ABSTRACT

MALONE, MEGAN ELIZABETH. A Comparison of the Vegetation and Soils of Restored Streams and their References in the NC Piedmont. (Under the direction of Theodore Henry Shear).

Common stream restoration practices inherently cause massive soil disturbance to the stream banks and floodplains. Soils affect plant community functions, and soil disturbance has been linked to exotic plant invasion. I designed this study to characterize the soils, determine the extent of invasion, and assess the presence of native woody plant species at stream restoration sites. I studied 11 restored streams in the NC Piedmont, as well as 6 reference streams. Reference streams are unrestored and generally undisturbed streams that are used as models during restoration design.

Restored streams, with 34% exotic cover, were more invaded than the references, with 10% exotic cover. The restored streams also had more exotic species present per m^2, greater frequency of exotic species, and greater exotic stem density. The native woody vegetation growing at the restorations and references differed in terms of the species present and their abundances. Fourteen of the 20 physical and chemical soil properties differed by site type, as did many morphological soil characteristics. Soil properties explained 20% of the variation in exotic species cover and 34% of the variation in native woody species cover.

The differences in vegetation and soil indicate the lasting impact of restoration practices. The restored stream communities do not have the same structure as the references, and are unlikely to have the same function. It would be very feasible for restorationists to address the differences we found. Efforts to chemically control exotic plants could be increased, and restorationists could limit the species they plant to those that are found in the project's associated reference community. Soils could be adjusted by testing and amending

as necessary. Efforts such as these, in addition to further research into restoration practices and design, will be necessary to improve restoration success.

A Comparison of the Vegetation and Soils of Restored Streams and their References in the NC Piedmont

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Natural Resources

Raleigh, North Carolina

2011

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DEDICATION

I moved to North Carolina not knowing a single person here. Nearly three years later, Raleigh has become my community and my home. I would like to dedicate this work to all of the people who have been part of my journey here and who have helped me have such a good time along the way.

BIOGRAPHY

Megan Malone was born in New Haven, CT in the June of 1984. Her career path into Natural Resources was nearly destined from the start. She was fortunate to grow up in Guilford, CT, a town where the beauty of nature is a constant inspiration. She was also lucky to have parents who didn't believe in sitting inside on a sunny day, and frequently kicked her and her older sister outside and shut the door behind them.

Megan's destiny was not always apparent to her. Growing up, she loved playing outside, but she also loved ballet, the color pink, and cats. She worked really hard at all of her classes, and thought about potential careers as a dancer, actress, violinist, lawyer, Radio City Rockette, teacher, photographer for National Geographic, groundskeeper for the New York Yankees, and balloon handler in the Macy's Thanksgiving Day parade. Needless to say, scientist never made the long or short list of careers she thought she might eventually choose.

However, a scientist she was meant to be. Things turned around when she was introduced to Ecology in her AP Biology class. By the time she enrolled as a freshman at Hamilton College she had decided upon Biology as her major and graduated four years later with a minor in Environmental Studies as well. However, upon graduation she felt lost and lacking direction. All of her science friends were entering medical school, but she knew that wasn't for her. On a whim she applied to be a Student Conservation Association intern at Richmond National Battlefield Park. She was offered the position, and spent a wonderful four months working for the Parks' Natural Resource Management Specialist. It was there that she decided to get her master's degree in Natural Resources.

Megan chose to work for a year to raise money for graduate school. In an odd chain of events she ended up working in loan servicing for a nonprofit financial organization in CT. She had the very dramatic experience of learning the world of mortgages during the advent of the housing crisis, which was an education in itself. Having raised enough money, and having had her fill of living and working in the "real world" she enrolled in North Carolina State University in 2008. When not studying or working she enjoys baking, spending time with her dog, Lucy, and loudly singing off-key.

ACKNOWLEDGMENTS

I would like to thank the North Carolina State University Department of Forestry and Environmental Resources for awarding me the research assistantship that made my education possible. I would also like to thank the North Carolina Exotic Plant Pest Council, whose scholarship greatly helped me finance the end of my graduate education.

I would like to sincerely thank the many people who helped me with my research. I would like to first recognize my committee members; Dr. Theodore Shear, Dr. Jon Stucky, and Dr. Jeffrey White, for all of the assistance, support, and time they contributed to help me successfully complete this project and learn a lot along the way. I would like to offer a special thanks to the intern who assisted me in this project, Andrew Blake, without whose constant support and unflappable good nature I would have never made it through. I would like to thank all of my friends and colleagues who helped me with fieldwork, including Joelle Lang, Yari Johnson, Kim Shumate, Kim Hamlin, Ashley Steele, Patrick Chess, Joseph Sullivan, Ryan Unks, and Shari Rodriguez – thank you so much for your help and camaraderie.   I would like to recognize Ruth Lanni, whose kindness and generosity made completing my lab analyses possible and Dr. Alexander Krings, without whose help I would still be trying to identify my plant specimens.   I would also like to thank the many people who assisted me along the way, including the NCSU Department of Forestry staff, the landowners that allowed me to access their properties, and the people at NCDOT and NCEEP who searched the archives to get me the information I needed. Lastly, I would like to thank my family and friends for being the support that kept me going. Thank you.

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CHAPTER 1: INTRODUCTION

Stream restoration has become an increasingly common practice in the last 20 years. As a student living and working in Raleigh, NC, I spent my graduate career within an hour drive of dozens of restorations, some of which were constructed more than a decade ago. Until very recently, stream mitigation projects in NC were monitored for 5 years (this has been increased to 7 years). After the monitoring period is over, these restorations are largely left alone; the stream structures are not maintained, the channel stability is not assessed, and the floodplains are not re-planted if vegetation cover declines below desired levels.

This project resulted from my advisor and I asking a very basic question – what happens at these sites once monitoring is done? We were particularly interested in the vegetation and soils of restored streams. Restored streams have an interesting history; they are restored because the stream had become degraded, but the restoration practices themselves also cause massive vegetation loss and soil disturbance. We were interested in how this history affects the vegetation and soils of the sites as they mature.

Stream restorationists use references when they design stream channel morphology and create planting plans. References are unrestored streams that are relatively undisturbed. We decided that if we were going to study restored streams, we should compare them to the models used to design them. We studied 11 restored streams and 6 of their reference streams within the NC Piedmont. All of the restorations were constructed between 1999 and 2005.

I conducted two interrelated projects. The first was an assessment of the vegetation of the restorations and references. I focused on the presence of exotic species, which are promoted by disturbance and often very detrimental to community functions. It seemed

Figure 1.1. *Yates Mill Tributary channel construction, highlighting the disturbance inherent in excavating a stream channel. Left photo during construction, right immediately following.*

logical that the restorations should have a greater amount of invasion than the references due to their disturbance histories, but no one had previously determined if this was true. We also studied the native woody species to gain an understanding of how the overstories of these sites might develop over time. We wanted to learn about as many streams as possible, and chose not to study native herbs because we would have had to sacrifice the number of study sites we used.

The second project was an analysis of the soils of these sites. During restoration the soils are churned and compacted. We believed that as a result of these practices, the soils of the restored banks would be very different than the soils of unrestored riparian banks. Again, no one had previously characterized the soils of restored and reference streams, so we set out to do so by studying their physical, chemical, and morphological properties.

This thesis fully describes the work I did, the reasoning behind it, and the results and implications of what I found. Because of the interrelated nature of the two projects, it was impossible to totally segregate them, and the vegetation and soils are both described in both chapters. However, Chapter 2 focuses on the vegetation study, and was written as a paper to be submitted to *Restoration Ecology*. Chapter 3 focuses on the soil study, and was written as a paper to be submitted to *the Soil Science Society of America Journal*.

CHAPTER 2: DOES RESTORATION MAKE STREAMS MORE SUSCEPTIBLE TO INVASION OF EXOTIC PLANTS?

Megan Malone, Theodore Shear, and Jon Stucky, for submission to the journal *Restoration Ecology*

Abstract

Exotic species can impact both the structure and function of riparian communities. Restored riparian zones are particularly at risk for invasion because of the soil disturbance they incur during restoration. We studied restored streams in urban and suburban locations within the North Carolina Piedmont to determine their extent of invasion as well as to assess the presence of native woody species. We compared the vegetation of these streams to reference streams, which are unrestored, generally undisturbed, and used as models for stream restoration design. We also assessed the chemical and physical properties of the soils at both site types. The restored streams had an average of 34% exotic cover, whereas the references had 10%. The restorations also had more exotic species present per m^2 as well as greater frequency of exotic species and density of exotic stems. The patterns of native woody species cover, frequency, and density were also different by site type. Seventy percent of the soil properties we tested were different at the restorations and references, and the soil properties explained 20% of the variation in exotic species cover and 34% of the variation in native woody species cover. The differences we found in vegetation and soils by site type indicate that the restorations do not have the structure of natural riparian communities and demonstrate the lasting effects of the disturbance inherent in many

restoration practices. In order for restoration practices to be improved, we need to further study and prioritize addressing the vegetation and soils of these sites.

Introduction

Although stream restoration practices are used primarily to reduce the degradation of riparian zones, they also inherently cause soil disturbance. Disturbance is problematic because it directly and indirectly affects resource availability, which can promote exotic plant invasion (Davis et al. 2000). Riparian zones are particularly at risk for invasion because flooding naturally disturbs stream banks and disperses invasive seeds downstream (Thébaud & Debussche 1991). Additional causes of disturbance, such as grazing or trampling by livestock, facilitate exotic plant invasion to riparian zones (D'Antonio et al. 1999; Richardson et al. 2007). The heavy construction equipment used to create and modify stream channels during restoration causes large-scale vegetation removal and disrupts the soil profile. One consequence of these restoration activities may be the increased susceptibility to invasion of exotic plants post-restoration.

We were unable to find any studies of invasive species in restored riparian zones. However, the connection between disturbance and invasion has been illustrated through various field studies in other communities. Removing leaf litter and disturbing soil nearly doubled the average distance between an existing patch of *Microstegium vimineum* and the location where the farthest propagule germinated the following year when compared to an undisturbed patch (Marshall & Buckley 2008). Disturbance did not affect *Rosa rugosa* seedling growth in all dune habitats, but in some dunes seeds planted in disturbed plots were as much as three times more likely to emerge (Kollmann et al. 2007). Seedlings in one dune habitat had 95% more biomass after two years than seedlings in undisturbed plots. The extent and pattern of disturbance also matters; a combination of several small and large gaps promoted invasion more than solitary large gaps in agricultural fields in the U.K. (Burke & Grime 1996).

Although the soils of restored streams are relatively unstudied, several researchers have compared the soils of restored and natural wetlands. Although wetland restoration involves a lesser degree of soil excavation and disturbance than stream restoration, some of the same basic practices are used, and the soils of wetland and stream restoration are impacted in similar ways. Many soil properties assessed during wetlands research affect plant growth; CEC and organic matter are generally correlated with fertility, high bulk density may impede root growth, and texture (amounts of sand, silt, and clay) affects properties including drainage and aeration. As a result, the conclusions of wetlands soils research are insightful when considering the soils and vegetation of restored streams.

Many soil properties of restored wetlands differ from soils of reference wetlands. Natural wetlands in the Coastal Plain of North Carolina had more than double the mean soil organic matter content than created and restored wetlands (Bruland & Richardson 2006). Twelve created wetlands in Pennsylvania, ranging from two to twelve years old, had lower soil organic matter content, higher soil chroma values, more rock fragments, more sand, less silt, and twice the bulk density than 14 natural reference wetlands (Campbell et al. 2002). Although the older created wetlands had more organic matter than the younger wetlands, bulk density did not significantly decrease with age. Cation exchange capacity (CEC), soil organic matter, and concentrations of P, K, Mg, and Ca increased and bulk density decreased with age in restored wetlands in central New York (Ballantine & Schneider 2009). However, even in the oldest restored wetlands studied (fifty to fifty-five years post restoration) the levels of CEC and soil organic matter were half, and the bulk density was double as in the natural reference wetlands.

While visiting local restored streams we observed that exotic plants were frequent colonizers of the banks and floodplains. In this study we addressed the invasion we observed by assessing the plant community and soils of stream restoration sites. We conducted the same assessments at the reference sites listed in the construction plans of the restored streams. Reference sites are relatively undisturbed streams that are cited as models when setting stream restoration goals (FISRWG 1998) and designing the channel morphology and riparian plant community (Doll et al. 2003). While conducting this work we asked several research questions: Are the restored streams more heavily invaded by exotic species than the reference streams? How do the native species communities compare by site type (restorations versus references)? Do the soil chemical and physical properties differ at the restorations and references? Is there a connection between soil properties and both exotic vegetation and native vegetation growth?

Methods

Site Selection

We studied eleven restored streams (Table 2.1) and six reference streams (Table 2.2) within the Piedmont of North Carolina. Monthly precipitation totals in the central Piedmont range from 7 to 16 cm and average monthly temperatures range from 7 to 27°C (NOAA n.d.).

The streams were selected based on proximity and age, with older restorations prioritized because their vegetation should be more established. All restoration projects studied were constructed between 1999 and 2005; their landscape contexts are provided in Table 2.1. In three of the projects an entirely new channel was dug, and in five projects the floodplains and channels were modified. Two projects had a combination of new channel excavation and floodplain and channel modification, and one project consisted of stream bank stabilization. All of the restorations were planted post-construction; the species planted are provided in Table 2.3.

We reviewed the design plans of the restorations and determined the references used. Most used one to three references, although two did not use any. Some of the references were used by more than one project. The distance between a restoration and its reference ranged from 11 to 48 km, with an average distance of 23 km. We could not study all of the references because some of them had become degraded by development, and in one case, the reference had been restored. The lengths of the reference streams we surveyed varied and were generally limited by land or stream degradation or residential development. The landscape contexts of the references are provided in Table 2.2.

Species cover and richness in urban stream buffers in North Carolina are affected by surrounding land use (Vidra & Shear 2008). Unfortunately, determining the influence of the surrounding land use on our study sites or comparing patch sizes between the restorations and references were outside the scope of this project. It is possible that the vegetation composition of the riparian zones we studied was impacted by the presence of exotic species growing nearby. However, many of the restorations and references were located in similar landscape contexts, suggesting that streams of both site types would be similarly impacted by invasion from bordering lands. In addition, patch size alone does not determine the extent of invasion (Vidra & Shear 2008) and the cover of three very common exotic species, *Microstegium vimineum, Lonicera japonica,* and *Ligustrum sinense* are not related to stream buffer width (Vidra 2004).

Vegetation Survey

Vegetation surveys were conducted between July and October 2009. We established a series of 2 m by 2 m plots along each stream on both banks. The plots were either 30 or 61 m apart depending on stream length and alternated being centered 3 and 5 m from the stream. We visually estimated the percent cover of all woody species and exotic plants rooted in or hanging over each plot, and assigned each species to one of eleven classes according to the cover class system we devised. Species covering less than 1% were listed as Trace, and entered as a 0.1% cover in the datasheet. All of the other cover classes were in 10% increments except for the interval between Trace and 10%, which was broken into two intervals: Trace – 5% and 5 – 10%. We calculated the total percent cover of exotic species for each plot by summing the covers of each individual exotic species growing in it, and did likewise for the native woody species totals. Because we summed the covers of numerous species together it was possible to have total covers greater than 100% per plot. We determined the basal area at each plot using a 10 BAF prism (Bitterlich 1948). We sampled a total of 283 plots, 89 at the reference sites and 194 at the restoration sites.

We also surveyed the vegetation in 4 m wide belt transects that bordered each stream on both banks. Within the transects we identified each woody plant, exotic or native, that was taller than 1.3 m and recorded its diameter at 1.3 m. For stream segments less than or equal to 457 m, the transects spanned the entire length of the study site. For segments longer than 457 m, 30 m transects were surveyed starting at each plot.

It was necessary to use both plots and belt transects to answer our research questions. The plots allowed us to study the understory but were not adequate for studying the overstory. The belt transects allowed us to inventory the midstory and overstory, but did not include any vegetation less than 1.3 m tall. The combination of these two methods gave us a thorough understanding of the species growing at these sites.

All species were identified in accordance with Weakley (2010). If it was not known in the field if an herb was exotic or native, a voucher specimen was collected and the herb was then identified. Voucher specimens were also collected for all of the exotic and native woody plants in the dataset and the species identifications were verified by expert review. These specimens were submitted to the North Carolina State University Herbarium. The status of each species, exotic or native, was verified in Weakley (2010) who defined exotic species as those that had been "introduced by whatever means and demonstrably established and reproducing (sexually or vegetatively) as a component of the flora."

Soil Study

Soils were sampled in 153 of 283 vegetation plots, 51 from the reference sites and 102 from the restoration sites, between May and July 2010. We sampled the soils in alternating pairs of vegetation plots along both banks of all the study sites. Sampling in pairs instead of alternating each vegetation plot allowed us to sample plots that were both 3 m and 5 m from the stream within the same site.

We divided each plot into four quadrats and used a 6.5 cm diameter barrel auger to extract a 15 cm deep core from each quadrat. We pooled the four cores per plot and took a subsample for chemical and particle size analyses. We sampled bulk density by hammering a $331 cm^3$ (7.5 cm height, 7.5 cm diameter) metal cylinder into the ground until the soil was even with the cylinder rim, then carefully excavating it. We took one bulk density sample from each quadrat and combined the four samples from each plot before drying and weighing.

We determined particle size distribution with a procedure modified from Gee and Bauder (1986). Bulk density was analyzed by drying samples at 65°C for 48 hr and weighing the following day. Weight per volume (Mehlich 1973); pH; humic matter (Mehlich 1984b); Mehlich-buffer pH acidity (Mehlich et al. 1976); and Mehlich-3 CEC, base saturation, and concentrations of P, K, Ca, Mg, S, Na, Cu, Mn, and Zn (Mehlich 1984a) were analyzed by the North Carolina Department of Agriculture & Consumer Services Soil Testing Laboratory (Raleigh, NC).

Data Analyses

We used t-tests to compare the number of plant species per area, vegetation cover, stem density, basal area, soil composition, bulk density, and particle size distributions between site types. All t-tests assumed unequal variances and were considered significant when $p \leq 0.05$ unless otherwise noted. Analysis of variance (ANOVA) of multiple linear regression models was used to determine the best models of plant cover as a function of soil properties. The models were selected using the Maximum R^2 Improvement (MAXR) technique in PROC REG with a minimum *p*-value of 0.05. Both of these analyses were performed with SAS Version 9.1.3 software (SAS Institute Inc. 2009).

Plant cover and soil chemical and physical properties were ordered by Non-metric Multidimensional Scaling (NMS) using PC-Ord software (McCune & Meffort, 2006). PC-Ord software was also used to construct species-area curves. The curves resulted from the combination of 500 random subsamplings of the dataset.

Results

Although we sampled more plots at the restoration sites, species-area curves comparing the restorations and references indicate that we sampled both site types adequately (Figure 2.1). On average, the restored sites had more than double the number of exotic species per m^2 than the references ($t = 3.372$, $df = 15$, $p = 0.004$; Table 2.4). The restorations had triple the number of exotic tree and grass species and approximately double the number of exotic herbs, vines, and shrubs. There was only one exotic species, *Mahonia* *bealei,* which was found at the reference sites in low density (2 stems/ha) but not at the restorations at all (Table 2.5).

The mean cover of exotic species was 34% in the restored plots and 10% in the reference plots ($t = 4.269$, $df = 15$, $p < 0.001$). *Microstegium vimineum,* an invasive grass, was the exotic species with the highest percent cover at both site types. The mean percent cover of *M. vimineum* was 14% at the restorations and 5% at the reference sites. With the exception of *M. vimineum*, the exotic species with the highest average percent cover differed by site type. Turf grass, *Ampelopsis brevipedunculata, Glechoma hederacea, and Pueraria montana* var. *lobata* were the species with the highest average cover at the restorations, whereas *Hedera helix, Elaeagnus umbellata,* and *Lonicera japonica* were the only species with average cover greater than a trace at the references.

Exotic species were found much more frequently in the restoration plots than the reference plots. There were 19 exotic species that were found in more than 5% of the restoration plots, and only 6 that were found in more than 5% of the reference plots. Of these 19 species, 10 were not found in the reference plots at all. *Lonicera japonica* was the only exotic species that was more frequent in the references than the restorations. However, its mean percent cover was very low (1%) at both site types.

There was no difference in the number of native woody species per m^2 by site type ($t = 1.132$, $df = 13$, $p = 0.278$). The mean cover of native species was 48% in the restored plots and 143% in the reference plots ($t = 6.848$, $df = 8$, $p < 0.001$). The high mean cover of native plants in the reference plots was due to the many large trees growing at the sites.

Because of the differences in stand maturity, the reference plots had, on average, more than double the basal area as the restoration sites (t $= 14.743$, *df* $= 186$, $p < 0.001$; Table 2.4).

With the exception of *Liquidambar styraciflua*, the native woody species with the highest percent cover differed by site type. *Salix nigra, Betula nigra,* and *Cornus amomum* had high mean cover in the restoration sites, whereas *Fagus grandifolia, Liriodendron tulipifera,* and *Carpinus caroliniana* had high cover in the references. Some of the species with the highest mean cover at one site type had very low mean cover at the other site type. *Salis nigra* was not found at any of the reference sites and *F. grandifolia* had only 1% cover at the restorations.

Native woody species frequency also differed by site type. The most frequently found native woody species at the restorations were *S. nigra, L. styraciflua, Rubus* spp., *C. amomum,* and *P. taeda*, whereas the most frequently found at the references were *F. grandifolia, C. caroliniana, A. rubrum, Euonymus americanus,* and *L. tulipifera.* Similar to the patterns of percent cover, some of the species with the highest frequencies in one site type had low frequencies at the other. *Salix nigra* had high frequency at the restorations but was not found at any references. *Cornus amomum* was not found in any of the reference plots, and was found at low density in the reference belt transects. *Carpinus caroliniana* and *E. americana* had high frequencies at the references and very low frequencies at the restorations.

The mean total stem density ($t = 3.503$, $df = 14$, $p = 0.004$) and native woody stem density ($t = 2.988$, $df = 13$, $p = 0.010$) were both twice as high at the restoration sites than the reference sites. Exotic stem density was also greater at the restorations than the references (at alpha ≤ 0.1; $t = 1.834$, $df = 15$, $p = 0.087$). The species (exotic and native) with the greatest densities at the restorations were *S. nigra, C. amomum, Salix spp., P. taeda*, and *L. styraciflua* whereas the species with the greatest densities at the references were *C. caroliniana, F. grandifolia, E. umbellata, L. tulipifera,* and *L. stryraciflua.*

We addressed the influence of exotic species that had potentially spread from bordering land by looking at the exotic species only found at one site. There were 14 exotic species only found at one site; 13 found at one restoration and one found at one reference. Of these 14 exotic species, four appear to have been planted; *Callitropsis* x *leylandii, Lagerstroemia indica,* and *Nandina domestica* were part of the landscaped grounds within the study area at Oakwood Cemetery and *Prunus cerasifera* looked to have been planted at Forest Hills Park. Of the remaining 9 exotic species that were only found at one restoration site, only one (*Rumex crispus*) was found in more than one plot, and three were found in the belt transect only (and not in any plots). The low frequency of these species indicates that our results are not confounded by the landscape context of our study sites.

Fourteen of the 20 soil chemical and physical soil properties differed between the restorations and references, including eight of the ten soil nutrients (Table 2.6). The magnitude of difference in the levels of some nutrients was very large; mean Ca was more than 2.5 times higher, Cu nearly 3.5 times higher, and Zn more than 5.5 times higher in the restorations than the references. All of the nutrients except Fe and Mn had higher concentrations in the restorations than the references. Bulk density was slightly higher in the restorations, but well within the range of typical riparian soils. All of the soils were acidic, but the reference soils had a lower pH. The six properties that did not differ by site type were weight per volume, K, S, and percentages of clay, sand, and silt. Multiple linear regression modeling indicated that four soil properties (humic matter, pH, Mn, and Cu) accounted for 20% of the variation in exotic species cover, while bulk density, Ca, Mg, and Mn accounted for 34% of the variation in native woody species cover (Table 2.7).

When NMS was conducted, and the sample plots were ordered by cover of all species, or by native species cover only, those from reference sites formed a small subset that resided within the larger and more widely spread swarm of plots from the restoration sites (Figure 2.2). The clustering of plots by site type demonstrates the differences in community composition between the restorations and references, but the overlap between the clusters indicates that there were also compositional similarities. When the plots were ordered just by exotic species cover, those of both site types occupied much of the same space. All plots with no invasive species were excluded from this ordering: four restoration plots (2%) and nine reference plots (10%). The soils ordination shows much of the same pattern as the vegetation ordinations. There is some clustering by site type, indicating some compositional differences, but there is also a good amount of overlap.

Discussion

The restored streams were much more invaded than the reference streams, in terms of the number of exotic species present per area, the amount of exotic cover, and the density of exotic stems. It is important to note that while the number of exotic species, exotic cover, and exotic density were substantially lower at the reference sites than the restored sites, they were not negligible. Because the restored streams are going through secondary succession, we expect that their species compositions will change, and the height and cover of their canopies will increase over time (Whittaker 1970). There are many factors that will influence the persistence of exotic species at these sites, one of which is light availability. More than half of the exotic species found at the restoration sites can at least tolerate partial shade (Brand 1997; Evans 2000; Hilty 2002; TNC 2005), suggesting that the increased canopy we expect at these sites in future years will not deter the growth of many of the exotic species we found. The adaptation of these species to tolerate shade is evident by the growth of some of them at the reference streams, despite their closed canopies.

These exotic species have serious implications for the riparian communities of the restored streams. *Microstegium vimineum,* for example, can maintain growth at a minimum of 5% sunlight (Winter et al. 1982). *Microstegium vimineum* negatively affected the growth of *L. tulipifera, A. rubrum* and *Q. rubra* seedlings in a Tennessee hardwood forest (U.S.A.; Marshall et al. 2009). The tree seedlings provided support for the neighboring *M. vimineum* plants that allowed them to maintain a taller height than otherwise possible. Taller *M. vimineum* plants are likely to disperse seeds farther than those that lean or lodge.

Invasive plants not only affect plant assemblages in riparian ecosystems, but can also influence the morphology of the stream channel, for example, by increasing vegetation flammability, or by trapping sediments, which increases habitat for both the invader and other alien species (Richardson et al. 2007). These effects are not considered in the restoration design process. Invasive plants can also affect soil community composition, thereby impacting other ecosystem processes (Wolfe & Klironomos 2005). For example, the microbial communities in the soil beneath *M. vimineum* differed in structure and function from the communities associated with native *Vaccinium* plants in New Jersey hardwood forests (Kourtev et al. 2002).

The native plant communities also differed by site type, and the woody species that dominated the reference sites were not present in the restorations in high abundance. Given the differences in stand maturity, we did not expect to find the same late-successional species growing in both the references and the restorations. However, some of the native woody plants intentionally planted by the restorationists were not part of the flora of the reference sites, e.g., *Salix nigra, Viburnum nudum,* and *Juglans nigra*. Seventeen species planted at the restorations were not found at any of the references, and 11 additional species had less than 5% frequency at the references. *Morella cerifera* was planted at one restoration even though it is considered exotic in the NC Piedmont. Planting species that are not part of the target community makes it unlikely that the restored riparian zones will have the same structure or function as the reference sites. If species are not suited for the exact riparian habitat in which they are planted, they are more likely to not thrive and/or die, thus creating additional opportunities for exotic species invasion.

Substantial differences in chemical and physical properties were found between restored and reference soils, demonstrating the lasting impacts of construction practices. In our regression models we also found a connection between soils and vegetation cover. The variables within these models are the soil properties that may have the greatest influence on vegetation cover patterns. Higher pH and humic matter content are related to increased cover of exotic species, whereas decreased bulk density is associated with higher amounts of native species cover. Mn was a variable in both models. Plant species exhibit a range of tolerances to Mn toxicity, however, lespedeza is injured by Mn concentrations as low as 1 ppm at pH 4.6 (Morris 1947). The acidic pH and high Mn concentration of the reference soils (Table 2.6) indicate that Mn toxicity may affect the patterns of vegetation growth. It is possible that the lower concentration of Mn at the restorations is due to the influence the exotic species are exerting on the soils. Mn concentrations were lower in soils sampled from patches of the exotic *Lantana camara* than in soils from nearby uninvaded patches (Osunkoya and Perrett 2011). We did not test to determine if the soil properties were causing differences in vegetation growth, or if the vegetation was modifying the soils. However, it is clear that there is a relationship between soil and vegetation cover.

During restoration new stream banks are formed out of subsoils and cut and fill materials and are a very different habitat than natural riparian soils. Given the impact they have on both vegetation and channel morphology, the soils of restoration sites are crucial to restoration success. However, little thought is typically given to the restoration of the soils themselves or monitoring them post-restoration. Sudduth et al. (2007) interviewed project managers of southeastern stream restorations regarding restoration goals, monitoring, and success. Soil condition was not on the list of commonly monitored variables.

Given the extent of invasion at the restoration sites, restorationists will need to devote more attention to exotics control to avoid this problem in future projects. Invasives removal has typically focused on “aboveground-centric” techniques, but a more holistic approach including consideration of soil properties and biota may be necessary (Wolfe and Klironomos 2005). Various studies have shown that amending disturbed soils is necessary to promote native plant growth and suppress exotic plants. Zink and Allen (1998) found that the volume of the native *Artemisa californica* seedlings they planted was 25% greater in plots that had oat straw mulch and 170% greater with pink bark mulch than the unamended plots. Experimentally adding sucrose to invaded soil can suppress some exotic species (Prober et al. 2005; Reever Morghan & Seastedt 1999) and can increase native plant biomass more than two times, probably by altering the C:N ratio (Prober et al. 2005).

If soil amending is to be done, the soil properties of the references should be evaluated as a point of comparison. We were unable to access all of the files detailing the work done at each restoration, and cannot know which (if any) sites were fertilized or limed post-construction. However, fertilizing is generally done when erosion control is of concern, and the high levels of nutrients including Ca and P in the restorations soils suggest that the soils may have been treated. In a study by Burke and Grime (1996) they found that disturbed soils with high fertility had greater cover of exotic species than disturbed soils with lower fertility. Increasing the levels of nutrients above the concentrations found in the reference soils may promote invasion.

In this study we showed that differences exist between the plant communities and soils of restored streams and their references. However, the importance of these results depends on restoration goals and objectives, which serve as the means to evaluate project success. From a structural standpoint, the success of the restorations we studied should be questioned due to the extensive presence of invasive plants and different soil properties relative to the references. From a functional standpoint, these restorations may be considered somewhat successful; the soils support a thriving plant community, and the plants stabilize the banks and provide a host of other ecosystem functions. Due to the different ways success may be evaluated, it is important to set goals that state structural, functional, and social (the involvement of humans at the site) performance criteria and define measurable parameters that indicate a range of ecosystem processes (Westman 1991).

Although goals are crucial to determining project success, they are not always stated in restoration plans. Eighteen percent of the southeastern projects in the National River Restoration Society Synthesis database do not state any goals, and 29% list one goal (Sudduth et al. 2007). According to interviewed project managers, 65% of project plans had pre-determined success criteria, but only 28% had criteria that could be measured. In order to determine restoration success, as affected by invasive plants, soil properties, and a wealth of other ecosystem components, restorationists need to determine which elements of ecosystem structure and function are important to a project and make goals accordingly.

Implications for Restoration

- If restorationists want to restore the structure of a site, the value of increasing invasive species control in the years post-restoration is clear. Doing so could possibly increase the survival rates of the native plants that have been planted and have naturally colonized.
- Planting species that are suited for riparian habitats (and particular zones within those habitats) is important for the successful restoration of the form and function of the project site, and may help to combat the invasion of these sites.

- Testing and amending the soils of restored riparian buffers as necessary may be essential for achieving the target plant community. The reference soils should be used as a guideline to determine appropriate levels of soil nutrients.
- Reference sites are not uninvaded. If these sites become increasingly disturbed or degraded their use as templates for restoration may need to be discontinued.
- Restorationists need to set explicit structural and/or functional goals with measurable performance criteria and monitor accordingly.

Conclusion

Restoration sites were much more heavily invaded than natural, unrestored streams, in terms of the number of exotic species present as well as their cover, frequency, and density. Restored streams have a history of massive soil disturbance, and the extent of invasion at these sites could be partially explained by the soil properties. The connection we found between the soils and cover of exotic plants supports the idea that disturbance promotes invasion. Although restorationists plant the sites post-construction, their efforts to reduce the threat of invasion are insufficient, which may be partially due to planting species that were not found in the flora of the reference communities. Heavily invaded riparian communities are unlikely to have the same structure or function as those communities with fewer or no invasive plants present. In order for stream restoration to more successfully attain reference structure and function, addressing the soils and plant communities needs to be prioritized.

Acknowledgements

We would like to thank North Carolina State University for providing funding in the form of a research assistantship for M. Malone as well as Dr. Alexander Krings, Director of the North Carolina State University Herbarium, for his assistance with plant identification.

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Table 2.1. The location of each restored study stream within the Piedmont of North Carolina. UT stands for Un-named Tributary. The landscape context gives a subjective description of the setting of each project. The references listed are only those that we studied, some projects had additional references. Oakwood Cemetery and Richland Creek did not have any references, and the reference for Forest Hills Park had been degraded by land development.

Stream	Location	Landscape context	Latitude and Longitude	Year constructed	References
Abbott’s Creek	Raleigh	Suburban neighborhood	35°46’21.24”N 78°43’45.65”W	1999	Brookhaven Park
Benbow Park	Greensboro	Park	36°03’07.47”N 79°46’25.87”W	2004	UT to Lake Jeanette
Forest Hills Park	Durham	Park	35°58’45.31”N 78°54’44.96”W	2005	None
Kentwood Park UT to Bushy Branch	Raleigh	Park	35°46’34.35”N 78°41’44.70”W	2002	UT to Mine Creek
Kentwood Park Bushy Branch	Raleigh	Park	35°46’31.53”N 78°41’41.63”W	2002	UT to Lake Wheeler
Oakwood Cemetery	Raleigh	Cemetery	35°47’11.12”N 78°37’39.36”W	1999	None
Richland Creek	Raleigh	Urban area	35°48’04.30”N 78°43’33.44”W	2002	None
Rocky Branch Phase 1	Raleigh	University campus	35°47’12.96”N 78°40’52.03”W	2002	Morgan Creek
Rocky Branch Phase 2	Raleigh	University campus	35°46’51.03”N 78°40’11.34”W	2005	Morgan Creek
Speight Branch	Cary	Park	35°43’09.04”N 78°45’07.88”W	2001	Sal’s Branch
Yates Mill Tributary 1a Phase 2	Raleigh	Agricultural area	35°43’43.99”N 78°42’04.36”W	2002	Sal’s Branch

Table 2.2. The location of each reference study stream within the Piedmont of North Carolina. UT stands for Un-named Tributary. The landscape context gives a subjective description of the setting of each project. The number of restorations gives the number of projects we studied that used the reference in their design plans.

Stream	Location	Landscape Context	Latitude and Longitude	Number of restorations
Brookhaven Park	Raleigh	Park	35°51’12.81”N 78°41’08.58”W	1
Morgan Creek	Chapel Hill	Forested and agricultural area	35°55’24.45”N 79°06’54.62”W	2
Sal’s Branch	Raleigh	Park	35°53’03.61”N 78°45’29.36”W	2
UT to Lake Jeanette	Greensboro	Suburban neighborhood	36°09’16.34”N 79°49’11.67”W	1
UT to Lake Wheeler	Raleigh	Suburban neighborhood	35°42’07.18”N 78°42’02.27”W	1
UT to Mine Creek	Raleigh	Suburban neighborhood	35°51’05.06”N 78°39’28.89”W	1

Table 2.3. The species planted at eight restoration sites, as were listed on project plans, monitoring reports, or as-built records, sorted by frequency. The two streams restored at Kentwood Park are treated as one project because the records did not differentiate what was planted at each stream.

Species Planted	Common Names	Plant Type	Number of Sites
Betula nigra	River birch	Tree	8
Platanus occidentalis	Sycamore	Tree	8
Salix nigra	Black willow	Tree	7
Cornus amomum	Silky dogwood	Shrub	6
Liriodendron tulipifera	Tulip-tree	Tree	6
Alnus serrulata	Tag alder	Shrub	5
Sambucus canadensis	Elderberry	Shrub	5
Fraxinus pennsylvanica	Green ash	Tree	4
Cornus florida	Flowering dogwood	Tree	4
Viburnum nudum	Southern wild raisin	Shrub	4
Quercus michauxii	Basket oak	Tree	3
Carya cordiformis	Bitternut hickory	Tree	3
Hamamelis virginiana	Witch-hazel	Shrub	3
Ilex decidua	Possum-haw	Shrub	3
Carpinus caroliniana	American hornbeam	Tree	3
Lindera benzoin	Spicebush	Shrub	3
Nyssa sylvatica	Sour gum	Tree	2
Acer rubrum	Eastern red maple	Tree	2
Celtis laevigata	Southern hackberry	Tree	2
Juglans nigra	Black walnut	Tree	2
Quercus phellos	Willow oak	Tree	2
Rhododendron periclymenoides	Pink azalea	Shrub	2
Acer negundo	Eastern box elder	Tree	1
Amelanchier arborea	Downy serviceberry	Shrub	1
Asimina triloba	Common pawpaw	Tree	1
Bignonia capreolata	Cross-vine	Vine	1
Callicarpa americana	Beautyberry	Shrub	1
Calycanthus floridus	Sweet-shrub	Shrub	1
Cephalanthus occidentalis	Buttonbush	Shrub	1
Cercis canadensis	Eastern redbud	Tree	1
Clethra alnifolia	Sweet-pepperbush	Shrub	1
Crataegus viridis	Green hawthorn	Shrub	1
Euonymous americana	Strawberry-bush	Shrub	1

Table 2.3 continued

Ilex opaca	American holly	Tree	1
Ilex verticillata	Winterberry	Shrub	1
Itea virginica	Virginia-willow	Shrub	1
Juniperus virginiana	Eastern red cedar	Tree	1
Morella cerifera	Wax-myrtle	Shrub/Tree	1
Oxydendron arboreum	Sourwood	Tree	1
Parthenocissus quinquefolia	Virginia creeper	Vine	1
Quercus alba	White oak	Tree	1
Quercus falcata	Spanish oak	Tree	1
Salix sericea	Silky willow	Tree	1
Symphoricarpos orbiculatus	Coralberry	Shrub	1
Ulmus americana	American elm	Tree	1
Viburnum dentatum	Arrow-wood	Shrub	1

Table 2.4. A summary of the main comparisons between the vegetation of the restored and reference streams. All statistics are from t-tests comparing by site type.

Statistic	Restorations	References	p-value
# Exotic spp. per m^2	0.28	0.12	0.004
# Woody spp. per m^2	0.54	0.63	0.278
Mean % cover exotic spp.	34	10	< 0.001
Mean % cover woody spp.	48	143	< 0.001
Mean density exotic species (stems/ha)	833	418	0.087
Mean density native woody species (stems/ha)	5878	2715	0.010
Basal area	61	150	< 0.001

Table 2.5. All species found within the plots and belt transects of the study sites. Species are arranged by type (native or exotic) and relative frequency (T "trace" indicates < 1%).

Species	**Common name**	**Mean Frequency (%)**		**Mean Cover (%)**		**Density (stems/ha)**	
		Rest	**Ref**	**Rest**	**Ref**	**Rest**	**Ref**
Exotic Species							
Microstegium vimineum	Japanese stilt-grass	56	44	14	5	--	--
Lonicera japonica	Japanese honeysuckle	40	70	1	1	--	--
Ampelopsis brevipedunculata	Porcelain-berry	26	0	3	0	--	--
Commelina communis	Common dayflower	17	2	T	T	--	--
Glechoma hederacea	Gill-over-the-ground	15	2	3	T	--	--
Lespedeza cuneata	Sericea lespedeza	14	2	T	T	--	--
Ligustrum sinense	Chinese privet	13	9	1	T	227	34
Persicaria maculosa	Lady's-thumb	13	3	T	T	--	--
Humulus japonicus	Japanese hops	12	0	1	0	--	--
Morus alba	White mulberry	11	0	1	0	92	0
Turf grass	Turf grass	10	0	3	0	--	--
Albizia julibrissin	Mimosa	10	6	T	T	55	14
Trifolium repens	White clover	10	0	T	0	--	--
Morella cerifera	Common wax-myrtle	9	0	1	0	127	1
Pueraria montana var. *lobata*	Kudzu	8	0	3	0	--	--
Dactylis glomerata	Orchard grass	8	0	T	0	--	--
Hedera helix	Common ivy	7	9	T	2	--	--
Rumex crispus	Curly dock	7	0	T	0	--	--
Schedonorus arundinaceus	Tall fescue	6	0	1	0	--	--
Ligustrum japonicum	Japanese privet	5	1	1	T	175	1
Elaeagnus umbellata	Spring silverberry	5	13	1	2	89	269
Dioscorea polystachya	Cinnamon vine	5	1	T	T	--	--
Liriope muscari	Liriope	5	2	T	T	--	--

Table 2.5 continued

Sorghum halepense	Johnson grass	5	0	T	0	--	--
Paulownia tomentosa	Princess tree	3	1	T	T	58	3
Pyrus calleryana	Bradford pear	3	0	T	0	19	1
Lotus corniculatus	Birdsfoot-trefoil	2	0	T	0	--	--
Reynoutria japonica	Japanese knotweed	2	0	T	0	--	--
Rosa multiflora	Multiflora rose	2	1	T	T	--	--
Carya illinoinensis	Pecan	1	0	T	0	7	0
Catalpa speciosa	Northern catalpa	1	0	T	0	8	0
Cucurbita moschata	Butternut squash	1	0	T	0	--	--
Daucus carota	Queen-Anne's-Lace	1	0	T	0	--	--
Hibiscus syriacus	Rose-of-Sharon	1	0	T	0	5	0
Ilex spp. Ornamental	Ornamental holly species	1	2	T	T	0	24
Lagerstroemia indica	Crape-myrtle	1	0	T	0	3	0
Lonicera maackii	Amur honeysuckle	1	0	T	0	0	0
Magnolia grandiflora	Southern magnolia	1	0	T	0	1	0
Malus pumila	Common apple	1	0	T	0	0	0
Pyrus communis	Common pear	1	1	T	T	1	0
Wisteria sinensis	Chinese wisteria	1	1	T	T	--	--
Ailanthus altissima	Tree-of-Heaven	1	0	T	0	0	0
Celastrus orbiculatus	Oriental bittersweet	1	0	T	0	--	--
Nandina domestica	Nandina	1	0	T	0	38	0
Callitropsis x *leylandii*	Leyland cypress	0	0	0	0	< 1	0
Elaeagnus pungens	Autumn silverberry	0	0	0	0	3	2
Euonymus alatus	Winged euonymus	0	0	0	0	2	0
Gleditsia triacanthos	Honey locust	0	0	0	0	1	0
Mahonia bealei	Leatherleaf mahonia	0	0	0	0	0	2

Table 2.5 continued

Melia azedarach	Chinaberry	0	0	0	0	7	0
Phyllostachys aurea	Golden bamboo	0	0	0	0	8	0
Prunus cerasifera	Cherry plum	0	0	0	0	3	0
Native species							
Salix nigra	Black willow	30	0	9	0	1955	0
Liquidambar styraciflua	Sweet gum	29	38	4	12	282	157
Rubus spp.	Blackberry species	29	11	2	T	--	--
Cornus amomum	Silky dogwood	26	0	4	0	1657	8
Pinus taeda	Loblolly pine	25	11	3	2	361	31
Toxicodendron radicans	Poison ivy	24	30	T	T	--	--
Quercus phellos	Willow oak	20	6	1	T	37	2
Betula nigra	River birch	18	3	4	1	169	9
Fraxinus pennsylvanica	Green ash	16	12	3	2	92	36
Parthenocissus quinquefolia	Virginia-creeper	15	16	T	T	--	--
Smilax rotundifolia	Common greenbriar	14	44	T	T	--	--
Acer rubrum var. *rubrum*	Eastern red maple	12	55	2	11	33	135
Sambucus canadensis	Common elderberry	13	2	1	T	197	7
Liriodendron tulipifera var. *tulipifera*	Tulip-tree	12	53	3	26	86	223
Prunus serotina var. *serotina*	Black cherry	10	33	T	2	32	56
Platanus occidentalis var. *occidentalis*	Sycamore	9	3	1	1	156	11
Quercus alba	White oak	9	44	1	11	7	88
Ulmus spp.	Elm species	9	15	1	T	30	20
Baccharis halimifolia	Silverling	8	0	1	0	73	0
Vitis vulpina	Frost grape	7	0	1	0	--	--
Lindera benzoin	Spicebush	6	2	1	T	95	13

Table 2.5 continued

Vitis rotundifolia var. *rotundifolia*	Muscadine	6	33	1	1	--	--
Salix spp.	Willow species	6	0	T	0	389	0
Acer negundo var. *negundo*	Eastern box elder	5	1	1	T	22	4
Alnus serrulata	Tag alder	5	1	1	T	233	5
Cornus florida	Flowering dogwood	5	24	1	5	7	80
Robinia pseudoacacia	Black locust	5	0	1	0	37	0
Viburnum nudum	Southern wild raisin	5	0	1	0	74	0
Nyssa sylvatica	Sour gum	4	11	T	T	27	54
Quercus velutina	Black oak	4	11	T	1	6	17
Cercis canadensis var. *canadensis*	Eastern redbud	3	0	1	0	5	0
Acer saccharinum	Silver maple	3	0	T	0	39	1
Diospyros virginiana	American persimmon	3	4	T	1	14	11
Carpinus caroliniana	American hornbeam	2	55	1	17	25	486
Fagus grandifolia var. *caroliniana*	White beech	2	63	1	31	5	463
Morus rubra	Red mulberry	2	2	1	T	32	6
Quercus stellata	Post oak	2	0	1	0	1	0
Clematis spp.	Clematis species	2	1	T	T	--	--
Hamamelis virginiana var. *virginiana*	Northern witch-hazel	2	1	T	T	13	6
Ilex decidua var. decidua	Possum-haw	2	2	T	T	8	9
Juglans nigra	Black walnut	2	0	T	0	11	0
Oxydendrum arboreum	Sourwood	2	16	T	4	11	134
Quercus nigra	Water oak	2	12	T	1	6	38

Table 2.5 continued

Rhus copallinum var. copallinum	Winged sumac	2	0	T	0	3	0
Taxodium spp.	Cypress species	2	0	T	0	0	0
Ulmus alata	Winged elm	2	0	T	0	2	0
Acer floridanum	Southern sugar maple	1	0	T	0	< 1	0
Aesculus sylvatica	Painted buckeye	1	0	T	0	1	0
Callicarpa americana	Beautyberry	1	0	T	0	3	0
Campsis radicans	Trumpet-creeper	1	0	T	0	--	--
Carya cordiformis	Bitternut hickory	1	0	T	0	2	0
Carya glabra	Pignut hickory	1	2	T	1	0	27
Carya spp.	Hickory species	1	1	T	T	0	2
Celtis spp.	Hackberry species	1	0	T	0	2	0
Cornus stricta	Southern swamp dogwood	1	0	T	0	20	0
Crataegus phaenopyrum	Washington hawthorn	1	0	T	0	3	0
Euonymus americanus	Strawberry-bush	1	54	T	T	7	37
Ilex opaca var. *opaca*	American holly	1	18	T	1	3	121
Ilex verticillata	Winterberry	1	1	T	T	10	15
Juniperus virginiana var. *virginiana*	Eastern red cedar	1	4	T	T	1	13
Magnolia virginiana	Sweet bay	1	0	T	0	7	0
Mitchella repens	Partridge-berry	1	7	T	T	--	--
Prunus caroliniana	Carolina laurel cherry	1	1	T	T	< 1	1
Quercus michauxii	Basket oak	1	2	T	1	21	4
Quercus rubra var. *rubra*	Red oak	1	20	T	3	1	27
Quercus spp.	Oak species	1	6	T	T	1	0

Table 2.5 continued

Rhododendron spp.	Rhododendron species	1	8	T	T	3	68
Symphoricarpos orbiculatus	Coralberry	1	0	T	0	22	0
Tilia americana var. *heterophylla*	Mountain basswood	1	0	T	0	0	0
Vaccinium spp.	Blueberry species	1	11	T	1	1	153
Viburnum dentatum	Arrow-wood	1	0	T	0	19	0
Viburnum rufidulum	Southern black haw	1	0	T	0	0	2
Viburnum spp.	Viburnum species	1	1	T	T	< 1	3
Carya alba	Mockernut hickory	0	22	0	3	0	28
Chionanthus virginicus	Fringe-tree	0	7	0	T	0	28
Eubotrys racemosa	Coastal fetterbush	0	4	0	T	1	11
Gelsemium sempervirens	Carolina jessamine	0	2	0	T	--	--
Hypericum spp.	St.-John's-wort species	0	4	0	T	0	0
Magnolia tripetala	Umbrella magnolia	0	7	0	2	0	49
Ostrya virginiana	American hop-hornbeam	0	6	0	2	0	80
Sassafras albidum	Sassafras	0	1	0	T	3	1
Vaccinium fuscatum	Hairy highbush blueberry	0	1	0	T	0	15
Viburnum acerifolium	Mapleleaf viburnum	0	3	0	T	0	14
Viburnum prunifolium	Black haw	0	7	0	T	0	3
Viburnum rafinesquianum	Downy arrow-wood	0	3	0	T	0	21
Vitis cinerea	Grape	0	2	0	T	--	--
Amelanchier arborea	Downy serviceberry	0	0	0	0	0	1
Aralia spinosa	Devil's-walking-stick	0	0	0	0	3	0
Celtis laevigata	Southern hackberry	0	0	0	0	4	0
Cephalanthus occidentalis	Buttonbush	0	0	0	0	3	0

Table 2.5 continued

Cornus spp.	Dogwood species	0	0	0	0	< 1	0
Corylus americana	American hazelnut	0	0	0	0	6	0
Ilex spp.	Holly species	0	0	0	0	< 1	0
Magnolia spp.	Magnolia species	0	0	0	0	1	0
Populus deltoides var. *deltoides*	Eastern cottonwood	0	0	0	0	1	0
Quercus falcata	Spanish oak	0	0	0	0	0	4
Quercus lyrata	Overcup oak	0	0	0	0	1	0
Quercus texana	Nuttall oak	0	0	0	0	< 1	0
Styrax grandifolius	Bigleaf snowbell	0	0	0	0	0	1
Unknown species							
Unknown grass	Unknown grass species	23	42	T	1	--	--
Total Num. Species	**137**	**88**					
Total Num. Exotic Species	**51**	**22**					
Total Num. Native Species	**85**	**65**					

Table 2.6. Mean soil chemical and physical properties by site type. P-values are from t-tests comparing the properties by site type. The properties are listed in order of increasing p-value. C.V. stands for coefficient of variation, and is provided as a percentage.

Soil property	Reference			Restoration			p-value
	Mean	**St. dev.**	**C.V.**	**Mean**	**St. dev.**	**C.V.**	
Bulk Density (g/cm^3)	0.97	0.16	16.5	1.10	0.15	13.6	< 0.001
CEC ($meq/100cm^3$)	4.9	1.28	26.1	7.8	2.80	35.9	< 0.001
Base Saturation (%)	58	14.52	25.0	84	11.96	14.2	< 0.001
Mehlich buffer pH acidity ($meq/100cm^3$)	2.0	0.56	28.0	1.0	0.52	52.0	< 0.001
pH	5	0.37	7.4	5.9	0.61	10.3	< 0.001
P (mg/dm^3)	8.7	2.6	29.9	14.9	8.21	55.1	< 0.001
Ca (mg/dm^3)	383	219.68	57.4	1044	481.88	46.2	< 0.001
Mg (mg/dm^3)	102	43.44	42.6	162	77.74	48.0	< 0.001
Zn (mg/dm^3)	2.8	1.51	53.9	15.6	15.23	97.6	< 0.001
Cu (mg/dm^3)	1.1	0.38	34.5	3.8	2.68	70.5	< 0.001
Fe (mg/dm^3)	703	172.55	24.5	531	152.92	28.8	< 0.001
Na (mg/dm^3)	15	4.03	26.9	19	8.01	42.2	< 0.001
Mn (mg/dm^3)	52.4	27.08	51.7	38.7	14.15	36.6	0.001
Humic Matter (%)	0.38	0.11	28.9	0.32	0.21	65.6	0.018
Weight per Volume (g/cm^3)	1.02	0.07	6.9	1.04	0.10	9.6	0.210
K (mg/dm^3)	62	24.29	39.2	66	25.75	39.0	0.355
Clay (%)	10	4.49	44.9	11	5.86	53.3	0.368
S (mg/dm^3)	14	3.75	26.8	15	10.19	67.9	0.381
Sand (%)	73.4	9.65	13.1	72.4	12.08	16.7	0.577
Silt (%)	16.7	6.78	40.6	16.9	8.21	48.6	0.850

Table 2.7. ANOVA regression models of vegetation percent cover as a function of soil properties.

a. Exotic Species Cover – r^2 = 0.20

Source	DF	SS	MS	F-value	Pr > F
Model	4	36275	9069	9.28	<0.0001
Error	148	144573	977		
Total	152	180848			

Variable	Parameter Estimate	Std Error	Type II SS	F-value	Pr > F
Intercept	-111.61	28.84	14631	14.98	0.0002
pH	28.03	5.22	28167	28.83	<0.0001
Mn	-0.44	0.13	10664	10.92	0.0012
Cu	-3.22	1.37	5405	5.53	0.0200
HM	36.67	15.61	5393	5.52	0.0201

b. Native Species Cover - r^2 = 0.34

Source	DF	SS	MS	F-value	Pr > F
Model	4	206750	51688	19.17	<0.0001
Error	148	399042	2696		
Total	152	605792			

Variable	Parameter Estimate	Std Error	Type II SS	F-value	Pr > F
Intercept	167.69	30.13	83515	30.97	<0.0001
Ca	-0.08	0.01	98061	36.37	<0.0001
Bulk Dens	-74.26	26.89	22179	8.23	0.0047
Mg	0.23	0.09	18355	6.81	0.0100
Mn	0.53	0.21	17087	6.34	0.0129

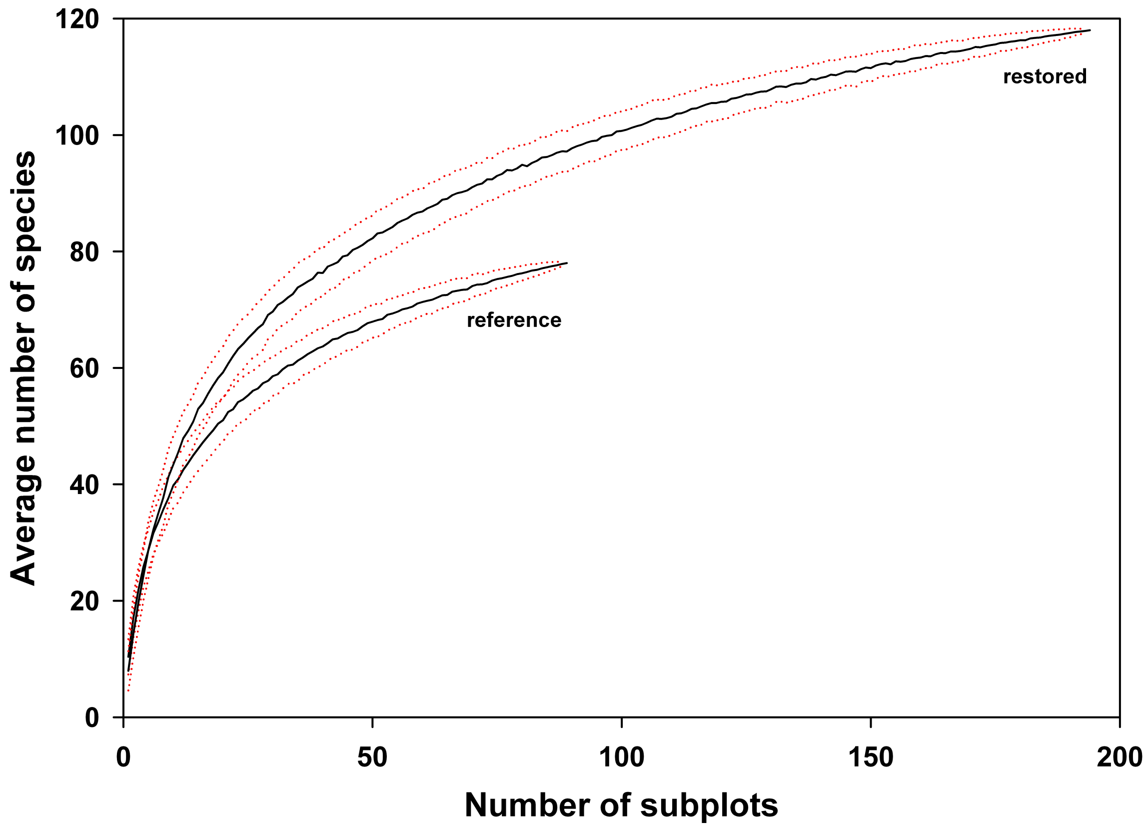

Figure 2.1. The species-area curves of the restoration and reference vegetation plots. The dotted lines indicate plus and minus one standard deviation.

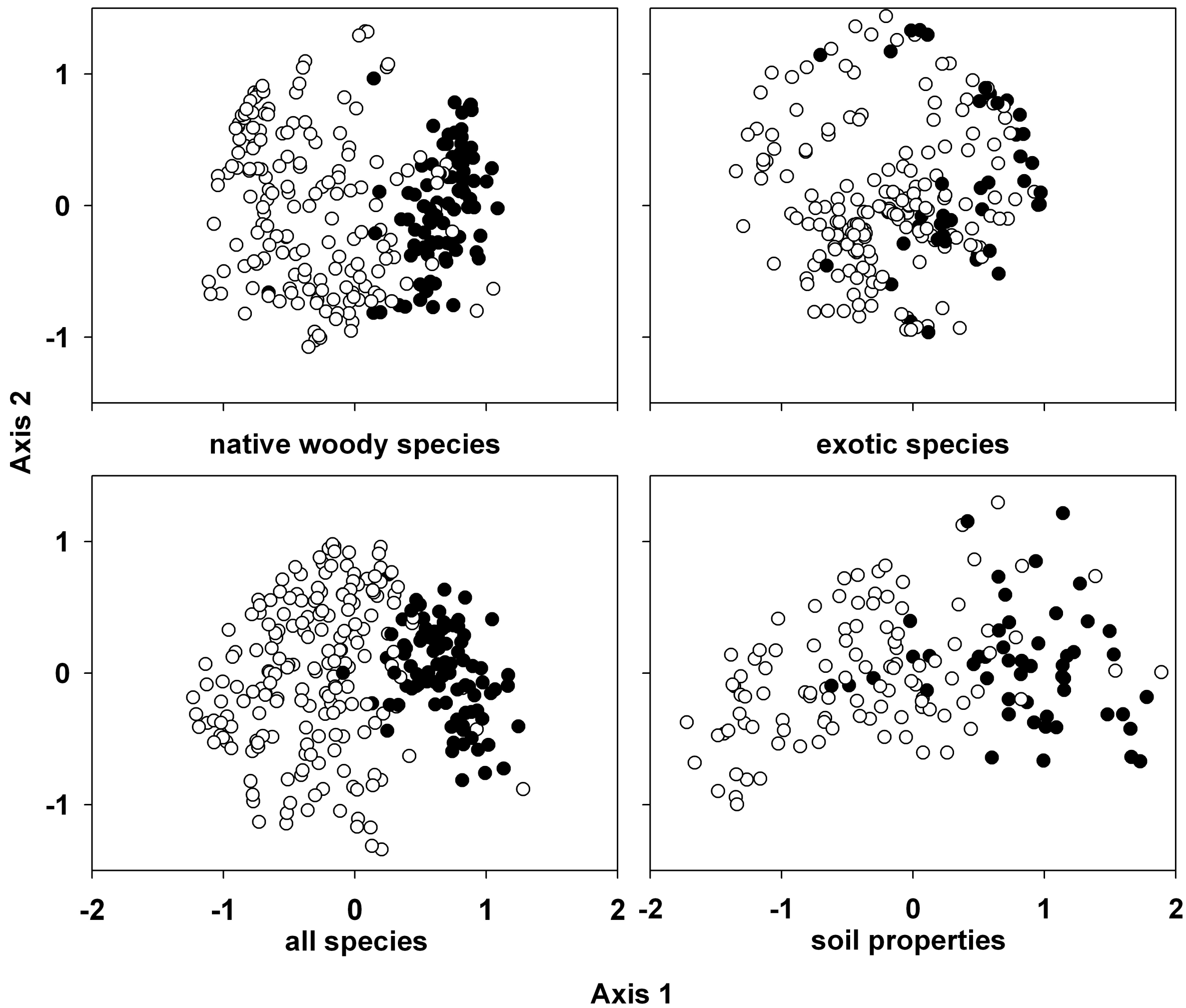

Figure 2.2. Non-metric Multidimensional Scaling community ordinations of vegetation or soil data. The open points represent the plots at the restoration sites, and the closed points represent the plots at the reference sites.

CHAPTER 3: A COMPARISON OF THE SOILS OF RESTORED AND REFERENCE STREAMS IN THE NORTH CAROLINA PIEDMONT

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Abstract

The soils of restored streams have been disrupted, churned, and compacted by restoration practices. Despite the integral role soils play in vegetation community structure and function, they are infrequently tested or monitored during and after the restoration. We sampled the soils of restored streams in the North Carolina Piedmont and compared them to soils we sampled from references, which are natural, unrestored streams that are used as models for restoration design. Fourteen of the 20 physical and chemical properties we tested differed by site type. The soils at both the restorations and references were highly variable, however, site type accounted for many differences in morphological characteristics. There were factors other than restoration that could have affected the soils of these sites, such as parent material or landscape context, but none of these explained the differences we found. To the extent that soil differences may adversely affect vegetation and eco-services, it may be feasible for restorationists to address the soil properties that differed by testing and amending the soil properties as necessary. Doing so may be crucial to successfully restore the structure and function of these sites. Continued research will be integral to determining the exact effects restoration practices have on riparian soils.

Introduction

Stream restoration practices cause severe and extensive soil disturbance. Heavy equipment is used to modify existing channels or excavate new ones, churning and compacting the soils. Stream channel and floodplain soils make important contributions to stream ecosystem functioning by influencing water flow, storing and cycling chemicals and nutrients, filtering and buffering materials, and supporting biological life (FISRWG 1998). The nutrient composition of soils can affect vegetation community structure by facilitating or reducing exotic species growth (Prober et al. 2005); other soil chemical and physical properties may act similarly. Although soils play an integral role in ecosystem functioning, soil condition is seldom considered during stream restoration.

Stream restoration is often practiced as a form of compensatory mitigation, which is required by law (Clean Water Act Section 404) whenever dredging or filling impact aquatic resources (EPA 1980). As a result of necessary compensatory actions, stream restoration has become a very common practice; a minimum of $14 to $15 billion was spent on stream restoration in the continental U.S. between 1990 and 2004 (Bernhardt et al. 2005). Although stream restoration is extremely costly, 18% of the southeastern projects in the National River Restoration Science Synthesis database reviewed by Sudduth et al. (2007) did not state any project goals, and 29% listed one. According to interviews with project managers of southeastern stream restorations, 65% of projects had predetermined success criteria, but only 28% had measurable criteria (Sudduth et al. 2007). Soils were not listed as a monitored variable, as reported by the interviewees.

Unlike restored wetland soils, restored stream soils have not been studied. Although wetland restoration normally involves a lesser degree of soil excavation and disturbance than stream restoration, some of the same basic practices are used, and the conclusions of wetlands research are applicable to restored streams. In a comparison of created, restored, and natural wetlands, Bruland and Richardson (2006) found that average organic matter content in the soils of natural, unrestored wetlands was more than twice that of the created and restored wetlands. This difference could possibly be due to prior land use, e.g. tillage, agriculture, or topsoil removal during creation or restoration. Campbell et al. (2002) compared 12 created wetlands with 14 natural wetlands in Pennsylvania and found that the created wetlands differed in bulk density, organic matter content, chroma at 5cm and 20cm depths, texture (at 5cm depth only), and rock fragments. There was some evidence of change in soil properties over time, but the older wetlands were still dissimilar from the natural wetlands. Ballantine and Schneider (2009) also found that the impacts of restoration affect soil development for years after project completion. They studied five natural wetlands and 35 restored palustrine emergent wetlands associated with small ponds in central New York that ranged in age from 3 to 55 yr. Bulk density decreased and organic matter content increased with age, however the average bulk density of all the restored wetlands was twice that of the natural wetlands, and the organic matter of each of the restored wetlands was less than half that of the natural wetlands. The levels of P, K, Mg, and Ca also increased with age, but Fe, Al, and Mn did not.

We wanted to determine if soil differences existed between restored and natural (reference) streams in the Piedmont of North Carolina. A reference is an unrestored and generally undisturbed stream that is cited as a model when setting stream restoration goals (FISRWG 1998). We hypothesized that the chemical, physical, and morphological properties of the restored and reference soils would significantly differ, and that such differences would be of a type and magnitude likely to affect vegetation community structure.

Methods

Site Selection

We studied eleven restored streams and six reference streams within the Piedmont of North Carolina (Table 3.1). Monthly precipitation totals in the central Piedmont range from 7 to 16 cm and average monthly temperatures from 7 to 27°C (NOAA n.d.).

All restoration projects studied were constructed between 1999 and 2005 and located in parks or urban-suburban landscapes. In three of the projects, an entirely new channel was dug, and in five projects, the floodplains and channels were modified through floodplain widening, excavation of floodplain benches, etc. Two projects had a combination of new channel excavation and floodplain and channel modification, and one project consisted of stream bank stabilization.

Reference streams are used to design the stream channel morphology and the riparian plant community. All but two of our projects used references; Oakwood Cemetery was constructed before references were routinely used, and Richland Creek was predominately a stream bank stabilization project. Six of our projects had one reference, two had two, and one had three. Some of the references were used by more than one project. The distance between a restoration and its reference ranged from 11 to 48 km, with an average of 23 km. We could not study all of the references associated with the restored streams because some of them had become degraded by development and, in one case, the reference had been restored. The references were all in suburban landscapes or parks.

Soil Sampling and Analysis

Soils were sampled in 2 m by 2 m plots between May and July 2010. The plot locations were determined by a companion study, in which we studied riparian vegetation in these plots which alternated being centered 3 and 5 m from the stream bank and positioned 30 or 61 m apart, depending on stream length. In order to keep the distance from the stream as a within-site variable, we sampled the soils in alternate pairs of vegetation plots. The distance within pairs was either 30 or 61 m, and the distance between pairings was either 91 or 183 m, both depending on stream length. We sampled the soils in 153 plots: 51 at reference streams and 102 at restored streams.

We divided each plot into four quadrats and used a 6.5-cm diameter barrel auger to extract a 15-cm deep core of soil from each quadrat. We pooled the four cores from a plot and took a subsample for chemical and particle size analyses. We sampled the bulk density by taking one 331 cm^3 (7.5 cm height, 7.5 cm diameter) sample in each quadrat and combining the four samples per plot prior to weighing and drying. We also described the soil morphology of a 0.3 m long core taken from the plot center in terms of horizonation, the boundaries between horizons, Munsell color, presence of mottles, texture by feel, structure (grade, size, and shape of peds), moist consistence, wet consistence, and root proliferation (Schoeneberger et al. 2002).

We determined particle size distribution with a hydrometer method modified from Gee and Bauder (1986). Bulk density was determined by drying samples at 65°C for 48 hr and weighing the following day. Weight per volume (Mehlich 1973); pH; humic matter (Mehlich 1984b); Mehlich-buffer pH acidity (Mehlich et al. 1976); and Mehlich-3 CEC, base saturation, and P, K, Ca, Mg, S, Na, Cu, Mn, and Zn (Mehlich 1984a) were analyzed by the North Carolina Department of Agriculture & Consumer Services Soil testing Laboratory (Raleigh, NC).

Data Analyses

T-tests were used to determine differences by site type for all soil properties. All variances were assumed unequal. The effects of soil sampling location (site, site type, age, distance along stream, and distance from the stream) on horizon thickness were assessed using analysis of variance (ANOVA). The effects of soil sampling location on horizon boundaries, hues, color names, textures, ped sizes, ped shapes, moist consistence, wet consistence, the presence of mottles, and the presence of roots were assessed using chi-square tests. All t-tests, ANOVA, and chi-square tests were run in JMP Version 9 (SAS Institute Inc. 2010). All of the morphological data were grouped and analyzed by horizon to allow for more direct comparisons of the soil profiles. Half of the profiles we described did not have a third horizon, so we only analyzed the first two horizons of all profiles. The reference data were excluded when analyzing the effects of site age on soil morphology.

Soils were ordered based on their chemical composition, weight per volume, pH, CEC, base saturation, humic matter content, and particle size distributions. Differences between site types were investigated through principal components analysis (PCA). We translated the hue, value, and chroma of the matrix color of each profile's first horizon into the Commission Internationale de l'Eclairage XYZ color system (CIE 1931) using the Munsell Color Converter (Gretagmacbeth n.d.) so that the data were on linear scales in three dimensions. Once converted, we ran the Multiresponse Permutation Procedure (MRPP) in on the XYZ coordinates clustered by site type. PC-Ord software (McCune & Meffort 2006) was used to conduct PCA and MRPP.

We compared the morphology of each core with the profile description of the soil series mapped in its location according to USDA-NRCS Web Soil Survey (Soil Survey Staff 2009). We used these maps in conjunction with the USDA-NRCS official soil series descriptions (Soil Survey Staff 2010). The series descriptions included many characteristics, including horizon thicknesses, boundaries, matrix colors, textures, ped grades, sizes, and shapes, etc. We summed the number of characteristics that matched and did not match between the series descriptions and our profile descriptions, and used chi-square tests to compare these sums by site type. We also used Euclidean distances to compare the color and texture of each core's superficial horizon with the color and texture of its corresponding map unit. We converted all of the textures of the map units into percentages of sand, silt, and clay using the centroid of each texture's polygon within the soil texture triangle to make our comparisons; centroids were obtained from Miller and White (1999). Once the Euclidean distances were calculated, we conducted t-tests of the distances by site type.

Unless otherwise stated, all statistics were considered significant at $p \leq 0.05$.

Results

Fourteen of the 20 chemical and physical properties differed by site type (Figure 3.1). Concentrations of eight of the 10 soil nutrients differed in concentration by site type and all of th0se except Fe and Mn were higher in the restorations. These differences were very pronounced in some cases; mean Ca was more than 2.5 times higher, Cu nearly 3.5 times higher, and Zn more than 5.5 times higher in the restorations than the references. Bulk density was slightly higher in the restorations, but the densities were not outside the range for typical riparian soils. All of the soils were acidic, but the restored soils had a higher pH.

Six properties did not differ by site type. The percentages of sand, silt, and clay, as determined by particle size analysis, did not differ; the most common textures were sandy loam and loamy sand, both of which are typically found in the first horizons of floodplain soils. Mean concentration of S and K and weight per volume also did not differ between site types.

When the reference and restoration plots were ordered by soil properties, there was some clustering by site type, but the plots generally occupied the same space (Table 3.2; Figure 3.2). The reference plots appeared to be a subset of the cluster of restoration plots. Any differentiation by site type occurred along the first axis, and was driven by differences in humic matter, acidity, base saturation, pH, Ca, Cu, and Zn. The second axis did little to differentiate the two groups. The translated matrix colors of the first horizons, as tested by MRPP, did not differ by site type ($T = -0.625$, $A = 0.002$, $p \leq$ delta $= 0.207$).

The two study factors with the strongest relationships with the morphology of the first horizon were individual site and site type (Table 3.3); six properties differed by site, and eight properties (including horizon thickness ($F(1,152) = 2.93$, $p = 0.09$)) differed by site type (Table 3.3; alpha ≤ 0.1). Sixty percent of the boundaries in the reference soils were clear smooth and 12 percent were gradual smooth, whereas half of the boundaries in the restoration soils were clear smooth and twenty percent were clear wavy. Twelve color names were recognized in the reference soils, with brown and dark brown most frequently found, whereas 25 color names were recognized in the restored soils, with brown and strong brown most frequently found. Sandy and loamy soils were prevalent at both site types. Seven soil textures were found in the reference soils, with clay loam, loam, sandy clay loam, and sandy loam all found nearly equally. Eleven soil textures were found in the restored soils, but the textures most frequently found were sandy clay loam and sandy loam. Soil ped structure for most of the reference soils was fine and granular in shape. The restoration soils were fine or medium in size and mostly granular in shape, although 30% of the restored soils were subangular blocky. All of the reference soils were friable or very friable, as were 87% of the restoration soils.

Site and site type each affected 3 additional morphological characteristics in the second horizon, and the patterns found by site type in the first horizon were not always the same in the second. Horizon thickness varied by site ($F(16,123) = 1.96$, $p = 0.02$) in the second horizon whereas it varied by site type in the first. Clear smooth and clear wavy were the most frequently found boundaries in the first and second horizons of the restoration soils, but clear smooth, clear wavy, and gradual smooth boundaries were found in nearly equal proportions of in the second horizon of the reference soils. This contrasts to the dominance of clear smooth boundaries of the reference soils' first horizons. Brown and strong brown were the most frequently found colors in the second horizons of the references whereas brown, strong brown, yellowish brown were found most often in the restorations. The textures of the second horizons followed the same general patterns of distribution as in the first horizons. The reference and restoration peds were mostly fine or medium in size, but the reference soils were predominately granular whereas the restoration soils were equal proportions of granular and subangular blocky. The second horizons of both the reference and restoration soils also had some observations of firm consistency, which was not found in the first horizons at all.

Less than 6% of the first or second horizons in the reference soils had mottles, whereas mottles were found in 5% of the first horizons and 45% of the second horizons of the restoration soils. A greater proportion of mottles were also found in the second horizons of soils that were farther away from the stream than soils that were closer to the stream.

A greater proportion of characteristics matched between the reference profiles and the soil series descriptions of their associated map units (44%) than between the restoration profiles and their map units (35%) ($X^2 = 19.45$, $df = 1$, $p < 0.0001$). A smaller Euclidean distance separated the textures ($t = 1.908$, $df = 144$, $p = 0.058$) and colors ($t = 1.837$, $df = 117$, $p = 0.069$) of the reference soils and their associated map units than the restoration soils and their map units (at the alpha ≤ 0.1).

Discussion

When restoration is done for mitigation purposes, success is typically determined by channel stability and plant survival. We showed that restoration and reference soils differed in their chemical, physical, and morphological properties. The reference sites were more similar to the soils mapped at these locations, in terms of the proportion of matching characteristics and the texture and color of their first horizons. The lesser degree of similarity between the soils of the restoration sites and the soil series that were mapped at those locations shows the lasting effects of restoration practices.

There are many factors besides restoration that could have influenced the soil properties of these sites, but none of them explain the differences we found. Some of the references and restorations had the same parent materials, so differences in geology do not account for the dissimilarities (Table 3.1). Urban streams typically have elevated levels of nutrients; concentrations of Ca, Mg, and P increased with watershed disturbance in the New Jersey Pinelands (Zampella 1994), and stormwater runoff increased levels of trace minerals including Fe, Zn, and Cu in Atlanta-area streams (McConnell 1980). However, none of our sites were remote enough to be unaffected by some degree of urbanization, so we cannot attribute the differences in soil between the restorations and references to differences in urban influence.

Stream restorationists typically attempt to establish vegetation on excavated subsoils. In his review of the practice, one restorationist referred to these soils as "relatively sterile subgrade." (Zentner 1997). Addressing the soils is important because there is a clear connection between the soils and vegetation of these stream sites. In a companion study, we modeled the relationships of chemical and physical soil properties with the cover of exotic vegetation and native woody vegetation growing in the same plots. Humic matter, pH, Mn, and Cu explained 20% of the variation in exotic species cover; bulk density, Ca, Mg, and Mn explained 34% of the variation in native woody species cover. Higher bulk densities were associated with reduced native vegetation cover. The low pH and high Mn concentration of the reference sites suggest that Mn toxicity may influence the vegetation patterns we observed; plant species have a range of tolerances to Mn, but lespedeza is injured by Mn concentrations as low as 1 ppm at pH 4.6 (Morris 1947). Although concentrations of Cu were higher in the restorations and negatively associated with exotic plant growth, none of the soil samples had Cu concentrations above the Mehlich 3-extractable toxicity level published for common crop plants at similar pH (Borkert et al. 1998). The results of this research do not imply that the soil properties caused the patterns we observed in plant growth. However, it is clear that there is a connection between soils and vegetation.

Without records detailing exactly what was done at each restoration site, we cannot know if the soils were amended, however soils are usually fertilized or limed when erosion and the survival of planted vegetation is of concern. The mean pH, P, and Ca concentrations were higher in the restorations than the references, suggesting that the soils may have been treated. In general, the soils of the restored streams were more fertile than the reference soils, having higher CEC and concentrations of most nutrients. If the soils were amended, doing so may have promoted exotic species growth. In a study by Burke and Grime (1996) exotic species had greater cover when growing on disturbed fertile soils than disturbed soils with lower fertilities.

Stream restoration is an extremely expensive process, which makes its success even more critical. The current fee for stream restoration in North Carolina ranges from $256 to $338 per linear foot (NCEEP 2010). Some restoration plans include soil testing post-construction, but not all do so. Given the potential influence of soils on restoration outcome, amending soil properties as needed would likely be relatively inexpensive and likely cost effective when compared to replanting. Bulk density can be decreased by mechanical means such as appropriate tillage. Harvesting the topsoil before construction and re-applying it after could promote the growth of exotic plant species if they were present in the seedbank, but the application of topsoil containing appropriate seed banks to disturbed areas has been suggested as a wetland restoration technique to reduce invasion (Brown & Bedford 1997), and would add humic matter to the restored soils.

It is important that amending the soils is done using the reference soils as a guide. If the restoration soils had lower fertility than their references, liming and/or fertilizing could easily amend the pH and concentrations of Ca, Mg, and Mn. If the restoration soils are already more nutrient-rich than their references, they should not be fertilized. Given the evidence that Mn toxicity may affect vegetation at the references, more research into the exact dynamics of the relationship between soils and vegetation at these sites is needed. The soil morphological properties can provide further insight into differences in soil form and function by site type. Many more restored soils than reference soils had mottles in their second horizons. Mottles result from the fluctuation of water tables, which suggests that the hydrology of the restored and reference streams differ. The second horizons of the restored soils also had yellowish brown colors, indicating that clay is being formed, whereas these colors were not frequently found at the references.

Additional research into the soils of restored sites is also important because even the most common restoration practices may negatively impact soils. Studies of soil microbiology have found that both similarities and differences exist between the soils of restored opencast coalmines and undisturbed sites (Bentham et al. 1992). Microbial communities impact vegetation; diversity of arbuscular mycorrhizal fungi (AMF) can affect the structure and composition of vegetation communities by increasing diversity, nutrient uptake, and productivity (van der Heijden et al. 1998). Farm fields have lower diversity of AMF when compared to woodlands (Helgason et al. 1998). The researchers suggested it was not the monoculture of the studied fields that reduced AMF diversity, but practices including plowing, fertilizing, and using fungicides. Since restorationists use many of these same practices, further research into AMF and other microbial communities at restoration sites is needed.

We found evidence that the soils of the restoration sites had developed since restoration, despite the small window of project ages we investigated. Although bulk density was higher in the restorations, it was lower than expected considering the use of heavy machinery at these sites, suggesting that earthworms and other megafauna may have enhanced soil porosity. However, the results of wetlands research have concluded that even after 50 yr restoration wetlands differ from their natural references. Because of the natural heterogeneity of wetlands systems, and narrow scope with which we model them in restorations, we are losing considerable amounts of wetland diversity (Bedford 1996). We know that the soils are very important at these sites, and by ignoring the impacts of their complexities we may be compromising ecosystem function. In order for the practice of restoration to improve, soils need to be more thoroughly considered.

Conclusion

The soils of stream restoration sites differed in many chemical, physical, and morphological characteristics from those of natural, unrestored references. It is clear that the soils of restoration sites have been affected by their history of disturbance, in which machinery was used to excavate, churn, and compact the soils of the stream channel, banks, and floodplains. The soils of these sites affect both channel stability and revegetation, both of which are crucial to project success for mitigation purposes. The soils play in integral role in community structure and function; however, they are largely ignored during the restoration process. Given the importance of soils in these communities, and the differences we found between restored and reference soils, the effects of restoration on riparian soils need to be further researched and addressed during and after project construction.

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Table 3.1. The names, types, locations, and ages of our study streams and the soils mapped at them (Soil Survey Staff 2009). Table A provides the projects and their associated references. The landscape context is a subjective description of the area surrounding each study site. The soil series mapped at the streams are referenced by number. The identifications of the map units and a brief description of associated parent materials (Soil Survey Staff 2009) are provided in Table B.

A.

Stream Name	Location	Year constructed	Landscape context	Map Unit	Reference	Ref. landscape context	Ref. Map Unit
Abbott's Creek	Raleigh	1999	Suburban neighborhood	8	Brookhaven Park	Park	2
Benbow Park	Greensboro	2004	Park	4	UT to Lake Jeanette	Suburban neighborhood	6
Forest Hills Park	Durham	2005	Park	3	None	--	--
Kentwood Park – UT to Brushy Branch	Raleigh	2002	Park	8	UT to Mine Creek	Suburban neighborhood	5
Kentwood Park – Brushy Branch	Raleigh	2002	Park	8	UT to Lake Wheeler	Suburban neighborhood	1
Oakwood Cemetery	Raleigh	1999	Cemetery	5	None	--	--
Richland Creek	Raleigh	2002	Urban area	1, 2	None	--	--
Rocky Branch – Phase 1	Raleigh	2002	University campus	2, 10	Morgan Creek	Forested and agricultural area	1, 7
Rocky Branch – Phase 2	Raleigh	2005	University campus	5	Morgan Creek	Forested and agricultural area	1, 7
Speight Branch	Cary	2001	Park	9	Sal's Branch	Park	2
Yates Mill Tributary 1a Phase 2	Raleigh	2002	Agricultural area	8	Sal's Branch	Park	2

Table 3.1 continued

B.

Map Unit #	Map Unit	Taxonomic Class	Parent Material
1	Appling sandy loam	Fine, kaolinitic, thermic Typic Kanhapludults	Saprolite derived from granite, gneiss, and/or schist
2	Chewacla sandy loam	Fine-loamy, mixed, active, thermic Fluvaquentic Dystrudepts	Loamy alluvium derived from igneous and metamorphic rock
3	Congaree silt loam	Fine-loamy, mixed, active, nonacid, thermic Oxyaquic Udifluvents	Loamy alluvium derived from igneous and metamorphic rock
4	Enon-urban land complex	Fine, mixed, active, thermic Ultic Hapludalfs	Saprolite derived from diorite, gabbro, diabase and/or gneiss, and transported materials
5	Pacolet sandy loam	Fine, kaolinitic, thermic Typic Kanhapludults	Saprolite derived from granite, gneiss, and/or schist
6	Poplar forest sandy loam	Fine, kaolinitic, mesic Typic Kanhapludults	Residuum weathered from mica schist and/or other micaceous metamorphic rock
7	Wedowee sandy loam	Fine, kaolinitic, thermic Typic Kanhapludults	Saprolite derived from granite, gneiss, and/or schist
8	Wehadkee and Bibb	Fine-loamy, mixed, active, nonacid, thermic Fluvaquentic Endoaquepts and coarse-loamy, siliceous, active, acid, thermic Typic Fluvaquents	Sandy alluvium and loamy alluvium derived from igneous and metamorphic rock
9	Wehadkee silt loam	Fine-loamy, mixed, active, nonacid, thermic Fluvaquentic Endoaquepts	Loamy alluvium derived from igneous and metamorphic rock
10	Worsham sandy loam	Fine, mixed, active, thermic Typic Endoaquults	Alluvium and/or colluvium over saprolite derived from granite and gneiss

Table 3.2. The extracted variances for the first ten axes of the principal components analysis.

Axis	Eigenvalue	% of Variance	Cum. % of Variance	Broken-stick Eigenvalue
1	6.977	34.884	34.884	3.598
2	3.729	18.647	53.531	2.598
3	1.843	9.217	62.748	2.098
4	1.646	8.229	70.977	1.764
5	1.155	5.774	76.750	1.514
6	1.004	5.021	81.771	1.314
7	0.733	3.663	85.434	1.148
8	0.629	3.145	88.579	1.005
9	0.549	2.745	91.324	0.880
10	0.456	2.282	93.605	0.769

Table 3.3. The results of chi-square tests of morphological characteristics as affected by site characteristics. Chi-square values are only listed for tests that were significant at alpha = 0.1.

Morphological characteristic	Site characteristic	Horizon 1		Horizon 2	
		X^2	$P > X^2$	X^2	$P > X^2$
Boundary	Site Type	19.72	0.03	15.35	0.08
Hue	Site	94.28	0.01		
	Site Type	9.00	0.06	16.62	0.03
	Plot distance along stream	13.38	0.01		
Color (name)	Site type	42.14	0.02	28.48	0.06
	Plot distance along stream	46.45	0.01	27.85	0.06
	Plot distance from stream	38.81	0.04		
Texture	Site	220.7	0.08	244.3	0.04
	Site Type	32.00	0.00	44.14	0.00
	Age	17.73	0.06		
	Plot distance along stream	23.79	0.02		
Ped size	Site	75.22	0.01	81.13	0.00
	Site type	7.41	0.06	7.89	0.05
	Age				
Ped shape	Site			62.84	0.00
	Site type	17.35	0.00	15.45	0.00
	Plot distance along stream	5.69	0.06		
Moist consistence	Site	60.00	0.00	73.70	0.00
	Site type	12.26	0.00	17.82	0.00
Stickiness	Site	47.64	0.04	59.97	0.00
	Site type			4.51	0.10
	Age			4.64	0.05
	Plot distance from stream			6.94	0.10
Plasticity	Site	54.44	0.01	83.88	0.00
	Site type			7.94	0.02
	Age			13.22	0.00
	Plot distance along stream			7.74	0.02
	Plot distance from stream	4.80	0.09		
Presence of Mottles	Site			50.22	0.00
	Site type			30.06	0.00
	Plot distance along stream			4.73	0.03
	Plot distance from stream			6.06	0.01
Presence of roots	Site			34.25	0.01
	Site type			16.43	0.00
	Age	3.54	0.06		
	Plot distance along stream			3.21	0.07
	Plot distance from stream	3.13	0.08		

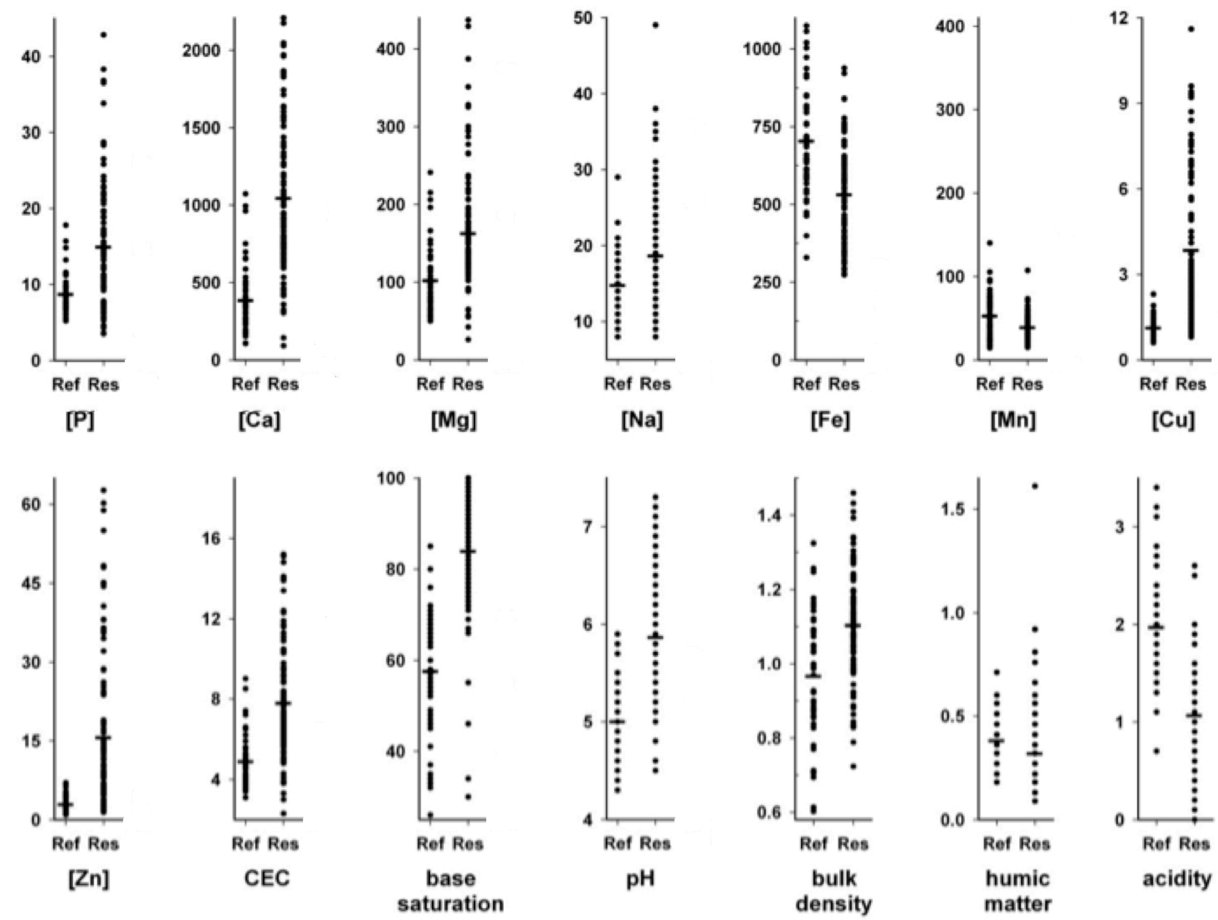

Figure 3.1. The soil properties that differed between the restorations and references. Mean values are indicated by bolded horizontal lines. The units for all nutrient concentrations are mg/dm^3, CEC and acidity are meq/100cm^3, base saturation and humic matter are percents, and bulk density is g/cm^3.

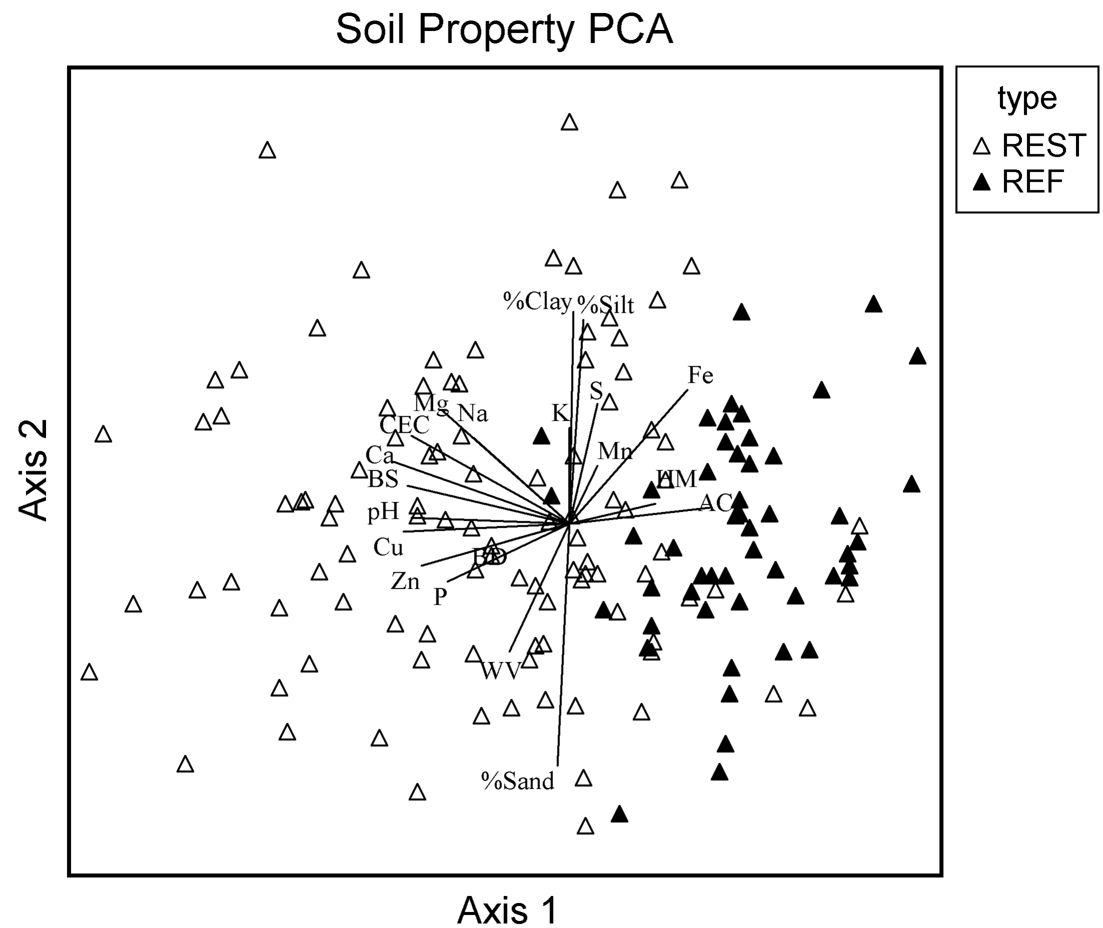

Figure 3.2. The principal components analysis of soil chemical and physical properties.