activities are completed.

The changes in mean exchangeable P differed from the changes in SOM, in that the mean P_{ex} was elevated 3-fold over pre-restoration levels, but was similar to SOM in that spatial structure decreased and its distribution became homogenized after restoration. We believe that this alteration in the characteristics of P_{ex} was also caused by the activities involved in restoration; this increase was not due to the input of new material to the site because soils were not amended with fertilizer or organic amendments, nor was fill brought onto the site. Therefore, we hypothesize two mechanisms that could explain the increase in P. First, the breakdown of SOM throughout the site, as a result of surficial soil disturbance caused by heavy machinery use, could have released organic phosphorus into the soil, which subsequently oxidized to inorganic form (i.e. PO_4) increasing inorganic phosphorus above pre-restoration levels. Another plausible explanation for the increase in phosphorus is that subsurface clay-rich soil with adsorbed phosphate may have been brought to the surface and mixed with the surficial soils during restoration activities. This mechanism would be most likely in areas closer to the stream channel where soil disturbance was most significant and where the only subsurface excavation occurred. Therefore, it is likely the soil homogenizing activities which altered the spatial distribution of SOM have affected the spatial distribution of P_{ex} in a similar way. These results are similar to other research that identified a similar decrease in soil variability and homogenized spatial distributions of soil properties resulting from the activities of restoration (Bruland & Richardson 2005). Levels of extractable P in our study, which ranged from 0.39 to 5.71 μg/g, were similar although a little lower than levels found in another study of a post-restoration riparian wetland which found levels of extractable P to range from 0.6 to 16 μg/g (Sutton-Grier et al. 2009).

Nitrite–nitrate nitrogen differs from SOM and P_{ex} in that mean levels were not significantly different post-restoration and the spatial distribution was minimally altered. We do not take these results to mean NO_2–NO_3 was unaffected by restoration, but that signs of disturbance have already faded because inorganic nitrogen is far more mobile than inorganic phosphorus in an ecosystem, being connected to both biological and geochemical processes (Craft 1996). Nitrite–nitrate nitrogen is more readily dissolved in solution and leached from a system than inorganic P and is also subject to a much faster biogeochemical turnover rate (Baldwin & Mitchell 2000). Therefore, we believe the reason that there was no difference in the mean values of NO_2–NO_3 can be explained by the rapid rate at which excess N is taken up by plants, cycled through biogeochemical activities, or removed from the site via denitrification, runoff, or leaching. This would also explain why NO_2–NO_3 has developed a higher degree of spatial dependency than the other two soil characteristics, and does not appear to be homogenized. Levels of total extractable $N(NO_2 - NO_3 + NH_4)$ in our study, which ranged from 0.70 to 39.23 μg/g, were relatively similar to levels found in another study of a post-restoration riparian wetland which found levels of total extractable N to range from 0.80 to 32.00 μg/g (Sutton-Grier et al. 2009).

We interpret our findings to suggest that the 4–5 years which have elapsed since the restoration has not been enough time for the restored ecosystem to recover from the disturbance associated with restoration activities, and to develop levels of variability and spatial structure comparable natural riparian wetlands. Our findings stress the importance of understanding what ecosystem characteristics are disturbed during restoration activities, and how they will affect rates of ecosystem development following restoration. Ecosystem properties, particularly soils, may be slow to develop post-restoration (Craft et al. 2002, 2003; Ballantine & Schneider 2009). For example, Craft et al. (2002, 2003) estimated the amount of time needed to accumulate pools of SOM equivalent to that of natural wetlands to be between 30 and 150 years, even in very productive and regularly inundated systems such as salt marshes.

Our results demonstrate that restoration activities have resulted in significant alterations to the soil characteristics of the study site which may have important impacts on soil microbial communities, plant communities, and biogeochemical transformations as well as the trajectory of ecosystem development. For example, loss of the intrinsic patchiness of soil resources may lead to a reduction in the diversity of plants at the site as those with competitive abilities best fit to exploit the specific conditions will proliferate across the entire site. These conditions may be competitively favorable to the takeover of invasive species (Zedler & Kercher 2004). Continued monitoring of the site in the years to come will provide valuable insights into how restoration activities impact plant communities and ecosystem development. In addition, although in this study we did not examine subsurface (below 10 cm) soils, research on salt marshes suggests that subsurficial (below 10 cm) soils are much slower in their recovery than soils above 10 cm, which ultimately leads to differentiation of upper and lower soil layers in young natural and constructed marshes (Krull & Craft 2009). Future research efforts should consider how both surface and subsurface soils are impacted by restoration activities. This study demonstrates that restoration activities impact soil properties and spatial patterns and therefore can potentially hinder ecosystem development and functioning.

Implications for Practice

- Soil disturbance is often an unavoidable part of stream and wetland restoration projects; however, it can result in significant changes to soil properties including the loss of soil organic matter pools and the loss of spatial structure of the soil properties.
- These changes in soil resources may impact the trajectory of ecosystem development because wetland soils influence wetland plant community diversity and distributions, as well as biogeochemical hotspots of nutrient transformations.
- To minimize the impacts of restoration activities on soil properties, restoration practitioners should: (1) only disturb surficial soils when necessary; (2) limit the use of heavy equipment as much as possible; and (3) add soil amendments or stockpile topsoil and redistribute after recontouring the project site.

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