ABSTRACT

Thesis of Mallory Hirschler for the Degree of
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IMPACTS OF SEDIMENT DEPOSITION ON STREAM FISHES IN THE DAN AND ROANOKE RIVER BASINS

Abstract approved by:

Amy Villamagna, Thesis Advisor

Excess fine sediment is a leading cause of impairment to river biota worldwide and greater understanding of how instream fine sediment influences fish occurrence is needed. Understanding the relationship between species traits and their habitat has been recognized as a valuable tool to help predict lotic species' distribution. Traits that influence the presence and absence of a species will change along environmental gradients, making traits vulnerable to habitat degradation, like sediment loading. This study aims to examine how fish species occurrences (presence or absence) vary across a gradient of fine sediment and if traits can predict which species' occupancies are more sensitive to sediment. We sampled riffle-run transects (2-4 times each) in 29 reaches selected to represent a gradient of fine sediment conditions in the Piedmont region of North Carolina and Virginia. For the first section of this analysis, we categorized the observed species by their predicted sensitivity to sediment based upon their feeding and reproductive traits, then used binomial logistic regressions to predict each species' occupancy based upon a suite of sediment metrics. Silt cover and embeddedness, commonly used fishery's metrics, did not explain as much variability in occupancy as anticipated among the species and other metrics like stream size and upland watershed variables may be more important in explaining occupancy. More species' occupancy significantly and negatively associated with embeddedness than silt cover, suggesting this form of sediment deposition could be more threatening to fish habitat. For some species, their association with these variables were context dependent on the stream's benthic substrate size. Overall, our groupings of sediment sensitivity could likely be better developed to by considering more traits and providing a dynamic, as opposed to equal scoring, for the traits of a species. The second section of this study takes a heuristic approach to define species sensitivity to deposited sediment via functional traits related to feeding and reproduction based on prior studies for fish species, focusing on species in our study area. We then analyzed co-occurrence patterns between traits and two snapshot measurements of deposited sediment, silt cover and embeddedness and compared these results back to our literature-based trait scores of sediment sensitivity. We analyzed these relationships through canonical correspondence analysis (CCA) and Kendal-tau correlation analysis utilizing fish and habitat surveys. Our results indicate that feeding preference and spawning behavior may influence species responses to deposited sediment. Herbivory and nest association were negatively associated, whereas generalism, omnivory, piscivory, and open-water spawning was positively associated with the presence of deposited sediment. The research presented here provides insight into what species and what traits may be particularly sensitive to sediment.

IMPACTS OF SEDIMENT DEPOSITION ON STREAM FISHES IN THE DAN AND RAONOKE RIVER BASINS

by

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I understand that my thesis will become part of the permanent collection of Plymouth State University, Lamson Library. My signature below authorizes release of my thesis to any reader upon request.

Mallory Hirschler, Lead Author

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Introduction

The aquatic world is dependent on the transport of fine sediments in riverine systems. Habitat heterogeneity (i.e. diversity) is driven by sediment supply and transport capacity of a river system. Sediments play a crucial role in the global geochemical system as its organic and inorganic material are transported from rivers to oceans (Walling and Fang, 2003; Kemp et al., 2011). Its organic material includes bacteria, algae, and detritus which then serves as a primary food source of riverine systems (Droppo, 2011). As fine sediment moves through the river landscape it connects the higher lands to the active channel while also creating habitat heterogeneity within a stream (Yarnell et al., 2006; Wharton et al., 2017). It is critical to the health of aquatic ecosystems (Sweitlik et al., 2003). If a stream's sediment load becomes too high it will homogenize the stream substrate by covering available habitat with fine sediment, decreasing depth, and simplifying the channel morphology. Increased sediment loads also cause unstable substrate habitat as sand and silt tend to shift making it harder to support flora and fauna (Tebo, 1955). However, if a stream's sediment load becomes too low, bed degradation will occur and lead to a simplified benthic habitat dominated by large uniform substrate. Thus, optimal habitat heterogeneity and species diversity stream systems requires a moderate sediment supply (Yarnell et al., 2006). Unfortunately, due to human activity (e.g. agriculture, forestry, mining, road construction, and urbanization), many streams are receiving higher than normal sediment loads causing habitat homogeneity. Sediment loading into streams far exceeds preindustrial levels and is only expected to increase with land cover and climate change (Kemp et al., 2011). As forest cover is transformed to urban and agriculture land, vegetation that would normally secure soil in place is no longer there exposing soil to rainfall impact. Rainfall is the largest driver of erosion as it causes particle dislodgment, transport and deposition (Jack et al., 2008). Soil displacement is expected to increase with increased storm intensity and precipitation events related to climate change North America and Europe and more specifically the Mid-Atlantic of the United States (Kemp et al., 2011; Christensen et al., 2007).

In the Southeast United States and the Piedmont region of Virginia and North Carolina excess sediment is a major threat to stream fish habitat (Scott, 2016), but complex impacts on fish populations and the mechanisms of sediment transport make mitigation of sediment challenging. This thesis is a part of a bigger project titled "Assessment of the Dynamics and Biotic Impacts of Fine Sediment to Assist Conservation of Stream Fishes in the Dan and Roanoke River Basins" which aims to help managers determine what types of riparian and floodplain management actions will be most effective to conserve silt-sensitive fish. The larger project's objectives include: 1) quantifying sediment erosion, transport, and deposition potential, 2) evaluating the ability of analytical alternatives to predict benthic habitat condition, 3) testing a traits-based model for predicting species' silt sensitivity, 4) quantifying species occupancy and benthic habitat condition, and 5) testing relationships among species occupancy, benthic habitat condition, and a suite of sediment metrics. This thesis focuses on the objectives concerned with quantifying species occupancy and benthic habitat condition and testing a traits-based model for predicting species' sensitivity to sediment.

In the first chapter, I focused on how fish species occurrences (presence or absence) vary across a gradient of fine sediment and if traits could be used to predict species' occupancy. In the second chapter, I examined how fish functional traits relate directly to sediment deposition metrics represented by silt cover and embeddedness. Although each chapter is designed as a single publishable unit, they draw from a shared pool of foundational trait-based research.

Chapter 1:
Fish Community Responses along a Gradient of Stream Sedimentation

Abstract: Excess fine sediment is a leading cause of impairment to river biota worldwide and greater understanding of how instream fine sediment influences fish species occurrence is needed. This study aims to examine how fish species occurrences (presence or absence) vary across a gradient of fine sediment and if traits can be used to predict species' sensitivity to sediment. We sampled 29 reaches along a gradient of fine sediment (silt cover, embeddedness, and substrate heterogeneity) conditions in the Piedmont of North Carolina and Virginia. We grouped the observed species (n=17) into high, medium, low predicted sensitivity to sediment groups and used binomial logistic regressions to explain species' occupancy based upon a suite of sediment metrics. Silt cover and embeddedness, commonly used fishery's metrics, did not explain as much variability in occupancy as anticipated among the species and other metrics like stream size variables may be more important in explaining occupancy. These sediment metrics are snapshot measurements and may not capture the chronic condition of sediment deposition in streams. Better sediment metrics focusing on more static conditions of the watershed may be more useful in predicting sediment deposition's impact on species' occupancy, like, for example, the Revised Universal Soil Loss Equation (RUSLE), based on estimates of soil loss, which corresponded negatively to more fish species than silt cover or embeddedness. More species' occupancy significantly and negatively associated with embeddedness than silt cover, suggesting this form of sediment deposition could be more threatening to fish habitat. For some species, their association with sediment deposition in both significance and directionality was context dependent on the stream's benthic substrate size. As species did not always respond as expected to sediment deposition, our groupings of sediment sensitivity could likely be better developed to by considering more traits and providing a dynamic, as opposed to equal scoring, for the traits of a species.

1.1 Introduction

Habitat quality is the primary driver of species distribution and occupancy (Lande 1987; Scott et al., 2002; MacKenzie et al., 2011). This is particularly true for freshwater systems that experience natural and anthropogenic disturbances that can rapidly change habitat condition. Additionally, habitat needs, for example during spawning or foraging, change throughout the life history of freshwater species (Schlosser, 1982; Falke et al., 2012). The dynamic nature of freshwater species and their habitats makes them susceptible to habitat degradation, the biggest threat to freshwater fishes (Jelks et al., 2008). This is being expedited by anthropogenic practices (e.g., farming, urbanization, mining) that are diminishing the natural variability of aquatic habitats worldwide (Ricciardi and Rasmussen, 1999; Roberts et al., 2013).

For decades, excess sedimentation has driven the decline of available fish habitat (Tebo, 1955) and caused the impairment of lotic biota (USEPA, 2000). High sediment loads influence fish habitat by means of turbidity, fine sediment particles and other dissolved substances suspended in the water column (Wood and Armitage, 1997; Henley et al., 2000), and sedimentation, the focus of this paper. Sedimentation occurs when suspended particulates fall to the substrata in slower and less turbulent areas. This results in silt cover, sediment covering the stream bed's surface, or embeddedness, sediment penetrating and filling the pore space of the substrate (Woo et al., 1986). In riverine ecosystems, the channel (i.e., beds and banks) and non-channel (i.e., drainage area) are sources of sediment. Deposited or suspended fine sediment, herein inorganic and organic particles less than two millimeters in width, including sand, silt, and clay (Wood and Armitage, 1997), has the potential to profoundly affect fish physiology, performance, behavior, and habitat (Kemp et al., 2011, Wharton et al., 2017), possibly changing a species' distribution or abundance.

Deposited sediment covers available habitat, decreases depth, and simplifies channel morphology. Deposited sediment degrades the benthic habitat, prompting fish reliant on the benthos to avoid these areas (Waters, 1995). Further, sand and silt deposition tend to shift, destabilizing habitat and making it harder to support flora and fauna (Tebo, 1955). The Orangefin Madtom (*Noturus gilberti*), a species under review for federal protection, is less common in reaches with greater silt deposition. This species is strictly a riffle dweller that requires interstitial spaces between small cobble for spawning. Silt can fill these spaces, making the habitat less suitable for the madtom (Burkhead, 1983; Simonson and Neves, 1992). Similarly, the federally endangered Roanoke Logperch (*Percina rex*) uses a variety of habitat types during its life history, but generally avoids areas of high sediment. This is due, in part, to their feeding strategy that involves flipping over loose gravel with their conical snout to access crevice-dwelling invertebrates. This feeding behavior is characteristic of all logperches (Burkhead, 1983; Jenkins and Burkhead, 1993; Rosenberger and Angermeier, 2003). The effects of sedimentation on fish have been documented as changes in a single species' occupancy as well as changes to or differences between assemblages affected by sediment. Schlosser (1982) found that species occupancy in an Illinois stream changed along habitat gradients and that community biomass generally decreased as habitat substrate changed from gravel-rock to silt-sand. Similarly, distributions of species endemic to the Etowah River in north Georgia that rely on coarse bed substrate contracted in response to sedimentation induced by urbanization (Walters et al., 2003).

Land uses such as agriculture, forestry, mining, road construction, and urbanization have drastically increased sediment loads to streams. Sediment loading far exceeds pre-industrial levels and we expect it to increase with land-cover and climate change (Kemp et al., 2011). Urbanization and agriculture conversion reduce vegetation, causing soil to be less stable and more exposed to rainfall. Rainfall is the largest driver of erosion as it causes particle dislodgment, transport and deposition (Jack et al., 2008). Given that climate change is predicted to increase storm intensity and precipitation events in parts of North America and Europe, we can expect an increase in soil displacement (Kemp et al., 2011; Christensen et al., 2007).

To date, research on the relationship between fish and sediment has largely focused on turbidity (Horkel and Pearson, 1976; Gradall and Swenson, 1982; Bruton, 1985; Rowe and Dean, 1998). Measurements of deposited sediment are tedious and labor intensive (Waters, 1995), which has likely limited research efforts. Given the recognized biotic importance of sediment deposits, studies have attempted to predict areas of deposition that could be problematic for fish. For example, Scott et al. (2018) showed how areas with greater filtration capacity had less sediment deposition, helping to inform conservation strategies for the sediment-sensitive Roanoke Logperch. However, their study did not specifically include fish response to instream conditions. More research is needed on how sediment deposition affects benthic habitat and fish occupancy (Sutherland and Meyer, 2007; Kemp et al. 2011), with particular focus on benthic species that are likely to be more sensitive to sediment deposition as they are reliant on the benthos. Greater understanding of how fish, particularly nongame species, respond to sediment-impaired habitat, and if certain traits, like the spawning and feeding behavior, make them more susceptible, will help inform instream habitat restoration and species conservation efforts (Kemp et al., 2011).

The research presented herein contributes to an integrative project that investigates the dynamics of sediment transport, deposition, and its effects on occupancy of fishes in 29 reaches in the Piedmont region of North Carolina and Virginia during 2018 and 2019. This study aims to enhance our collective understanding of how fish species occurrences (presence or absence) vary across a gradient of fine sediment and assessing whether traits help explain species' occupancy. To accomplish these objectives, we analyzed species occupancy using binomial logistic regressions and evaluated the results through the lens of expected species sensitivity which we derived from previously published studies.

1.2 Methods

Study Area:

Our study area encompasses the upper Piedmont portion of the Roanoke and Dan river basins, home to many sediment-sensitive species: the Roanoke Darter (*Percina roanoka*), the Riverweed Darter (*Etheostoma podostemone*) (Matthews et al. 1982), the Rosyside Dace (*Clinostomus funduloides*) (Zamor and Grossman 2007; Hazleton and Grossman, 2009), and the, aforementioned, Roanoke Logperch and Orangefin Madtom. This area holds one of the richest fish faunas in North America, and the number of threatened species is increasing (Rhode et al., 1994; Burkhead and Jelks, 2001). The primary cause for fauna decline is the degradation and loss of freshwater habitat. Many of the streams in this area are listed as impaired according to Section 303d of the Clean Water Act, in part because of increased sediment loading from land development, agriculture practices, and storm intensification (VADEQ, 2014; Scott, 2016).

We first defined the range of our study area by selecting 12-digit hydrologic units (HUC 12s; hereafter, subwatersheds) (Seaber et al, 2007) within the known and expected distribution of the Roanoke Logperch and the Orangefin Madtom. We compiled collection records from the Virginia Department of Game and Inland Fisheries and the North Carolina Wildlife Resources Commission and used Anderson's (2016) report on Roanoke Logperch habitat suitability to identify small watersheds where either or both species potentially occur and have habitat impacted by sediment. We focused on smaller watersheds for our sites because they tend to be more amenable to sampling fish communities and have fewer confounding factors, like dams, compared to larger watersheds.

For each subwatershed in our defined range, we calculated potential annual soil loss using an ArcGIS (ESRI, 2017) model based on the Revised Universal Soil Loss Equation (RUSLE), developed by Scott et al. (2018). The RUSLE calculates annual soil erosion (A) in tons per acre per year, based on inputs of soil erosivity (R-factor), soil erodibility (K-factor), length-slope calculations (LS-factor), cover management practices (C-factor), and the practice factor (P-factor; assumed to be 1) (Equation 2.1; Lim et al. 2005; Jabar, 2003).

$$A = R*K*LS*C*P \qquad \textbf{Eq. 1.1}$$

We used results from the RUSLE analysis to select subwatersheds representing a gradient of soil loss, which we used as a proxy for a gradient of sediment loading. We grouped the subwatersheds into categories of low, low-medium, medium-high, and high predicted soil loss using geometric interval classification in ArcMap 10.5. We initially selected 15 HUC 12s: one with low, four with low-medium, five with medium-high, and five with high predicted soil loss. For the second year of data collection, we added one low-medium HUC 12 and two high HUC 12s to increase representation of high-sediment subwatersheds.

Study Reaches

We further summarized expected soil losses, derived from the aforementioned ArcGIS model, for catchments of stream segments, where segment endpoints were defined by stream confluences based on the USGS national hydrography data set (U.S. Geological Survey, 2017). We used expected soil losses (proxies for sediment loading) from segment-scale catchments to guide our selection of study reaches, which were subsets of segments. We assigned segment-scale catchments to groups of high, medium-high, medium-low, or low expected soil loss using the geometric interval classification in ArcMap 10.5. Within each of the 18 subwatersheds, we selected several segments to represent a wide range of estimated soil loss. We constrained reach selection to Strahler stream orders of 2-5 (USGS, 2017) and eliminated reaches with drainage areas >750 km^2 because they were too large for our fish-sampling methods.

We selected specific study reaches with access via public right-of-way or permission from landowners and then looked for sections of the stream that were wadeable, contained substantial riffle-run habitat, and for which the downstream endpoint was at least 300 fluvial meters from a larger stream. We selected 24 reaches in 2018: three from catchments with low predicted soil loss, eight with low-medium predicted soil loss, ten with medium-high predicted soil loss, and three with high predicted soil loss. In 2019, we added six additional reaches in four catchments with low and two catchments with low-medium predicted soil loss, for a total of 30 reaches. To identify these additional reaches, we revised our selection method to include the sum of the estimated soil loss of all upstream catchments that drain into the selected reach (i.e. cumulative soil loss) as opposed to just using the estimated soil loss of the local reach catchment. The cumulative catchment soil loss was calculated all reaches and was later used in our data analysis.

At a site, reaches were defined as the downstream end of the first transect to the upstream end of the last transect (described below, Figure 1.2) and varied in length roughly from 100 to 300 meters. Reach lengths were defined such that the sampling protocol was feasible and collectively represented the full range of riffle-run habitat, where benthic species are likely to be more common, within the vicinity of a reach.

Survey Transects

We adopted cross-sectional transects as our spatial unit of sampling. We sampled four to five cross-sectional transects (i.e. bank to bank) within each reach, depending on availability of riffle-run habitat amenable to our sampling methods. Each transect extended longitudinally for four meters. We selected transects after visually surveying all available riffle-run habitats along the potential reach length, noting observed conditions. Transect locations were selected such that the sampling protocol was feasible and they collectively represented the full range of riffle-run habitat available at the reach.

Sediment-related variables across reaches

To better understand and visualize how sediment-related parameters varied across study reaches and related to each other, we ran a principal component analysis. We excluded year, visit, width, depth, and habitat cover since they do not directly relate to sediment deposition. To build the PCA, we used the FactoMineR package in R (Lê, 2008; R Core Team, 2013). The first time we ran the PCA, the site at the Smith River was an evident outlier, likely due to it being dam-controlled and having a drainage area almost twice as large as our next largest site. We decided to exclude the Smith River site visits from further analysis and reran the PCA.

The study sites collectively represent a gradient of benthic habitat related to sediment deposition and stream size. The first principal component represents a low to high gradient of embeddedness and silt cover from left to right and embeddedness variability from right to left. The second principal component represents a low to high gradient of drainage area and cumulative soil loss from bottom to top and substrate heterogeneity from top to bottom.

Data Collection

Fish Habitat Surveys

We collected habitat data before collecting fish to minimize disturbance of the benthic habitat. To sample a transect, we set block nets to prevent fish movement into or out of the transect. We flagged the center-line along with lines 2 m upstream and 2 m downstream. We entered the stream downstream of the transect, being careful to minimize disturbance within the transect, to first set up the downstream blocknet. We then exited the stream and re-entered upstream of the transect to set up the upstream blocknet. We sampled the downstream-most transect first, then worked our way upstream until all transects were sampled (Figure 2).

We used a modified USGS NAWQA (National Water Quality Assessment) protocol that included measures of channel and bankfull width, water depth and velocity, substrate composition, fish habitat cover, embeddedness, and silt cover (Fitzpatrick et al., 1998). Bankfull and wetted channel width were measured along the center-line of the transect. We then suspended a measuring tape along the center-line to guide habitat data collection. For streams less than ten meters wide, measurements were taken at five points: 30 centimeters from left wetted edge, 30 centimeters from the right bank edge, center, the mid-point between left bank and center (mid-left bank), and the mid-point between right bank and center (mid-right bank) (Figure 2). For wider streams, the number of measurements varied with stream width and included locations at the left and right banks and at 2-meter intervals between these. We measured depth and velocity with a flow meter (Hach Mf Pro). We used a 0.6-m by 0.6-m PVC quadrat to frame surveys of dominant substrate, subdominant substrate, silt cover, visual embeddedness, and fish habitat cover along the centerline of the transect. Substrate type had to occupy at least 50% of the quadrat to be considered dominant and at least 10% to be considered subdominant. We estimated silt cover and visual embeddedness to the nearest 20% of the quadrat that was covered by fine particles. We quantified silt cover as the amount of the stream's substrate surface that was covered by fine particles and embeddedness by how much of the substrate's interstitial spaces were filled with fine particles (Figure 3). We also assessed particle-specific embeddedness, wherein five mineral particles were measured from the quadrat, including the largest from each corner and the largest from the center. We recorded beta-axis height, total height, and height of visual discoloration from embeddedness for each particle. Fish habitat cover included any non-mineral structure that was large enough (at least 5 cm by 5 cm) for a fish to take shelter beneath; cover types included woody debris, undercut banks, anthropogenic items, and aquatic macrophytes.

Additionally, for each of the 30 sites, we calculated channel slope from the USGS 3D Elevation Program Data Set (2017) at 1/3 arc-second (approximately 10 m) resolution using the Slope tool in ArcMap 10.5.

For our analysis, discussed below, we used the median value of transect-level habitat data to characterize reach-level conditions. Dominant and subdominant substrate were combined, and their categories were transformed to the smallest particle size for that category. We calculated the coefficient of variation (COV) for habitat metrics to account for variation among transects within a reach. COV reflects the variation an individual fish experiences within a reach. We excluded particle-specific embeddedness because it was highly correlated with visual embeddedness.

Fish Surveys

After assessing habitat, we surveyed fishes in each transect using a Smith Root LR 24 electrofisher. We ran the Quick Setup on the electrofisher and used the associated voltage settings for the entire reach. Starting at the left bank, two crew members held a 2-m wide seine so the lead line of the set seine aligned with the lead line of the downstream block net. A third crew member electrofished the area upstream of the set seine, starting at the upstream block net and finishing at the set seine; this was one electrofishing pass. As soon as the electric current was turned off, we quickly lifted the set seine, trying to retain as many fish as possible. We placed captured fish in a bucket of stream water after each electrofishing pass. The process was repeated in adjacent seine-sets along the transect until the entire transect was electrofished. The fish were then placed in an aerated tub located downstream of the transect. If needed, fish were intermediately placed in the aerated tub to prevent overcrowding in collection bucket during electrofishing. The crew then carefully lifted the downstream block net, trying to retain as many fish as possible. These fish were also placed in the aerated flow-through tub where all fish were counted, identified, and finally returned to the stream downstream of the transect. If the next transect was within five meters of the completed transect, the upstream block net was left intact until the downstream block net for the next transect was installed. Fish and habitat data collection was completed for a reach within one day for small streams, but sometimes took two days for larger streams.

We surveyed 24 reaches in 2018 and 30 reaches in 2019. We sampled five transects at most reaches but sampled only four transects at three of our widest reaches. We sampled all transects twice per year, except for the Dan River reach in 2018 due to flooding. We resampled all 2018 reaches in 2019 except for the Smith River due to higher water levels.

Data Analysis

Focal Species

We focused our data analysis on 17 of the 48 fish species captured that were both present and absent at an adequate number of sites to allow for occupancy model convergence and analysis via binomial logistic regression (Table 1.3). In order to better understand the community-level response to sedimentation, we categorized the 18 species into high, medium, and low potential sensitivity to sediment deposition based on feeding and reproduction attributes. A species was considered to have high sensitivity if it had three or more traits with high predicted sensitivity. A species was considered to have low sensitivity if it had three or more traits with low predicted sensitivity or if it had two or more traits with low predicted sensitivity and two traits with moderate predicted sensitivity. All other species were considered moderately sensitive (Table 1.4). For greater discussion of individual trait sensitivity scorings, see Chapter 2.

Occupancy Models

We used binomial logistic regressions to predict the occurrence (presence or absence) of each fish species during a site visit (n=103). Since we had repeated visits to each site, we attempted to build a mixed-effects model, randomizing for site, but we were unable to reach model convergence and settled for a fixed-effects model, excluding site. These models were built with the glm function in R (R Core Team, 2013) and the final model was selected using the 'step' function in R via a forward and backward stepwise selection based upon AIC (Akaike Information Criterion) score. We included interaction effects between silt cover and substrate and between embeddedness and substrate because the impact of sediment deposition will likely depend on the underlying substrate. To create a better-fit model, we scaled all predictors (except year and visit) by subtracting the mean and dividing by the standard deviation of the variable to center each variable. We used the 'compare_performance' function in the Performance package in R (Lüdecke et al., 2019) to calculate Tjur's R^2, commonly used for binomial logistic regressions (Tjur, 2009). Variables were significant with a p value below zero (Murtaugh, 2014).

2.3 Results

Occupancy Models

<u>*Species with high sensitivity*</u> All species predicted to be highly sensitive to sediment deposition had their observed variation in occupancy explained by at least one sediment related variable (Table 1.5). The median observed variation explained (R^2) by best-fit occupancy models was 0.453 across species predicted to be highly sensitive to sediment deposition. The Mountain Redbelly Dace had the most variation explained (R^2=0.605) and the Blacktip Jumprock had the least variation explained (R^2=0.346). These occupancy models accounted for modest amounts of observed variation in these species' occupancy, suggesting there may be unmeasured, but important variables influencing species occupancy.

All species' occupancy within this group except for the Glassy Darter was significantly associated with a variable reflecting benthic habitat condition. Three out of the eight species (Rosyside Dace, Riverweed Darter, and Johnny Darter) had strong negative association with embeddedness. Based on their coefficients, the odds of observing these species decreased by 89% (Rosyside Dace), 80% (Riverweed Darter), and 87% (Johnny Darter) when embeddedness increased by one standard deviation (based on scaled variables). The Riverweed Darter and Johnny Darter were also negatively associated with embeddedness variability, implying the slight presence of embeddedness could potentially limit these species' occupancy. Surprisingly, none of these highly sensitive species were negatively associated with silt cover. One of these species (Glassy Darter) were negatively associated. Surprisingly, two out of the four species (Johnny Darter and Glassy Darter) related to slope had an inverse relationship with slope, which was unexpected since areas of higher slope tend to have less silt cover and embeddedness (Table 1.2).

The interactions between substrate and sediment deposition and the variability of the benthic habitat were also significant in explaining species' occupancy. Occupancy of the Blacktip and the Bigeye Jumprocks significantly increased with substrate size interacting with silt cover and/or embeddedness, suggesting sediment deposition impacts on these species' occupancy will be dependent on the underlying substrate. As sediment deposition increases, the odds of observing these species will increase at sites with larger substrate size. Occupancy for some species predicted to be highly sensitive was significantly related to embeddedness variability (n=4) and substrate heterogeneity (n=2) (Table 1.5), suggesting that species respond to habitat variability. Overall, sediment variables explain less variation than other variables, particularly stream-size related variables, suggesting that they were not the main driver of species occupancy.

Occupancy for all species predicted to be highly sensitive was significantly related to stream size. Of the stream size metrics, species occupancy was most often associated with wetted width (n=6) followed by stream order and drainage area (n=3).

Species with medium sensitivity The median observed variation explained (R^2) was 0.315 across medium sensitivity species. The White Shiner had the most variation explained (R^2=0.562) and the Roanoke Hogsucker the least (R^2=0.173). Once again, these occupancy models accounted for modest amounts of observed variation in these species' occupancy, suggesting there may be unmeasured, but important variables influencing species occupancy.

Occupancy of five out of the six medium sensitive related species was significantly or moderately significantly associated to silt cover, embeddedness, or their interaction with substrate (Table 1.6) but only two were inversely associated. The only species negatively associated, albeit of moderate significance, with silt cover was the Rosefin Shiner whose odds of being observed decreased by 45% at a site with a one standard deviation increase in silt cover. The Redlip Shiner, was the only species to show a negative association, of moderate significance, with embeddedness, but the association was dependent on substrate size such that embeddedness decreased the odds of observing this species more for larger substrate than smaller substrate size. All other responses to the sediment variables were opposite of expectations. Two species had positive association with embeddedness (Satinfin Shiner, Roanoke Hogsucker), such that the odds of observing these species increased 2-3 times, based on their coefficients, at a site with a one standard deviation increase in embeddedness. The White Shiner's occupancy had moderate significant and positive association with embeddedness interacting with substrate such that embeddedness would increase the odds of observing a species in sites with larger substrate. Occupancy of four species was associated with cumulative soil loss and three of those were direct associations.

Occupancy for only two of the medium predicted sensitive species was significantly related to benthic habitat variability. The Central Stoneroller was positively associated with embeddedness variability, and the Redlip shiner was negatively associated to silt cover variability. The Redlip Shiner was also negatively related with silt cover or embeddedness, suggesting this species may especially be vulnerable to sediment deposition. No species was associated with substrate heterogeneity.

Similar to the highly sensitive counterparts, observed variability of medium sensitive species' occupancy was generally explained more by non-sediment variables, like stream size. All species' occupancy significantly associated with wetted width, stream order, and drainage area except for the Roanoke Hogsucker which still showed a moderate significant relationship with wetted width.

Species with low sensitivity *Species with low sensitivity* As expected, the median observed variation for the low predicted sensitive species (R^2=0.273) was lower than the high and medium groups variability explained (R^2=0.453,0.315). The Largemouth Bass had the most variation explained (R^2=0.495) and the Green Sunfish had the least variation explained (R^2=0.025). Once again, these models accounted for modest amounts of observed variation in these species' occupancy, suggesting there are unmeasured, but important variables influencing species occupancy.

Two out of the four low sensitive species had sediment-related variables explain more variance than the other two species (Table 1.7). The Bluegill Sunfish negatively correlated with embeddedness and positively associated with silt cover interacting with substrate, and the Largemouth Bass positively associated with silt cover and embeddedness variability. Slope was the only habitat variable to be significantly, although moderately, inversely associated for more than one species. Species of low sensitivity would be expected to have an inverse relationship with slope since it is inversely related with sediment deposition (Table 1.2). All significant relationships were positive with sediment deposition variables except the Bluegill Sunfish with embeddedness and the Redbreast Sunfish with cumulative soil loss. These results generally align with our expectations, but it is important to note for the relatively low site occupancy and/or detection probability calculated from the simple multi-season model developed by MacKenzie et al. (2019) and the small group size of four species, which were largely comprised of juveniles (Table 1.3).

Comparison of high, medium, low sensitivity groups

All the species considered to be highly or moderately sensitive to sediment deposition had at least one sediment-related variable significantly explain its observed variability. As anticipated more high sensitive species' occupancy (n=3) are negatively associated with embeddedness than medium sensitive (n=1, moderate significance) and low sensitive species (n=1). No species among all the groups had any negatively strong significant association with silt cover. All groups, even the highly sensitive species, had positive associations with the sediment metrics. Overall, not as many significant associations were observed as expected for the high and moderately sensitive groupings and species responses were not consistent among species within the same group.

2.4 Discussion

Silt cover and embeddedness did not explain as much variability in occupancy as anticipated among the species and other metrics like stream size variables may be more important in explaining occupancy. Species' occupancy may not have been explained by the sediment deposition metrics because these were snapshot measurements and our sites may have been below the threshold to impact species occupancy Other sediment metrics may be better at explaining species occupancy, like the cumulative soil loss metric calculated via RUSLE that considers upland factors that are largely static. Interestingly though, species varied in their response to these two metrics and this could be due to their mechanistic differences. Species responses to sediment deposition were also dependent on the underlying substrate of the site. Lastly, based upon our results, our predictions of potential sensitivity were not supported by the selected sediment metrics and were likely oversimplified as there are more traits that can influence sensitivity and not all traits should be weighted equally.

Stream size

Silt cover and embeddedness never explained all the variability observed in species' occupancy, suggesting other metrics included and not included in our analysis may more greatly impact species occupancy. According to the River Continuum Concept, fish assemblages are expected to change as the river flows downstream, making the effects of sedimentation to likely be dependent on stream size. Thus, stream size will likely explain more variation of observed occupancy than sediment metrics. This was seen in our results as 12 out of 17 of species had significant association with a stream size related variable (wetted width, depth, stream order, and drainage area).

Given the clear influence of drainage area on cumulative soil loss, we anticipated it to also have significant relationships with fish species' occupancy. Cumulative soil loss was calculated by summing predicted soil loss and as expected increased with drainage area (Figure 1.4). However, these two parameters were not consisted in their directional influence on species occupancy as seen in the occupancy models' coefficients. This suggest the RUSLE calculation, regardless of drainage area, may be a valuable predictor of species occupancy, as it was significantly associated with five of our species. Other studies have linked upland factors to altering fish assemblages (Walters et al., 2003; Freeman et al., 2001; Jones III et al., 1999, Poff and Allan, 1995; Tebo, 1955), so RUSLE may be a valuable predictor of species occupancy due to the watershed factors the calculation is based on.

Silt cover and embeddedness as sediment deposition metrics

Overall, not as many species' occupancy was influenced by silt cover or embeddedness. More specifically, species predicted to be highly sensitive to deposited sediment, based on the aggregation of four traits related to feeding and reproduction, was not always explained by silt cover or embeddedness. They are snapshot metrics and may not accurately capture chronic conditions of sediment loading, which could be why not more species had significant negative responses to these sediment deposition metrics as expected. Although, silt cover is considered more transient than embeddedness, both can be washed away from a high flow event (Levasseur et al. 2006; Beschta and Jackson 1979). There may be better indicators of chronic sediment in a system like for example, estimated cumulative soil loss, which was more often negatively associated with species' occupancies than silt cover and embeddedness. These watershed factors may be more indicative of species response to long-term sediment movement in a system.

In general, the sediment gradient represented by the study sites was one of low to moderate sedimentation. Deposited sediment observed may be below the threshold to significantly impact species occupancy, and a non-linear relationship between species occupancy and sediment could exist. Our sampling methods were geared towards especially sediment-sensitive, benthic fish that predominantly occupy riffle-run habitats and limited us to smaller waterways. Riffles and runs tend to have less sediment deposition than pools and smaller streams usually will have less sediment than larger ones. Occupancy may not have been impacted in these conditions, but other fish responses, like density, of sediment sensitive species could be. From a preliminary analysis, we found that five out of six species' density decreased with increasing embeddedness (Appendix D). Factors affecting ability to access resources, like habitat degradation via sediment loading, will first effect individual's ability to survive and reduce species' density before species' occupancy will be impacted (Frimpong and Angermeier, 2010, Poff and Allan 1995). Our sites could represent the beginning of sediment loading and have not yet reached the threshold of sediment deposition that would limit species occupancy. Additionally, some species' occupancy may respond to inconsistent conditions or the presence of even a small amount of embeddedness or silt cover as some species were inversely associated with site-level variability of embeddedness and silt cover. For example, the Johnny and Riverweed Darter's occupancy both had strong negative associations with embeddedness and embeddedness variability, suggesting these species are especially sensitive to sediment.

Silt cover and embeddedness are common habitat measurements for fish biologists (Fitzpatrick et al., 1998), but individual species' occupancies seem to respond to these sediment deposition metrics differently. Species that responded to one sediment deposition metric did not always respond the other one or in the same direction. More species' occupancies were inversely associated to embeddedness than silt cover and more often associated to embeddedness variability than silt cover variability. Embeddedness, deposited sediment in spaces between substrate, is likely evidence of a more chronic condition, whereas silt cover, sediment deposited on the substrate's surface tends to be more easily flushed from a system (Figure 1.3, Levasseur et al.

2006; Beschta and Jackson 1979). There also may be watershed-level factors, like land cover in riparian areas (Scott et al. 2018), influencing these differing fish relationships between silt cover and embeddedness.

Not only did more species respond to embeddedness but they also showed stronger responses than they did to silt cover, especially the species that were predicted to be highly sensitive. Thus, certain species may be especially vulnerable to embeddedness. For example, the Rosyside Dace, the Johnny Darter, and the Riverweed Darter odds of being observed at a site decreased by at least 80% if embeddedness increased by one standard deviation, which is consisted with other studies documenting a negative relationship with these species and sedimentation (Matthews et al., 1982; Propst and Carlson, 1989; Zamor and Grossman, 2007). Species showing positive associations with embeddedness were not as strong as their highly sensitive counterparts. The Roanoke Hogsucker and the Satinfin Shiner, species in the moderately sensitive group, were the only species positively associated with embeddedness regardless of substrate. The low to moderately embedded substrate may offer organic matter for food to the omnivorous Roanoke Hogsucker (Jenkins and Burkehead, 1994). The positive correlation was unexpected for the Satinfin Shiner, as another crevice-spawning shiner, the Tricolor Shiner (*Cyprinella trichroistia*), has been documented to have decreased reproductive success with increasing levels of suspended sediment (Burkhead and Jelks, 2001). The positive correlation of the Satinfin Shiner with embeddedness could again allude to our sites representing only moderate embeddedness, or that species' occupancy response to sediment could not just be influenced by feeding and reproduction.

Other species' occupancy did have positive associations with sediment deposition, but these associations were dependent on the underlying substrate. For certain species their occupancy responses to sediment deposition will likely depend on what type of benthic substrate sediment is depositing on, like the six species that were at least moderately significantly associated with silt cover or embeddedness interacting with substrate. Four of these species had positive association with these interactions, suggesting that these species are more likely to be found at sites that have higher amounts of sediment deposition with larger substrate (i.e. cobble, boulder) than smaller substrate (i.e. sand, fine gravel).

Multiple Traits as a Predictor of Sensitivity

Our classification of potentially sensitive species based on feeding and reproductive attributes may not accurately reflect sediment sensitivity. First, this could be due to the measurements of deposited sediment and our sites not capturing the threshold of sediment to impact species occupancy as previously discussed. Secondly, our groupings were probably overly conservative as we only considered four attributes and other traits, (i.e. morphological and behavioral traits), are likely to influence species sensitivity to sediment. For instance, the Glassy Darter showed lower occupancy at sites with higher slopes, which tends to have less sediment deposition (Burdon et al, 2013). This species was classified by its feeding and reproductive traits as a potential highly sensitive species, but it has several morphological adaptions that allow it to inhabit shifting sands where it is commonly found (Fischer, 1992). Thirdly, our groupings of high, medium, and low sensitivity did not allow fair comparisons of species of low sensitivity to high sensitivity since our sampling methods were geared towards riffles and runs of smaller water, where species of low sediment sensitivity are not likely to reside. This led to collecting predominantly young of year for these species and low estimates of site occupancy and detection probability. However, with the exception of the Bluegill Sunfish, these centrarchids', considered as low sensitive species, occupancy was not limited by sediment, consistent with other studies demonstrating an increase abundance of centrarchids compared to other species in areas of high sediment (Sutherland et al., 2002; Freeman, 2001, Jones III et al., 1999). Lastly, not all feeding and reproductive traits may be equally influential and certain traits may need to be weighted more heavily when considering sensitivity of species. As species are a combination of traits, bundling traits to predict species will likely be more informative as traits can compensate for others. Chapter 2 will look at multiple attributes to explain trait occurrences and aim to identify what attributes and traits within those attributes may cause a species to be more sensitive to sediment.

2.5 Conclusions

This study demonstrated sediment deposition does have the potential to limit species occupancy and explain, at least, a modest amount of its variation, although stream size is likely to be a better predictor. Surprisingly, silt cover and embeddedness were only negatively correlated with a few fish species. This may be due to our sites not yet representing the threshold of sediment to impact species' occupancy and the relationship between species occupancy and sediment deposition may be non-linear. These sediment deposition metrics are also temporary measurements of sediment and better metrics that capture the long-term condition of sediment deposition need to be developed. We offer a beginning framework of how predicting species sensitivity to sediment based on feeding and reproductive traits, but future research could better develop these classifications examining other traits and dynamically weighing traits for species sensitivity scores. The research here provides some insight on what species could be particularly sensitive to sediment deposition, but better metrics of sediment deposition and more knowledge of species traits could enhance fish conservation efforts as sediment deposition will only increase with land use and climate change, impacting more species occupancy.

Ch. 1: Figures and Tables

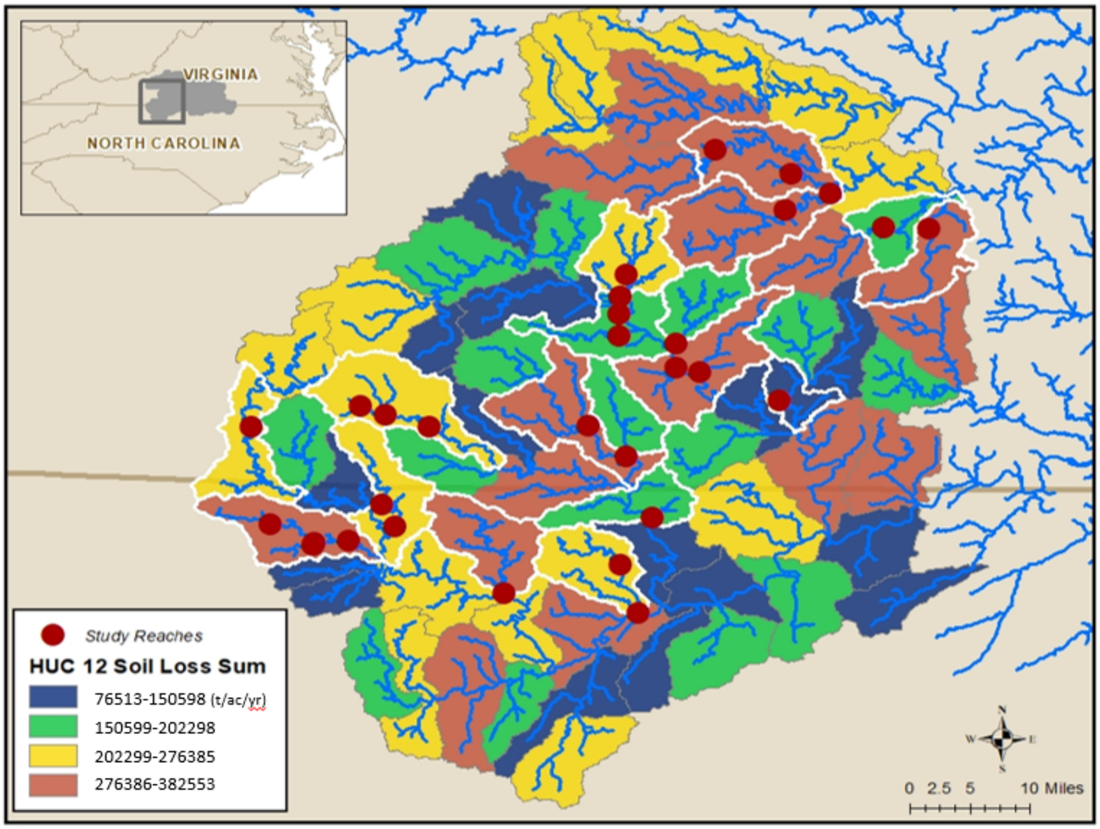


Figure 1.1. Map of the 30 study reaches (red dots) distributed through the upper Piedmont portion of the Roanoke and Dan river basins and the spatial distribution of predicted annual soil loss summarized by 12-digit hydrologic units (HUC 12s). The 18 HUC 12s sampled in 2018 and 2019 share white outlines.

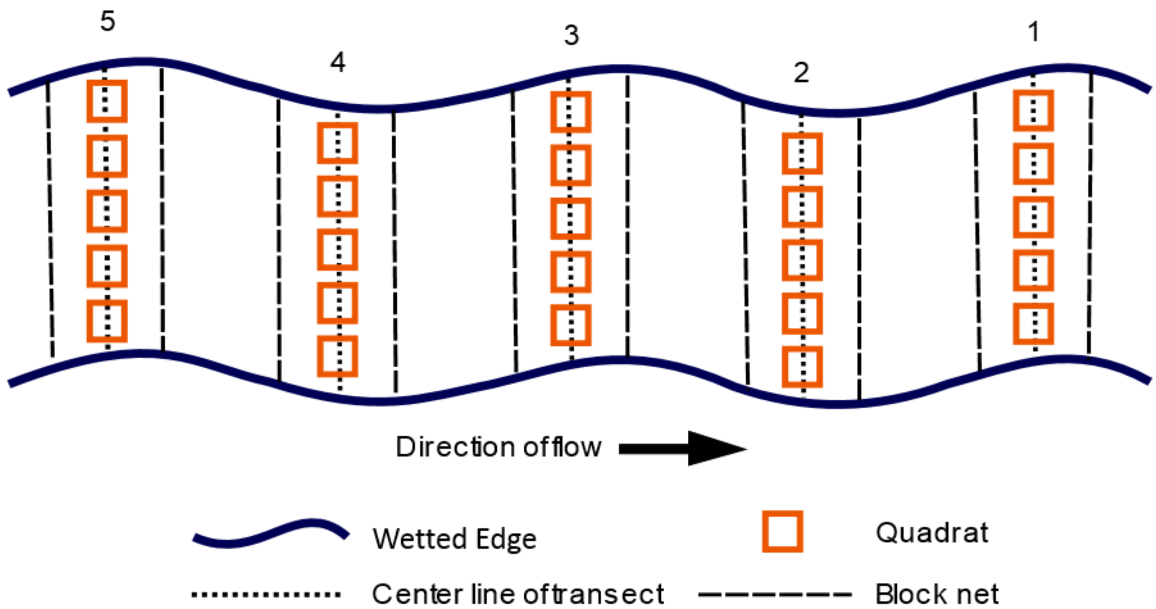


Figure 1.2. Diagram of fish and habitat survey locations along five transects within a study reach. Habitat data were collected from at least five 0.36-m^2 quadrats along the centerline.

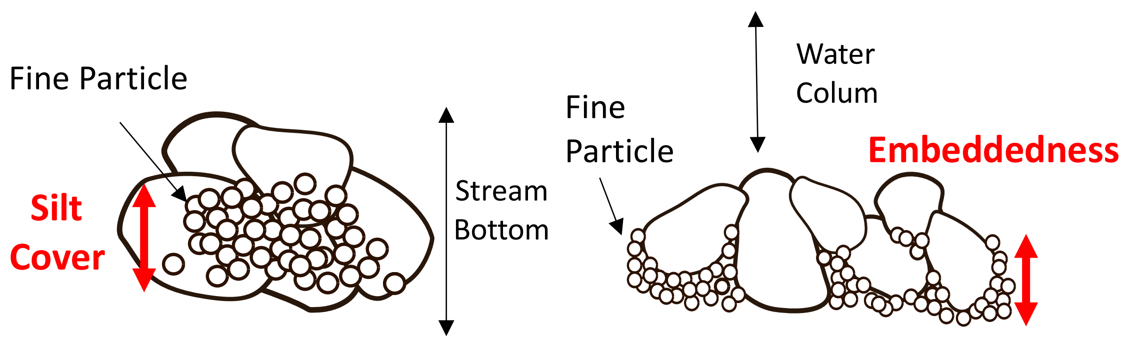


Figure 1.3. Silt cover (left) measured as the amount of the stream substrate covered by fine particles. Embeddedness (right) measured as the amount of the substrate's interstitial space filled with fine particles.

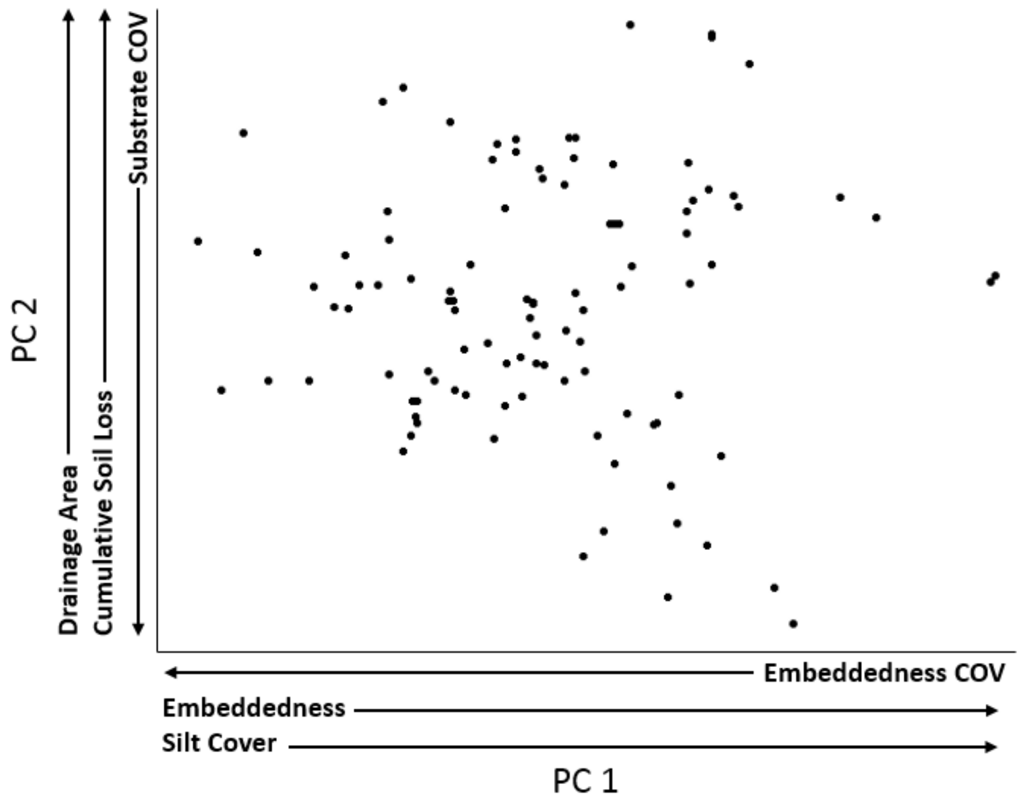


Figure 1.4. Principal component (PC) plot of 29 sites during 103 visits in principal component space defined by 10 sediment-related variables. “COV” = coefficient of variation.

Table 1.1. Number of HUC 12s and catchments in estimated (Est.) soil loss bins sampled each year. “Med” = medium.

Est. Soil Loss Bin	**HUC 12**		**Catchment**	
	2018	**2019**	**2018**	**2019**
Low	1	1	3	7
Low-Med	4	4	8	10
Med-High	5	5	10	9
High	5	7	3	3

Table 1.2. Results of principal components (PC) analysis of 103 site visits based on 10 sediment-related variables. The loadings for each variable, the eigenvalue, and cumulative percent of variation for the first three principal components are provided. Blanks indicate no loading was associated with that variable for the PC. “COV”=coefficient of variation.

	PC1	*PC2*	*PC3*
Drainage Area	0.348	-0.437	0.193
Stream Order	0.337	-0.339	□
Cumulative Soil Loss	0.343	-0.42	0.213
Channel Slope	-0.204	-0.221	-0.432
Substrate	-0.235	-0.239	-0.443
Substrate COV	□	0.449	0.278
Embeddedness	0.389	0.337	□
Embeddedness COV	-0.409	-0.13	0.154
Silt Cover	0.372	0.259	-0.322
Silt Cover COV	-0.305	-0.114	0.57
Eigenvalue	3.409	2.382	1.207
Cumulative Percent of Variation	34.095	57.913	69.987

Table 1.3. Species analyzed, their families, and the number of site visits during which they were observed (Obs). Site occupancy estimates (SOE), detection probability estimate (DPE), and the standard error (SE) are shown for each species, as derived from the simple multi-season model developed by MacKenzie et al. (2019). “Mtn.” = Mountain.

Family	**Common Name**	**Species**	**Obs**	**Occ Est (SE)**	**Det Prob (SE)**
Catostomidae	Roanoke Hogsucker	*Hypentelium roanokense*	55	0.68 (0.11)	0.72 (0.06)
	Blacktip Jumprock	*Moxostoma cervinum*	48	0.72 (0.13)	0.61 (0.07)
	Bigeye Jumprock	*Moxostoma ariommum*	12	0.31 (0.19)	0.33 (0.18)
Cyprinidae	Rosefin Shiner	*Lythrurus ardens*	63	0.92 (0.08)	0.73 (0.06)
	Satinfin Shiner	*Cyprinella analostana*	18	0.39 (0.16)	0.44 (0.15)
	White Shiner	*Luxilus albeolus*	39	0.41 (0.10)	0.77 (0.07)
	Rosyside Dace	*Clinostomus funduloides*	62	0.95 (0.05)	0.68 (0.06)
	Redlip Shiner	*Notropis chiliticus*	54	0.63 (0.09)	0.95 (0.03)
	Mtn. Redbelly Dace	*Chrosomus oreas*	32	0.63 (0.11)	0.65 (0.09)
	Central Stoneroller	*Campostoma anomalum*	35	0.49(0.12)	0.628(0.10)
Percidae	Riverweed Darter	*Etheostoma podostemone*	46	0.63 (0.12)	0.68 (0.07)
	Johnny Darter	*Etheostoma nigrum*	58	0.82 (0.09)	0.79 (0.06)
	Glassy Darter	*Etheostoma vitreum*	57	0.68 (0.10)	0.88 (0.05)
	Redbreast Sunfish	*Lepomis auritus*	19	0.26 (0.14)	0.29 (0.07)
Centrarchidae	Bluegill Sunfish	*Lepomis macrochirus*	10	0.62 (0.53)	0.20 (0.17)
	Green Sunfish	*Lepomis cyanellus*	9	1 (0)	0.11 (0.04)
	Largemouth Bass	*Micropterus salmoides*	9	0 (0)	0.16 (0.05)

Table 1.4. Species grouped by predicted sensitivity to sediment deposition. Each trait for a given attribute was rated as high (H), medium (M), or low (L) sensitivity. “Ins” =Insectivore. “Pisc” =Piscivore. “Mtn.” = Mountain. “Sub”= Substrate. “OW”=Open Water

	Feeding		**Spawning**		**Sediment**
Species	**Location**	**Preference**	**Behavior**	**Substrate**	**Sensitivity**
Mtn. Redbelly Dace	Benthic (H)	Herbivore (L)	Nest Associate (H)	Hard (H)	High
Rosyside Dace	Water Column (L)	Insectivore (H)	Nest Associate (H)	Hard (H)	
Blacktip Jumprock	Benthic (H)	Insectivore (H)	Sub Egg Scatterer (M)	Hard (H)	
Bigeye Jumprock	Benthic (H)	Insectivore (H)	Sub Egg Scatterer (M)	Hard (H)	
Riverweed Darter	Benthic (H)	Insectivore (H)	Nester (M)	Hard (H)	
Johnny Darter	Benthic (H)	Insectivore (H)	Nester (M)	Hard (H)	
Glassy Darter	Benthic (H)	Insectivore (H)	Sub Egg Scatterer (M)	Hard (H)	
Rosefin Shiner	Water Column (L)	Omnivore (L)	Nest Associate (H)	Hard (H)	Medium
Satinfin Shiner	Water Column (L)	Ins/Pisc (M)	Brood Hider (M)	Hard (H)	
White Shiner	Water Column (L)	Ins/Pisc (M)	Nest Associate (H)	Hard (H)	
Redlip Shiner	Water Column (L)	Generalist (L)	Nest Associate (H)	Hard (H)	
Roanoke Hogsucker	Benthic (H)	Omnivore (L)	OW Egg Scatterer (L)	Hard (H)	
Central Stoneroller	Benthic (H)	Herbivore (L)	Nest Builder (M)	Hard (H)	
Redbreast Sunfish	Water Column (L)	Ins/Pisc (M)	Nester (M)	Soft (L)	Low
Bluegill Sunfish	Water Column (L)	Generalist (L)	Nester (M)	Both (L)	
Green Sunfish	Water Column (L)	Ins/Pisc (M)	Nester (M)	Both (L)	
Largemouth Bass	Water Column (L)	Ins/Pisc (M)	Nester (M)	Both (L)	

Table 1.5. Best-fit occupancy model results for species predicted to be highly sensitive to sediment. Numbers indicate variable was selected in final logistic model and blanks indicate variable was not selected. Bold numbers denote significance (p<0.05). “COV”=coefficient of variation; “Cum SL”=cumulative soil loss, “Sub”=Substrate, “Emb”=Embeddedness; “SC”=Silt Cover; “Mt.”=Mountain.

	Mt. Redbelly Dace		Rosyside Dace		Blacktip Jumprock		Bigeye Jumprock		Riverweed Darter		Johnny Darter		Glassy Darter	
	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P
Year	**-2.124**	**0.041**	**-2.545**	**<0.001**			1.963	0.110			**-2.792**	**0.001**	-1.040	0.108
Visit					0.455	0.075			**-0.493**	**0.044**				
Width	**-1.812**	**0.008**	**1.638**	**0.012**			**2.155**	**0.007**	**1.035**	**0.003**	**1.112**	**0.013**	**1.892**	**0.035**
Depth	0.870	0.157					**-1.869**	**0.020**			**0.848**	**0.025**		
Habitat Cover	-0.998	0.083			**-0.574**	**0.045**								
Stream Order	-1.031	0.076	**-0.948**	**0.058**	**0.902**	**0.016**	1.311	0.059	0.659	0.076			**-1.714**	**0.003**
Drainage Area	**2.403**	**0.017**			**-1.514**	**0.049**							**5.142**	**<0.001**
Cum SL	-1.461	0.112	-0.736	0.133	1.430	0.051					-0.780	0.064	**-2.235**	**0.028**
Slope	**1.111**	**0.012**	**1.259**	**0.003**							**-2.813**	**<0.001**	**-1.991**	**0.002**
Silt Cover	-0.258	0.734			**1.370**	**0.017**			-0.698	0.139				
SC COV														
Embeddedness			**-2.215**	**<0.001**	0.814	0.217	**2.916**	**0.020**	**-1.602**	**0.006**	**-2.043**	**<0.001**		
Emb COV	**1.207**	**0.011**					**1.114**	**0.049**	**-0.765**	**0.049**	**-0.821**	**0.029**		
Substrate	0.565	0.457			**3.515**	**0.001**	2.637	0.111						
Sub COV	-0.958	0.130	**1.359**	**0.001**					**1.059**	**0.007**				
SC*Sub	2.228	0.053			**2.096**	**0.034**								
Emb*Sub					**1.673**	**0.047**	**3.098**	**0.018**						
R2	0.605		0.458		0.346		0.453		0.372		0.412		0.547	
AIC	85.831		100.090		123.950		57.223		122.110		107.080		84.955	

Table 1.6. Best-fit occupancy model results for species predicted to be moderately sensitive to sediment. Numbers indicate variable was selected in final logistic model and blanks indicate variable was not selected. Bold numbers denote significance (p<0.05). "COV"=coefficient of variation; "Cum SL"=cumulative soil loss, "Sub"=Substrate, "Emb"=Embeddedness; "SC"=Silt Cover.

	Rosefin Shiner		Satinfin Shiner		White Shiner		Redlip Shiner		Roanoke Hogsucker		Central Stoneroller	
	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P
Year			**-4.293**	**0.031**	**4.522**	**0.007**						
Visit	**-0.473**	**0.044**	1.368	0.091	**-1.840**	**0.017**			0.392	0.055		
Width	**1.485**	**0.007**	**1.629**	**0.023**			**2.042**	**0.002**	0.423	0.062	-0.579	0.133
Depth							**-1.031**	**0.006**				
Habitat Cover												
Stream Order			**-1.190**	**0.034**	**1.018**	**0.036**	-0.755	0.070			0.537	0.117
Drainage Area	**1.789**	**0.032**	**2.030**	**0.001**	**5.922**	**<0.001**	**-3.743**	**0.008**			**1.293**	**0.081**
Cumulative Soil Loss	**-2.038**	**0.006**			**-4.906**	**<0.001**	**2.171**	**0.024**			**-1.443**	**0.042**
Slope	**-1.032**	**0.002**	**-1.888**	**0.017**	-0.687	0.151	**0.925**	**0.023**	0.450	0.071	**-0.801**	**0.024**
Silt Cover	-0.602	0.075			0.212	0.729						
SC COV	-0.470	0.114					**-0.497**	**0.082**				
Embeddedness			**1.117**	**0.042**	-0.758	0.357	0.536	0.397	**0.853**	**0.002**		
Emb COV											**1.458**	**0.080**
Substrate					0.845	0.503	0.247	0.796				
Sub COV					0.678	0.148						
SC*Sub					-1.702	0.119						
Emb*Sub					2.126	0.078	-1.537	0.067				
R2	0.315		0.532		0.562		0.443		0.173		0.208	
AIC	115.470		60.858		93.479		110.100		133.030		126.140	

Table 1.7. Best-fit occupancy model results for species predicted to have low sensitivity to sediment. Numbers indicate variable was selected in final logistic model and blanks indicate variable was not selected. Bold numbers denote significance (p<0.05). "COV"=coefficient of variation; "Cum SL"=cumulative soil loss, "Sub"=Substrate, "Emb"=Embeddedness; "SC"=Silt Cover.

	Redbreast Sunfish		Bluegill Sunfish		Green Sunfish		Largemouth Bass	
	Coeff	P	Coeff	P	Coeff	P	Coeff	P
Year			-1.936	0.117				
Visit	**0.938**	**0.003**					**3.074**	**0.015**
Width								
Depth			1.085	0.090				
Habitat Cover			-1.099	0.090				
Stream Order			0.977	0.070				
Drainage Area	1.651	0.151						
Cumulative Soil Loss	-2.132	0.085						
Slope	-0.531	0.142	-2.348	0.051			-1.193	0.067
Silt Cover	0.404	0.150	1.904	0.095	-1.113	0.151	**1.551**	**0.011**
SC COV								
Embeddedness			**-3.058**	**0.049**				
Emb COV							**2.020**	**0.022**
Substrate	0.900	0.132	-2.557	0.201	-1.706	0.155		
Sub COV								
SC*Sub			**4.153**	**0.037**	-1.540	0.173		
Emb*Sub			-3.288	0.062				
R2	0.240		0.299		0.025		0.495	
AIC	88.858		65.834		65.863		38.078	

Chapter 2:
Relationships between functional traits of stream fishes and sediment deposition

Abstract: Understanding the relationship between species traits and their habitat has been recognized as a valuable tool to help predict lotic species' distribution and abundance. Traits that influence the presence and absence of a species will change along environmental gradients, making species with certain traits vulnerable to habitat degradation. Excessive sediment loading degrades habitat and directly impacts fish with traits that make them poorly suited for conditions. This study takes a heuristic approach to define species sensitivity to deposited sediment via functional traits related to feeding and reproduction based on prior studies for fish species throughout the Roaoke-Dan River Basin in the Piedmont Region of North Carolina and Virginia. We then analyzed co-occurrence patterns between traits and two snapshot measurements of deposited sediment, silt cover and embeddedness and compared these results back to our literature-based trait scores of sediment sensitivity. We analyzed these relationships through canonical correspondence analysis (CCA) and Kendal-tau correlation analysis utilizing fish and habitat surveys. Our results indicate that functional traits, particularly those associated with feeding preference and spawning behavior, may contribute to species responses to deposited sediment. Herbivory and nest association were negatively correlated, whereas generalism, omnivory, piscivory, and open water spawning was positively correlated with the presence of deposited sediment. Traits varied in their directional relationship to embeddedness and silt cover. Although species-level responses to sediment are likely shaped by their full composition of functional traits, the sensitivity analyses explored herein help identify which traits may be more influential in a species response and therefore species sensitivity to sediment deposition.

2.1 Introduction

Habitat is thought to provide the template on which life history evolves. Commonly referred to as the habitat concept (Southwood 1977; 1988), studies have found clear relationships between habitat and life history traits that influence species fitness (i.e., functional traits; (Poff and Allan, 1995; McGill, 2006) and others have suggested these relationships can be used to predict lotic species' distribution and abundance (Poff, 1997; Goldstein and Meador, 2004; Pease, 2015). Goldstein and Meador (2005) defined a species trait as a morphological, physiological, and/or behavioral expression of species' adaptations to their environment. Frimpong and Angermeier (2009) later extended this to include ecological and life history expressions (e.g. temperature and salinity tolerances) and suggested that these traits are the units through which evolutionary forces and ecological processes shape fish assemblages. Traits that influence the presence and absence of a species will differ along environmental gradients (Poff and Allan, 1995; Goldstein and Meador, 2004). For example, Pease et al. (2015) found species in pool habitats to have long gill rakers, which are typically associated with filter feeders that tend to frequent lower gradient, streams with larger pools (Gatz, 1979). They also found that larger streams with greater pool habitat and streams with high volumes of wood commonly had species with longer fins and deeper bodies, features that are thought to increase mobility (Gatz, 1979). In further support of the habitat concept, Blanck et al. (2007) showed fish to be smaller and short-lived with low fecundity in riffle habitats, which likely reflects the energy demands of high velocity habitats (Lamouroux et al., 2002).

Given the strong relationship between traits and habitat, it follows that the diversity of functional traits (i.e. functional diversity) is correlated with habitat diversity, quality, and naturalness (Pease et al., 2015). Functional diversity reflects the number, type, and distribution of functions performed by individuals within their ecosystem (Díaz and Cabido, 2001; Strecker et al., 2011). The more heterogeneous a habitat, the more available trait space, which supports greater functional diversity. Pease et al. (2015) found that the volume of functional trait space, quantified by species richness, correlated with indices of stream biological integrity and habitat quality index scores. Their study found functional trait space was higher in streams with less agriculture and urban development. As habitat becomes more homogenous, the diversity of traits supported may decrease; however, taxonomic diversity may remain the same or even increase as generalist species replace specialists (Strecker et al. 2011). Thus, assessing the diversity of species traits may provide a stronger indicator of ecosystem health or impairment than species diversity (Townsend and Hildrew, 1994; Hooper et al., 2005).

Functional diversity, and therefore ecosystem health, is at risk from habitat degradation and homogenization (Jelks et al., 2008). In a lotic system, habitat heterogeneity is partly driven by sediment supply and transport capacity. However, if a stream's sediment load becomes too high it can homogenize the stream substrate by covering available habitat with fine sediment, decreasing depth, and simplifying the channel morphology. Increased sediment loading is driving the decline of available fish habitat in the United States (Kemp et al., 2011), reducing the potential trait space species can occupy (Strecker et al. 2011; Pease et al. 2015), and is causing impairment to stream and river biota (USEPA, 2000).

High sediment loads have the potential to limit species' occupancy, depending on their traits. For example, Harding et al. (1998) showed that increased sediment loading from agricultural practices corresponded with a complete loss of species that forage or breed in streambeds. Further, species needing clean gravel and relatively coarse substrate to spawn have been shown to suffer from sediment deposition (Kemp et al., 2011). For example, the Orangefin Madtom, a species under review for federal protection, requires interstitial spaces between small cobble for spawning. This species is generally less abundant in stream reaches with higher silt cover, likely because silt fills the interstitial spaces it depends on (Simson and Neves, 1992). Along similar lines, Rainbow Trout are visual feeders that grow slower when high suspended sediment concentrations (i.e., turbidity) reduce prey capture (Shaw and Richardson, 2001). Moreover, the federally endangered Roanoke Logperch avoid areas of high sediment. This may be explained by use of their conical snout to access invertebrates under loose gravel; a feeding behavior that is characteristic of all logperches (Rosenberger and Angermeier, 2003).

On the other hand, some fish possess traits that enable them to benefit from increased sediment loading. For instance, some centrarchids and cyprinids and centrarchids excavate pits in soft sediment and have been found in higher abundance in sites with higher turbidity (Sutherland et al., 2002). Species may also indirectly benefit from sedimentation through reduced competition with species possessing silt-sensitive traits. Harding et al. (1998) found species that reside in the water column or actively clean sediment from their nests were able to replace benthic species in streams with higher sediment concentration. Similarly, species with tapetum lucidum, a reflective layer in the retina that increases light sensitivity, have increased foraging ability in turbid waters that has allowed them to outcompete other visual feeders for prey under turbid conditions (Kemp, 2011).

Like those cited above, studies linking habitat modification, traits, and population responses help fish ecologists understand anthropogenic influences on fish assemblages. Schwartz et al. (2011) provided critical insight on relationships between species functional traits and suspended sediment; however, few have attempted to explicitly link observed fish traits to in-stream sediment deposition. Using functional traits considered sensitive to sediment, we can assess how fish assemblages correspond to sediment and perhaps identify thresholds at which in-stream sediment deposition limits the presence of specific functional traits, and therefore species. Given sediment loading in human altered landscapes far exceeds preindustrial levels and is only expected to increase with further land cover and climate change (Kemp et al., 2011), a better understanding of the relationships between traits and in-stream sediment conditions can help fish ecologists predict how rare, endangered, hard to capture, and/or understudied species might be impacted by sediment. This would ultimately improve the cost-effectiveness of conservation and habitat restoration (Frimpong and Angermeier, 2010).

Species are representations of an array of traits; thus, their population responses likely cannot be distinctly linked to a specific trait. However, traits can be used to help identify general trends in community ecology (Frimpong and Angermeier, 2010) and may provide useful insight into how fish communities across geographic areas can be impacted by sediment. Despite growing concern over the impacts of increased erosion and sediment loading to lotic systems, there are few studies that focus explicitly on relationships between sediment and fish at their trait level. Schwartz et al. (2011) explored the relationship between traits and turbidity, but we have not come across studies explicitly focusing on in-stream sediment deposition. To better predict species sensitivity to sediment we explored relationships between functional fish traits and in-stream sediment deposition by conducting fish and habitat surveys throughout the Roanoke-Dan river basin of the Piedmont region of North Carolina and Virginia, an area with historically high fish diversity and in-stream sediment loads (Burkhead and Jelks, 2001; VADEQ, 2014), focusing specifically on riffle and run habitat, where benthic stream fish likely to be impacted by deposited sediment commonly reside. We focused our assessment on species reproductive and feeding traits and their relationships with silt cover and embeddedness, two common measures of in-stream sediment (Fitzpatrick et al., 1998). Our specific objectives were to 1) assign a sediment sensitivity score (low, moderate, high) to reproductive and feeding traits held by species within the study region based on prior studies 2) assess the relationship between trait occurrence and in-stream sediment deposition, and 3) compared the results from data analysis back to the literature-based trait scores . Given we expect observed trait-sediment relationships to be consistent across zoogeographic regions, (Poff and Allan, 1995, Pease et al., 2015), we suggest this analysis will inform conservation of lotic systems by helping to identify what species may be vulnerable to sediment deposition beyond the study area.

2.2 Methods

Fish surveys

We surveyed fish and habitat in 30 stream reaches throughout the upper Piedmont portion of the Roanoke and Dan River basins (Figure 1 in Chapter 2). Sites were sampled 2-4 times each throughout the summers of 2018 and 2019. Within each reach, we surveyed four to five cross-sectional transects (i.e. bank to bank) depending on the availability of riffle-run habitat. Block nets were set-up four meters apart on the downstream and upstream edges of each transect to prevent fish passage. We used a 0.6-m by 0.6-m PVC quadrat to frame samples of visual embeddedness and silt cover and estimated each to the nearest 20% of the quadrat that was covered by fine particles. We quantified silt cover as the amount of the stream's substrate surface that was covered by fine particles and embeddedness by how much of the substrate's interstitial spaces were filled with fine particles. For streams less than ten meters wide we collected five quadrat samples along the center line of the transect from right to left bank; for streams greater than ten meters wide we collected samples along each bank and then every two meters in between. After our visual habitat assessment of a transect was complete, we surveyed fish using a Smith Root LR 24 backpack electrofisher and a 2-m wide seine moving from the left bank to right bank so that the entire transect was sampled. We then collected any fish caught in the downstream block net. Fish were identified, counted and returned downstream of the block net. Complete details of our survey methods can be found in Ch. 2.

Trait sensitivity scoring

Using Frimpong and Angermeier (2009), that built a data base of ecological and life-history traits of freshwater fish, and Schwartz et al. (2011), which examined trait relationships with turbidity we identified a suite of focal traits that correspond to reproductive and feeding strategies based on their known connection to individual survival and reproductive/evolutionary fitness (Frimpong and Angermeier, 2010). As of this study, a list of sediment sensitivy scores have not been developed for species' traits. We used lists of previously observed species across the upper Piedmont portion of the Roanoke and Dan rivers provided from the Virginia Department of Game and Inland Fisheries and the North Carolina Wildlife Resources Commission to help define the range of functional traits we could expect to observe in our study area. We then organized these feeding and reproductive traits by attribute (ie., a collection of traits that relate to a single function, like feeding location). Using an extensive literature review, including Jenkins and Burkehad (1993), Rhode et al. (1994), Froese and Pauly (2019) and others (Table 2.1), each trait was assigned a sediment sensitivity score relative to other traits within the same attribute ranging from low to high.

We defined species feeding strategies by two attributes: location and preference. Within a stream, a species can feed at the surface, within the water column, and/or at or in the benthic substrate; these were classified as the traits. Since, sediment deposits at the bottom of a stream, we anticipated benthic feeding to be the trait most sensitive to sediment. Feeding preference consisted of generalism (varying diet), omnivory (both plant and animals), piscivory (primarily fish), herbivory (primarily plant material), and insectivory (primarily macroinvertebrates). Generalism included three or more of the following items: phytoplankton, filamentous algae, macrophytes, crustaceans, annelids mollusks, insects, and fish (Schwartz et al., 2011; Cocker et a., 2001). Generalism and omnivory were predicted to have low sensitivity to deposited sediment since they can likely adapt their feeding to what is available. Piscivory was predicted to be moderately sensitive to deposited sediment because some of their prey may be negatively impacted by sediment. Herbivory and insectivory are likely to be highly sensitive to sediment deposition because many plants and macroinvertebrates depend on benthic substrate that becomes covered by sediment. Further, sediment destabilizes and shifts benthic habitat, making it harder to support flora and fauna (Tebo, 1955).

Species reproduction strategies were defined by two attributes: spawning behavior and oviposition substrate. Spawning behavior which is modified from Balon's classification of reproductive guilds (1990) refers to how and where a species spawns its eggs and includes: egg scatterers (deposits eggs in water column of any substrate), nesters (deposits eggs in their nest), nest association (spawns on other species nests), and brood hiding (hides eggs in cavity or crevice). We expected egg scatterers, referred to now as open water spawners, that leave their eggs in the water column to be less sensitive to sediment as fish show no preference for specific substrate to spawn on and Schwartz et al. (2010) documented a positive relationship between open water spawners and turbidity. Egg scattering on specific substrate (e.g. rocks, gravel, sand, plants, etc.) will likely be moderately sensitive to deposited sediment. Although sediment will decrease the available substrate, these species, now referred to as substratum spawners, can likely tolerate some sediment because they do not rely on the crevices of substrate. Nesters are also predicted to be moderately sensitive because some excavate nest in soft substrate (e.g. Cyprinids) or clean sediment from their nest material (e.g. Nocomis). Nest association is likely to be highly sensitive to sediment deposition since nest availability will likely decrease due to sediment deposition. Brood hiding we rated it as highly sensitive because it depends on unfilled crevices to provide shelter to their eggs and Harding et al. (1998) documented a decrease in their abundance due to sediment. We chose not to look at parental care because a preliminary principal component analysis used to reduce the dimensionality of our dataset showed it not to load heavily on any of the data's principal components.

Oviposition substrate is the material on which fish deposit their eggs, including mud, vegetation, miscellaneous hard surface (logs, concrete, boulders, etc.), or gravel and cobble. Species that deposit their eggs on soft substrate will likely be unimpacted by sediment deposition (Sutherland et al., 2002). Species that spawn on miscellaneous hard surfaces are inherently flexible and likely not be greatly impacted by sediment. However, we suspect spawning on vegetation and gravel will likely be most impacted by sediment since sediment deposition would cover these surfaces.

Trait Occurrence

Each species observed during fish surveys represents a composite of feeding and reproductive traits. Following the methods of Schwartz et al. (2011), we translated species occurrence into trait occurrences by considering a trait present if a single individual of a species that posessed that trait was observed. We later refined this list to include only those traits that corresponded to species observed during 2018 and 2019 sampling (Table 2.1). If a species possessed a given trait they were assigned a "1" and if not a "0". For some attributes, it was possible for a species to receive a "1" for multiple traits within a given attribute (e.g feeding at water surface and water column). Using this data, we created a matrix where site was represented by row and silt cover, embeddedness, and number of trait occurrences were represented by columns. All trait occurrences were summed by site visit (n=105), which was treated as an individual record, and divided by species richness.

Data Analysis

We performed multiple Canonical Correspondence Analyses (CCA) to assess how functional traits correspond to sediment deposition. We assume species are a combination of all their traits, so we first performed a CCA relating silt cover and embeddedness to all the functional traits described in Table 2.2 to see if a particular trait, in the presence of all other traits, corresponded with silt cover and/or embeddedness. We then conducted a CCA seperately for all traits specifically associated with feeding and then reproduction, to evaluate if any traits, within these, corresponded with sediment deposition. Lastly, we ran an individual CCA for each of the functional trait attributes (e.g. spawning location) to assess within an attribute which traits most corresponds with silt cover or embeddedness. After we narrowed down our focus from all the traits that could comprise a species to the specific traits within an attribute that are most influenced by sediment deposition, we performed a Kendal-tau Correlation analysis between each trait and the sediment metrics to better understand the significance and directionality of the relationship between the functional traits and the sediment deposition metrics. With this finer resolution analysis, we can see how individual traits alone responded to just silt cover or embeddedness. We also used these correlations to validate the sediment sensitivity scores assigned to feeding and reproductive traits based on our literature review. If our score assignments were accurate, we expected traits with high predicted sensitivity to have significant and larger negative Kendal-tau coefficients compared to traits with medium and low sensitivity. In contrast, we also expected to find a significant positive, weakly positive, or non-significant relationship between low sensitivity traits and deposited sediment. Medium sensitivity was expected to fall somewhere in between high and low sensitivity traits. The CCAs and Kendal-tau Correlations were completed in R (R Core Team 2013) and the CCAs were built using the vegan package (Okansen et al., 2019).

2.3 Results

Trait Sensitivity Scores

We observed 48 species during 105 site visits in 2018-19. Each species observed was translated into the occurrence (1) or absence (0) of feeding and reproductive traits. Figure 2.1 provides a visual summary of the proportion of species with a given trait during the 2-year study period. The traits and their sediment sensitivity scores are organized by strategy and attribute in Table 2.2.

Canonical Correspondence Analysis

The coarse resolution CCA that included all traits showed that neither silt cover nor embeddedness significantly explained the variability of trait occurrences among the 105 site visits. The CCA focusing on feeding location and preference traits was significant and explained 5.1 % of variability. Examining this relationship more closely with a CCA that included only feeding preference traits, we found silt cover and embeddedness were significant factors collectively explaining 5.9% of variability in trait occurrence (Table 2.4). As suggested by the ordination diagram (Figure 2.2A), generalism and piscivory corresponded positively with silt cover and embeddedness whereas insectivory and herbivory corresponded negatively. Interestingly, omnivory corresponded negatively with silt cover and positively with embeddedness (Figure 2.2A).

We found no significant correspondence between silt cover or embeddedness when all reproductive traits were included in a CCA; however, embeddedness corresponded significantly with traits specifically associated with spawning behavior, explaining 4.5 % of variability (Table 2.4). Embeddedness had strong positive association with open water spawning and had weak negative association with nest building (a.k.a nesters). Silt cover, though it was not significant, had a slight positive association with substratum spawning and slight negative association with nest association in the ordination diagram (Figure 2.2B). Brood hiding was not associated with either silt cover or embeddedness (Figure 2.2B).

Kendall-tau Correlation Analysis

Kendal-tau correlation analysis was used to quantify and characterize the relationships between functional traits and sediment deposition metrics. These relationships were compared back to CCA results and prior studies from literature review. As expected, significant Kendall-tau correlations of silt cover and embeddedness with functional traits supported the same directional associations that were revealed from CCAs (Table 2.5). However, neither strongly supported the literature-based trait sensitivity scores defined in Table 2.2. Although the significant relationship for each trait was as anticipated (i.e. less sensitive traits had positive relationships, and more sensitive traits had negative relationships), the coefficients were relatively weak. Nest association, considered highly negative, was the only trait to have a significant negative correlation with silt cover.

2.4 Discussion

Trait occurrence is only partially explained by deposited sediment. Our results indicate that functional traits, particularly those associated with feeding preference and spawning behavior, may help explain species occurrence along a gradient of deposited sediment. Herbivory and nest association were negatively correlated, suggesting that species with these traits, potentially among other traits, may be negatively impacted by deposited sediment in riffle and run habitat. Generalism, omnivory, piscivory, and open water spawning were positively correlated with sediment, which may help explain the occurrence of species with these traits in areas with sediment deposition in riffles and run habitat. Unexpectedly, individual traits varied in their directional relationship to embeddedness and silt cover, as seen by species' occupancy in Chapter 2, which could be due to their mechanistic differences. Lastly, results from our field analysis did not confirm the pattern of trait sensitivity expected from the literature. In the subsections that follow, we discuss why: 1) trait variability might not have been explained by our sediment metrics 2) certain traits may have a stronger relationship with sediment deposition than others, and 3) traits differed in their response to silt cover and embeddedness. We conclude by describing how our sensitivity scores could be improved.

Trait Occurrence and Sediment

Feeding preference and spawning behavior, two of the five functional attributes predicted to be impacted by sediment deposition, corresponded significantly with silt cover and/or embeddedness, but little variation in the occurrence of these traits was explained by silt or embeddedness. However, given the statistical significance of the sediment metrics, it is plausible that species with these traits may be impacted in habitats with higher rates of sediment deposition, suggesting a non-linear relationship and the existence of sediment thresholds. Most of the sites had low to moderate sediment deposition and may not have captured the gradient needed to observe significant trait variability for all of these attributes (see Chapter 2 for a greater discussion of the sediment gradient our sites represented). While there are likely stream and river reaches that experience greater deposition, these were not accessible given our choice of fish survey methods. Other studies have shown species with these presumed sediment-sensitive traits to be negatively impacted by sediment deposition. Berkman and Rabeni (1987) demonstrated a decrease of benthic insectivory and herbivory in riffle communities as siltation increased and increased quantities of fine sediment have been clearly linked to decreased abundance of crevice spawning fish (Harding et al., 1998). Nest association was the only trait significantly and negatively correlated with a sediment metric in this study. These species may seek out these nest of other species, that are cleaned of sediment, for increased chance of egg survival (Johnston, 1991). If nests are not available, either due to competition or lack of nest builders, some may seek out clean gravel (Jenkins and Burkehead, 1993). Excess sedimentation will likely decrease the availability and increase the competition for both spawning habitats, making nest associates especially vulnerable to sediment deposition.

Albeit relevant, the current occurrence of functional traits is at most only partially explained by the observed sediment gradient. We suspect this can be explained by a combination of factors not included in this study. First, current variation of traits in the Piedmont region may be partially explained by non-sediment related environmental variables and/or evolutionary history (Walters et al., 2003). Second, we relied on rapid assessment (i.e. snapshot) measures of embeddedness and silt cover that may not fully capture chronic conditions of sediment deposition since this sediment may be washed away with a high flow event (Levasseur et al. 2006; Beschta and Jackson 1979). Other sediment metrics, like landscape factors (i.e floodplain and riparian characteristcs) or bank features (i.e. exposed tree roots and vegetation density) that influence sediment loading, may better explain the variability of traits; however, these broader metrics were not found to be of statistical importance to species occurrence (Appendix B, Table 2.).

Given the lack of studies that specifically focus on traits with respect to embeddedness and silt cover, we looked to studies of suspended sediment to better understand our observed relationships. Interestingly, Schwartz et al. (2011) found relatively strong negative relationships between elevated levels of suspended sediment frequencies with generalism, omnivory, and piscivory, whereas our results suggested positive correlations between deposited sediment and these feeding behaviors. We suspect this may be attributed to trait linkage. For example, many species with the aforementioned feeding preferences are generally visual feeders and turbidity can limit their ability to access resources. Given that suspended sediment deposits on the stream bed with decreased water velocity and turbulence, thereby decreasing turbidity (Henley et al., 2000; Wood and Arimitage; 1997), we suspect that depositional areas may act as a refuge for visual feeders. A similar pattern of results between Schwartz et al. (2011) and our study was demonstrated by the occurrence of herbivory. Our results revealed negative association with deposited sediment and herbivory, whereas Schwartz et al. (2011) found positive association with suspended sediment. Both deposited sediment and turbidity have negative effects on aquatic macrophytes (Ryan, 1991; Lloyde et al., 1987; Brookes, 1986), but our results suggest that herbivory may be more vulnerable to deposited sediment as opposed to suspended, demonstrated by Schwartz et al. (2011).

As initially posited, species with tolerant (low sensitivity) traits may benefit from sediment deposition. Generalism and omnivory had positive associations and correlations with silt cover and embeddedness. Species with these traits, such as hog suckers and redhorses, may favor areas with moderate sediment deposition to feed on organic matter. Similarly, open water spawners strongly associated and correlated with embeddedness. These direct relationships could be at least partially explained by a reduced risk of egg predation over embedded areas. Also, many open water spawners are r-strategists and energy is likely to be allocated to producing more eggs rather than finding better, non-embedded spawning habitat. Species with these positively associated traits may be more likely to increase in abundance than species with more sensitive traits in relation to sediment deposition. Thus, if sediment loading persists, communities will likely shift as fish with sediment tolerant traits replace fish with sediment sensitive traits, a trend supported in the literature (Kemp, 2011; Walters et al., 2003; Harding et al., 1998). Traits positively correlated with deposited sediment, such as generalism, omnivory, piscivory, and open water spawning (Table 2.5), are also common to generalist species. Habitat degradation, which could be caused by sediment deposition, is often associated with generalist species replacing specialist species (Walters et al., 2003; Wilson et al., 2008; Dunn and Angermeier, 2018), thus reducing the amount of specialist traits and decreasing functional diversity (Strecker et al. 2011).

Embeddedness vs. Silt Cover Influence on Traits

We initiated this study with the assumption that the visual measures of deposited sediment commonly used in rapid fish habitat assessments were correlated and would impact species and trait occurrence similarly. We were relatively surprised to find that the functional traits assessed herein differed in their response to silt cover and embeddedness. We suspect this may be attributed to mechanistic differences between the two metrics. Silt cover tends to be a more temporary form of sediment deposition as it rests on the surface of substrate, as opposed to embeddedness where sediment gets trapped in the crevices of substrate. Thus, silt cover has greater potential to become suspended again. This could help explain why embeddedness was significant in both the feeding and reproduction strategy CCAs where silt cover was only significant for feeding. Spawning is seasonal and takes place over a period of time, making it more likely to be impacted by longer lasting embeddedness than transient silt cover. As feeding is a year-round, daily activity, any form of sedimentation, can temporarily affect a fish's feeding strategy. Omnivory had a strong positive correlation and association with embeddedness but was only slightly negatively associated with silt cover. In contrast, piscivory showed stronger positive association and correlation with silt cover than embeddedness. As our study sites were focused on smaller streams suitable for our sampling methods, most of the fish captured were not large. Thus, we suspect these smaller piscivorous fish, like others, likely benefited from areas with suspended sediment for protection against visual predators (Gregory and Levings, 1998). This is further supported by Schwartz et al. (2011) who documented positive relationships between durations of suspended sediment and piscivory. The differing nature of embeddedness and silt cover is further evident in the negative correspondence between insectivory and embeddedness, but no correspondence with silt cover. We attribute this to the how embeddedness fills the interstitial spaces in coarser substrate that decreases habitat for macroinvertebrate prey (Burdon et al; 2013), making it a more threatening form of sediment deposition to insectivory.

Trait Predictions

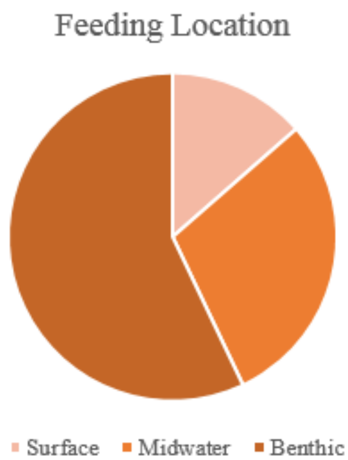
The pattern of trait sensitivity to sediment deposition was not as strong as expected. All the traits for which we inferred a high sensitivity, except for brood hiding, corresponded negatively with either silt cover, embeddedness, or both. Traits assigned lower sensitivity exhibited positive relationships with sediment deposition, and these relationships were surprisingly more significant than those with more sensitive traits. The negative and positive relationships observed corroborated our predictions from the literature review, but since they were not as strong as anticipated, it is possible that, as previously discussed, other factors, including other traits, are influencing species occupancy in relationship to sediment. Further our trait sensitivity scores may not accurately reflect vulnerability to sediment. We found generalism and piscivory, trait expressions for the feeding preference attribute, had similar associations and correlation coefficients with silt cover and embeddedness but varying sediment sensitivity scores based on the literature. This may be explained at least partially by the initial use of turbidity-based research to guide sensitivity scores given the paucity of studies published on deposited sediment (Bruton, 1985; Rowe and Dean, 1998). In retrospect and with the comparison of our results to Schwartz et al. (2011), we realize piscivory is probably more likely to be impacted by suspended sediment than deposited sediment. Therefore, we suggest a lower sensitivity score for piscivory. Although species-level responses to sediment are likely shaped by their full composition of functional traits, the sensitivity analyses explored herein helped identify traits that might be more influential in a species response and therefore species sensitivity to sediment deposition. This series of analyses could be used to shift species sensitivity scoring presented in Chapter 1 from an equal-weighted approach to a weighted approach that places greater emphasis on feeding preference and spawning behavior, attributes that showed the greatest association with deposited sediment. More research is needed on how strategies and traits relationships with sediment, especially deposited sediment, can be used to better predict species sensitivity.

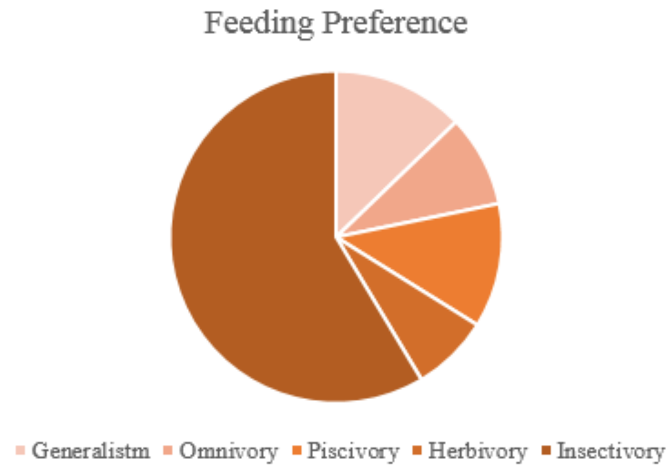
3.5 Conclusions

This study demonstrated reproductive and feeding traits, specifically feeding preference and feeding behavior, have significant but weak associations with sediment deposition in the Piedmont region of North Carolina and Virginia. We suspect these relationships may become stronger in areas with higher sediment deposition, suggesting a non-linear relationship and the existence of sediment thresholds. Our results, in concert with previous related studies, suggest certain traits, particularly generalism, omnivory, piscivory and open water spawning, may equip species to survive better in sediment-impacted areas than others. If this is the case, higher rates of sediment loading, which is predicted to increase with climate and land use change, will shift trait assemblage leading to a decrease in functional diversity. Although the magnitude of sediment loading into rivers will vary greatly across climates, geology, and land use practices (Walling and Moorhead, 1989), we suspect the trait relationships documented to be consistent. Anticipating the impact of sediment on lotic environments will continue to be a challenge, but by understanding sediment's relationship with traits and life history strategies we will be equipped to predict species sensitivity and potentially avoid irreversible loss of species diversity.

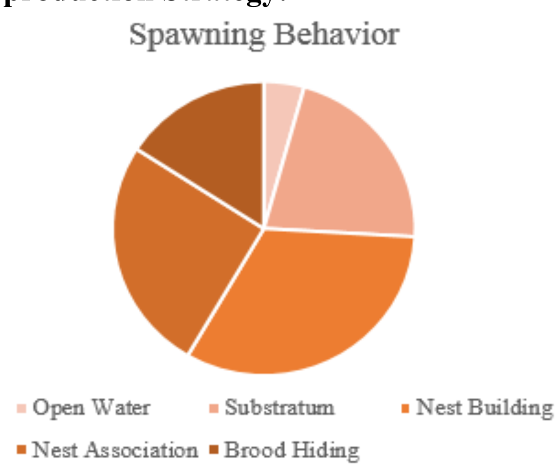
Ch. 2: Figures and Tables

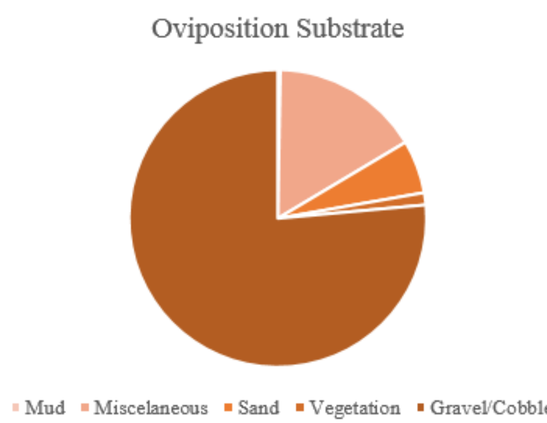
Feeding Strategy:





Reproduction Strategy:





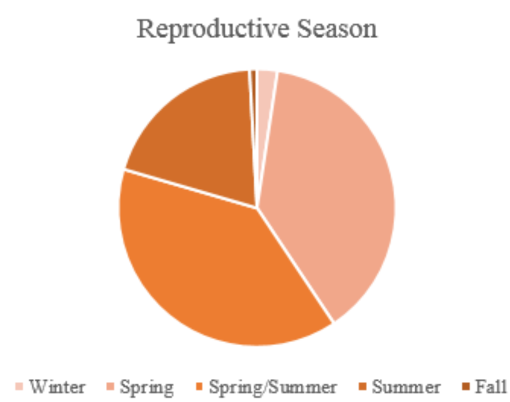


Figure 2.1 The proportion of traits that were observed for each attribute. The proportion of traits is composed of the number of species with that trait that were observed in the 105 site visits.

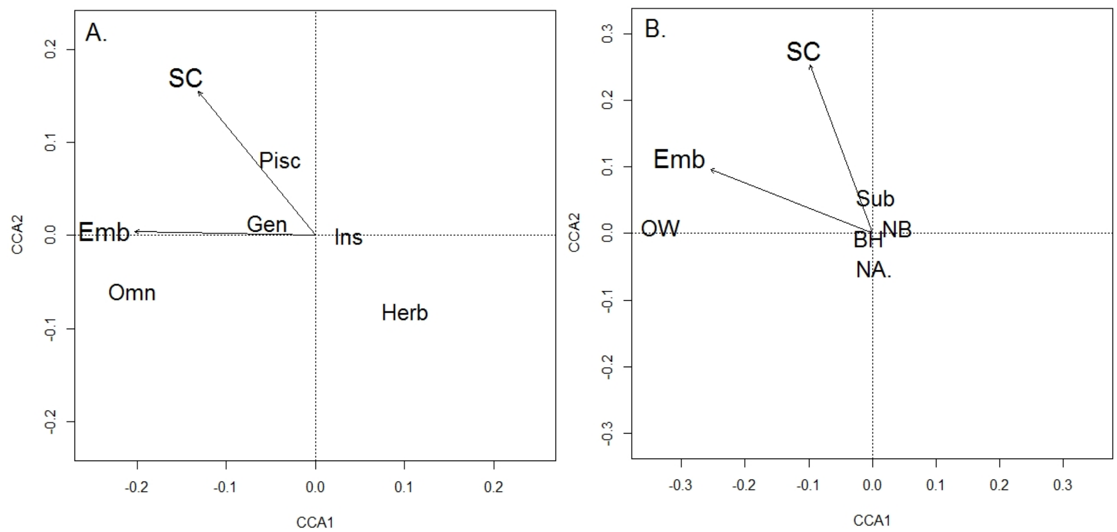


Figure 2.2. Ordination diagrams from significant CCA models showing the ordination of species traits along the first two axis and sediment deposition for (A) feeding preferences: generalism (Gen), omnivory (Omn), herbivory (Herb), piscivory (Pisc), and insectivory (Ins), and (B) spawning behavior: open water egg scatterer (OW), substrate egg scatterer (Sub), brood hider (BH), nest association (NA), and nester (NB) are located in relation to the influence of silt cover (SC) and embeddedness (Emb).

Table 2.1. List of species observed, frequency of observation (Obs), and traits analyzed for each species. All species' trait data was compiled from Jenkins and Burkehad (1993), Rhode et al. (1994) and Froese and Pauly (2019); source of any additional data for a given species is noted with a superscript. "FL"=Feeding Location. "FP"=Feeding Preference. "SB"=Spawning Behavior. "B"=Benthic. "M"=Midwater. "S"=Surface. "Gen"=Generalism. "Omn"=Ominvory. "Herb"=Herbivory. "Ins" & "I"=Insectivory. "Pisc" & "P"= Piscivory. "OW"=Open Water. "Sub"=Substratum. "NB"=Nester. "NA"=Nest Associate. "BH"=Brood Hider. "Grav & "G"=Gravel. "S"=Sand. "Veg" & "V"=Vegetation. "Misc"=Miscellaneous.

Family	Common Name	Species	Obs	FL	FP	SB	OS
Catostomidae	Quillback	*Carpiodes cyprinus*	1	B	Omn	OW	Grav
	Northern Hogsucker[1]	*Hypentelium nigricans*	5	B	Omn	OW	Grav
	Roanoke Hogsucker	*Hypentelium roanokense*	55	B	Omn	OW	Grav
	Bigeye Jumprock	*Moxostoma ariommum*	12	B	Ins	Sub	Misc
	Blacktip Jumprock[2]	*Moxostoma cervinum*	48	B	Ins	Sub	Misc
	Golden Redhorse[3]	*Moxostoma erythrurum*	7	B	Omn	Sub	Misc
	Rustyside Sucker	*Thoburnia hamiltoni*	5	B	Gen	NB	Grav
Centrarchidae	Roanoke Bass[4..]	*Ambloplites cavifrons*	19	M/B	I/P	NB	S/G
	Rock Bass[5]	*Ambloplites rupestris*	3	M/B	I/P	NB	S/G
	Redbreast Sunfish[6]	*Lepomis auritus*	19	S/M/B	I/P	NB	Sand
	Green Sunfish	*Lepomis cyanellus*	9	S/M/B	I/P	NB	S/G
	Bluegill Sunfish	*Lepomis macrochirus*	10	S/M/B	Gen	NB	S/G
	Smallmouth Bass	*Micropterus dolomieu*	3	M/B	I/P	NB	Grav
	Spotted Bass	*Micropterus punctulatus*	5	M/B	I/P	NB	Misc
	Largemouth Bass	*Micropterus salmoides*	9	M/B	I/P	NB	Misc
	Black Crappie	*Pomoxis nigromaculatus*	1	S/M	I/P	NB	V/G/S
Cottidae	Mottled Sculpin	*Cottus bairdii*	3	B	I/P	NB	Misc
Clupeidae	American Gizzard Shad	*Dorosoma cepedianum*	1	S/M	Gen	OW	V/G/S/M
Cyprinidae	Central Stoneroller	*Campostoma anomalum*	35	B	Herb	NB	Grav
	Mtn. Redbelly Dace	*Chrosomus oreas*	32	B	Herb	Sub/NA	Grav
	Rosyside Dace[7]	*Clinostomus funduloides*	62	S/M	Ins	NA	Grav
	Satinfin Shiner	*Cyprinella analostana*	18	S/M	I/P	BH	Misc
	White Shiner[8]	*Luxilus albeolus*	39	M	Ins	Sub/NA	Grav
	Crescnet Shiner[8]	*Luxilus cerasinus*	101	M/B	Ins	Sub/NA	Grav
	Rosefin Shiner	*Lythrurus ardens*	63	S/M	Omn	NA	Grav

	Bluehead Chub	*Nocomis leptocephalus*	103	M/B	Gen	NB	Grav
	Bull Chub	*Nocomis raneyi*	6	M/B	Gen	NB	Grav
	Comely Shiner	*Notropis amoenus*	9	S/M/B	Omn	NA	Grav
	Redlip Shiner	*Notropis chiliticus*	54	S/M/B	Gen	NA	Grav
	Spottail Shiner	*Notropis hudsonius*	9	S/M/B	Gen	Sub	S/G
	Swallowtail Shiner	*Notropis procne*	7	B	Omn	Sub	S/G
	Creek Chub[9]	*Semotilus atromaculatus*	2	M	Gen	NB	Grav
	Eastern Blacknose Dace	*Rinichthys atratulus*	5	S/M/B	Gen	Sub/NA	S/G
Ictaluridae	Flat Bullhead	*Ameiurus platycephalus*	8	B	Omn	BH	Misc
	Orangefin Madtom[10]	*Noturus gilberti*	8	B	Ins	BH	Misc
	Margined Madtom	*Noturus insignis*	95	B	I/P	BH	Misc
Percidae	Fantail Darter[11]	*Etheostoma flabellare*	102	B	Ins	NB	Grav
	Johnny Darter[12]	*Etheostoma nigrum*	58	B	Ins	NB	Misc
	Riverweed Darter[11]	*Etheostoma podostemone*	46	B	Ins	NB	Grav
	Glassy Darter[13]	*Etheostoma vitreum*	57	B	Ins	Sub	Grav
	Yellow Perch	*Perca flavescens*	1	M/B	I/P	Sub	Veg
	Chainback Darter	*Percina nevisense*	8	B	Ins	BH	Grav
	Roanoke Logperch[14]	*Percina rex*	8	B	Ins	BH	Grav
	Roanoke Darter[11]	*Percina roanoka*	90	B	Ins	BH	Grav
Poeciliidae	Eastern Mosquito Fish*	*Gambusia holbrooki*	1	S	Ins		
Salmonidae	Rainbow Trout	*Oncorhynchus mykiss*	2	M	I/P	NB	S/G
	Brown Trout[15]	*Salmo trutta*	10	M/B	I/P	NB	V/G/S

*Eastern Mosquito Fish is a liverbearer, a trait not included in our analysis.

1. Raney and Lachner, 1946 2. Thompson et al., 20153. Kwak and Skelly, 1992 4. Petrimoulx, 1983 5. Gross and Nowell, 1908 6. Helms et al., 2017 7. Hazleton and Grossman, 2009 8. Maurakis and Woolcott, 1993 9. Gradall et al., 1982 10. Simonson and Neves, 1992 11. Matthews et al., 1982 12. Propst and Carlson, 1989 13. Winn and Picciolo, 1960 14. Rosenberger and Angermeier, 2003 15. Scheurer et al., 2009

Table 2.2. Feeding and reproduction attributes and traits and their predicted negative impact to sediment deposition. “Sub”= Substrate. “OW”=Open Water.

Strategy	Attribute	Trait	Sediment sensitivity
Feeding	Location	Sace	low
		Water column	low
		Benthic	high
	Preference	Generalism	low
		Omnivory	low
		Piscivory	medium
		Herbivory	high
		Insectivory	high
Reproduction	Spawning Behavior	OW Egg Scatterer	low
		Sub Egg Scatterer	medium
		Nester	medium
		Nest Associate	high
		Brood Hider	high
	Oviposition Substrate	Mud	low
		Misc. Hard Sace	medium
		Vegetation	high
		Gravel/Cobble	high

Table 2.3. Canonical Correspondence Analysis (CCA) for each combined and individual feeding and reproduction functional trait attributes. Eigenvalues of the first two axis of each analysis and percentage of variance explained. Significance of the first canonical axis is included, * denotes significance (<0.05).

Functional Trait Attribute	Axis	Eigenvalue	Significance	% Cumulative Variance
All Feeding and Reproduction	I	0.003	0.23	1.9
	II	0.002	-	2.8
All Feeding	I	0.003	0.01 *	4.1
	II	0.001	-	5.1
Feeding Location	I	0.001	0.24	2.5
	II	0.000	-	2.7
Feeding Preference	I	0.006	<0.01*	4.6
	II	0.002	-	5.9
All Reproduction	I	0.003	0.45	1.3
	II	0.002	-	2.0
Spawning Behavior	I	0.005	0.04*	3.6
	II	0.001	-	4.5
Oviposition Substrate	I	0.005	0.38	1.6
	II	0.001	-	1.9

Table 2.4. Results from the feeding preference and spawning behavior CCA. Eigenvalues for the first two axes and the significance of sediment variable in significant attribute-based CCA models the model.

	Feeding Preference			Spawning Behavior		
	Axis I	Axis II	Variable Significance	Axis I	Axis II	Variable Significance
Silt Cover	-0.648	0.761	0.04*	-0.362	0.932	0.24
Embeddedness	-1.000	0.022	0.01*	-0.935	0.354	0.02*

Table 2.5. Coefficients and significance (p-value) of Kendall-tau correlations between functional traits associated with feeding preference spawning behavior and sediment metrics (silt cover and embeddedness). Terms in **bold** denote a significant correlation ($p < 0.05$).

Functional Traits	Silt Cover		Embeddedness	
	p	τ	p	τ
Feeding Preference				
Generalism	**0.05***	**0.14**	**0.02***	**0.16**
Omnivory	0.06	0.13	**<.01***	**0.27**
Piscivory	**0.05***	**0.14**	0.14	0.1
Herbivory	0.08	-0.12	0.23	-0.08
Insectivory	0.77	0.02	0.47	0.05
Spawning Behavior				
Open Water	0.57	0.04	**<.01***	**0.22**
Substratum	0.71	0.03	0.75	-0.02
Nester	0.22	-0.09	0.19	-0.09
Nest Associate	**0.04***	**-0.14**	0.06	-0.13
Brood Hider	0.13	0.11	0.21	0.09

Future Directions

Although silt cover and embeddedness did exhibit some significant relationships with species occurrences, it did not explain the variation that we anticipated. We expect this could be partly due to our sampling methods that limited us to reaches that were low to moderately impacted by sediment and that measurements of silt cover and embeddedness do not accurately measure chronic sediment loading. Newcombe and McDonald (1991), through a meta analysis, found that it was both the concentration and duration of exposure of suspended sediment that is crucial to aquatic biota. Just as species differ in our responses to silt cover and embeddedness, as shown here, species will differ in their responses to suspended and deposited sediment (Sherk et al., 1975), meaning we cannot rely on suspended sediment measures to capture the benthic habitat condition. Thus, there is a need to be able to measure both the concentration and duration of sediment deposition to see if we can capture the persistent impact of sediment on benthic habitat.

Future goals of this project are to provide analytical alternatives to predict benthic habitat condition. We attempted to use the cumulative soil loss metric derived from the RUSLE equation to capture more chronic, landscape-based measurement of sediment loading into a stream, which we found was a significant predictor of half of our species occupancy. This measurement does have potential to be a better predictor of pervasive sediment loading and a future goal of this project is to improve this equation's capabilities. However, both our preliminary analysis and Scott et al. (2016) showed that it did not significantly predict silt cover or embeddedness. Another future goal is to see how turbidity relates to silt cover and embeddedness, but as this data was collected sparingly it may not capture the persistent sediment or benthic habitat condition. This study could have better quantified the benthic habitat condition by taking more frequent measurements of silt cover and embeddedness within our study reaches, as opposed to 2-4 times throughout the year. As these infield measurements can be time and resource demanding, we thought better to use our resources to sample more sites and better represent the sediment gradient within our study region. This cost-benefit decision is one often made in fisheries management and speaks to the growing need of more cost-effective ways to measure sediment deposition. If we did have better sediment deposition metrics available, we may have captured more and stronger relationships between species occupancy and trait occurrences.

Although we did not see the magnitude we expected, our sediment metrics did explain some variability of species and species' trait occurrences. The traits that correspond to sediment deposition in Chapter 2, belonged to species whose occupancy correlated with sediment related variables in Chapter 1. For instance, embeddedness was a positive predictor of the Roanoke Hogsucker (Table 1.7), which is an omnivore and an open water spawner (Table1.4), traits that positively correlated with embeddedness (Table 2.5). Embeddedness was a negative predictor of both the Riverweed and Johnny Darter (Table 1.6), which are insectivores, a trait that negatively corresponded with embeddedness (Figure 2.2 A). These results show that traits could potentially influence species occupancy in relation to sediment. As species within families often have similar traits, like the Riverweed and Johnny Darter, understanding traits relationship with sediment will allow us to better understand how families will react to sediment loading.

Kemp et al. (2011) used an extensive literature review exploring indirect and direct impacts of sediment on fish to advise setting meaningful thresholds for setting sediment load targets in streams. They recognized family dependency as a constraint since different fish families will have both differing tolerances and requirements of sediment. We are optimistic that the insight we provide on trait sensitivity to sediment will build understanding of family relationships with sediment. Kemp et al. also identified sediment dependency as a hindrance for determining sediment loading thresholds as different type of instream sediment will have different effects on fish, so we hope this research informs management on fish's relationship with specifically sediment deposition.

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APPENDIX A: VARIATION OF SEDIMENT ACROSSS SITES

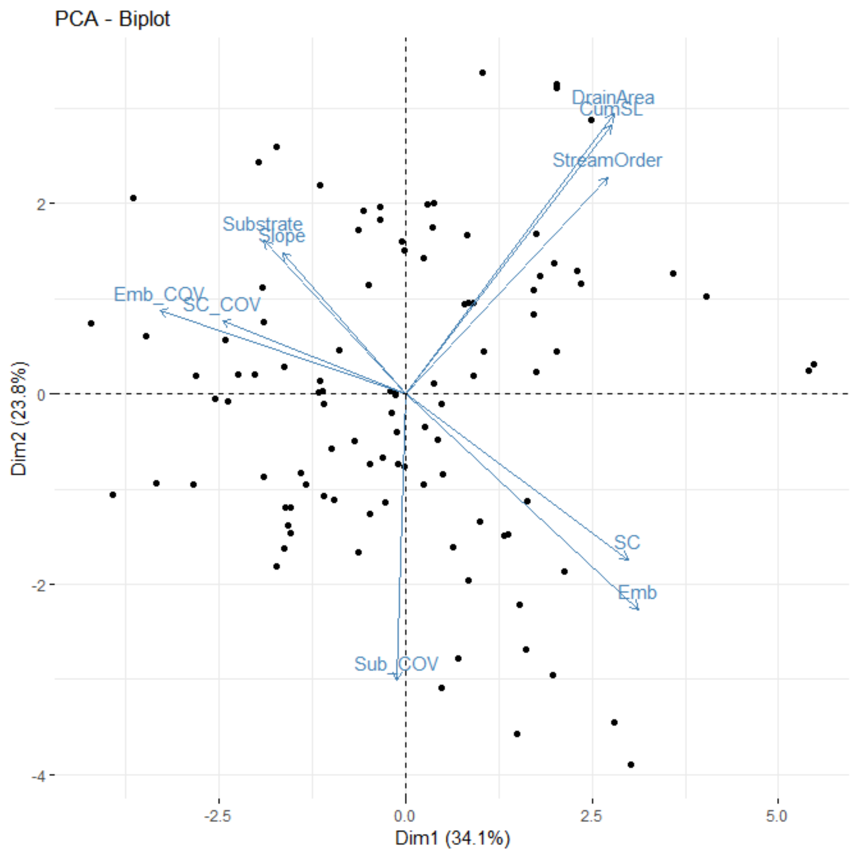

Figure 1. Biplot of Principal Component Analysis (PCA) plot of 29 sites during 103 visits in principal component space defined by 10 sediment-related variables. "COV" = coefficient of variation.

58% of the variation among sites was explained by the first two principal components that were predominantly attributed to six variables (Figure 1.4 and Table 1.2). The first principal component's, accounting for 34% of the variation, highest loading was embeddedness coefficient of variation (COV) which was negatively correlated to the next two highest loadings, embeddedness and silt cover. The second principal component's, accounting for 24% of variation, highest loading was substrate's particle size COV which was negatively correlated with the next two highest loadings drainage area and cumulative soil loss.

Variation within a site explains much variation across sites as COV, a metric explaining the variation among transects within a site for each sediment metric collected at the transect level, for two variables was the highest loadings for the first two principal components (Table 1.2). The 29 sites represented a well range of variation of embeddedness (COV) within a site as seen by the normal distribution in Figure 1.4. Most of our 29 sites had little variation of substrate size within its site (right skewed distribution) even though the variation range was greater than that of embeddedness COV.

Sediment deposition also explained much variation across our sites, as the two metrics directly measuring it, embeddedness and silt cover, had high loadings in the first principal component (Table 1.2). They were also correlated with each other. Embeddedness showed a normal distribution across our sites, where silt cover skewed heavily to the right (Figure 1.4).

Stream size related variables, drainage area and cumulative soil loss, had high loadings in the second component. Cumulative soil loss is the total sum of RUSLE's predicted soil loss of each catchment draining into the site. The larger the drainage area likely means more catchments draining into a given site leading to a larger cumulative soil loss estimate. Hence, drainage area and cumulative soil loss are highly correlated. Our sites represented a normal distribution of drainage area, with some missing representation of sites with larger drainage areas. Cumulative soil loss did skew to the right. The differing distributions of the two do allude that other watershed factors besides drainage area have important contribution in the predicted soil loss of a given site.

APPENDIX B: OCCUPANCY MODELS WITH OTHER SEDIMENT METRICS

Table 1. Percent of observed species with specified trait (vertical header) that were significantly related to sediment-related variables (horizontal header). Number of observed species noted in () beside each trait. Traits are listed in order of high (top) to low (bottom) potential sediment sensitivity for each attribute. "-" indicates no species with that trait had a significant correlation with that variable. FL: feeding location; FP: feeding preference; SB: spawning behavior; SS: spawning substrate; Ins: Insectivory; Pisc: Piscivory; Associat: Association; Cum SL: cumulative soil loss; COV: coefficient of variation.

		Cum SL		Silt Cover		SC COV		Embeddedness		Emb COV		Substrate		Sub COV		SC*Sub		Emb*Sub	
		+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
FL	Benthic (8)	0.11	0.33	-	-	-	-	0.11	0.22	0.22	0.22	0.11	-	0.11	-	0.22	-	0.22	-
	Nonbenthic (10)	0.10	0.30	0.10	0.10	-	0.10	0.10	0.20	0.10	0.10	-	-	0.10	-	0.10	0.10	0.10	0.10
FP	Herbivory (2)	-	0.50	-	-	-	-	-	-	0.50	-	0.50	-	-	-	0.50	-	-	-
	Insectivory (6)	0.14	0.29	-	-	-	-	-	0.43	0.14	0.29	-	-	0.29	-	0.14	-	0.29	-
	Ins/Pisc (6)	-	0.33	0.17	-	-	-	0.17	-	0.17	0.17	-	-	-	-	-	0.17	0.17	-
	Omnivory (2)	-	0.50	-	0.50	-	-	0.50	-	-	-	-	-	-	-	-	-	-	-
	Generalism (2)	0.50	-	-	-	-	0.50	-	0.50	-	-	-	-	-	-	0.50	-	-	0.50
SB	Nest Associat. (5)	0.20	0.40	-	0.20	-	0.20	-	0.20	0.20	-	-	-	0.20	-	0.20	-	0.20	0.20
	Brood Hiding (1)	-	-	-	-	-	-	1.00	-	-	-	-	-	-	-	-	-	-	-
	Nest Building (8)	-	0.38	0.13	-	-	-	-	0.38	0.13	0.38	0.13	-	0.13	-	0.13	0.13	-	-
	Substratum. (3)	0.33	0.33	-	-	-	-	-	-	0.33	-	-	-	-	-	0.33	-	0.67	-
	Open Water (1)	-	-	-	-	-	-	1.00	-	-	-	-	-	-	-	-	-	-	-
SS	Hard (14)	0.13	0.33	-	0.07	-	0.07	0.13	0.20	0.13	0.20	0.07	-	0.13	-	0.13	0.07	0.20	0.07
	Soft (1)	-	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Both (3)	-	-	-	0.33	-	-	-	0.33	0.33	-	-	-	-	-	0.33	-	-	-

Species' traits and sediment

Table 1 summarizes the proportion of species with a specific trait that were significantly related to sediment-related variables from each species' final occupancy model. Within each attribute, we expected the number of negative relationships to decrease from the most sensitive trait at the top to the least sensitive trait at the bottom and expected the number of positive relationships to increase from top to bottom. This pattern was not seen consistently for the attributes across the sediment-related variables. Also, if one particular trait could influence species occupancy, we would expect a large proportion of species with that trait (>50%) to be significantly positively or negatively correlated to one of the variables, but this was not seen for traits represented by more than three species. Little attention should be paid to traits with less than three species (herbivory, omnivory, generalism, brood hiding, substratum, open water, soft substrate, both hard and soft substrate) since it is unreasonable to interpret the proportions from such a small sample size. Thus, how species' occupancy responds to sediment cannot be explained by an individual trait alone but rather the combination of traits. Accordingly, we then ranked species as predicted to have low, medium, or high sensitivity to sediment deposition based upon the four attributes analyzed (Table 2.2).

Although we did not see a consistent trend among the attributes, a few traits had a greater proportion of negative relationships then others. Almost half of the insectivores' (0.43) and nest builders' (0.38) occupancies negatively corresponded with embeddedness. Also, a large portion of the nest builders' (0.38), Nest associations' (0.4), and hard substrate spawners' (0.33) occupancy inversely correlated with estimated cumulative soil loss.

APPENDIX C: OCCUPANCY MODELS WITH OTHER SEDIMENT METRICS

Table 1. Variables selected for final traditional fisheries habitat site level occupancy model. Values in bold denotes significance.

	Water Column Feeder								Generalist Bottom Feeder								Specialist Benthic Feeder							
	Rosefin Shiner		Satinfin Shiner		White Shiner		Rosyside Dace		Mt. Redbelly Dace		Blacktip Jumprock		Roanoke Hogsucker		Central Stoneroller		Roanoke Darter		Riverweed Darter		Johnny Darter		Glassy Darter	
	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P
Year			-5.844	0.089	0.352	0.123	-4.412	0.076			-3.754	0.081	-4.063	0.055			**5.532**	**0.064**						
Day			6.3	0.078			3.652	0.139	**-1.45**	**0.001**	4.244	0.053	**4.396**	**0.041**			**-6.193**	**0.042**			**-0.61**	**0.009**		
Slope									**0.598**	**0.034**					-0.487	0.082							0.323	0.163
Width			**0.747**	**0.029**	**0.532**	**0.028**	-0.488	0.112	**-1.493**	**0.002**									**0.712**	**0.009**			**0.649**	**0.022**
Depth	-0.477	0.083	-0.65	0.136					**1.602**	**0.001**			**0.539**	**0.05**										
Depth COV	**-0.821**	**0.015**					-0.883	0.012							**0.593**	**0.027**					-0.516	0.053	-0.556	0.08
HabCov									**-1.062**	**0.031**	-0.405	0.135												
HC COV													-0.386	0.089	**0.646**	**0.007**	0.616	0.1			0.377	0.098	**0.61**	**0.025**
Silt Cover	0.484	0.21			**0.695**	**0.027**			-0.761	0.208	**1.171**	**0.027**			-0.674	0.073			-0.252	0.542				
SC COV					0.527	0.086							0.45	0.072	-0.502	0.081								
Embed			**2.281**	**0.045**			**-2.066**	**<.001**	**-1.141**	**0.011**	1.228	0.043	**0.878**	**0.002**			0.935	0.316			**-0.748**	**0.017**	0.328	0.152
Emb COV																								
Substrate	0.077	0.811	0.678	0.63			-0.47	0.074	0.607	0.28	**3.687**	**<.001**			0.641	0.158	2.902	0.071	**1.306**	**0.037**	-0.64	0.213		
Sub COV					-0.439	0.096	**0.907**	**0.008**											0.506	0.081				
SC*Sub	**1.231**	**0.044**							1.592	0.098	**1.917**	**0.047**							1.449	0.063				
Emb*Sub			2.043	0.175							**1.616**	**0.048**					1.94	0.091						
R^2	0.13		0.185		0.154		0.355		0.465		0.252		0.212		0.212		0.181		0.217		0.142		0.204	
AIC	138.86		91.257		133.901		115.171		93.659		132.965		135.123		124.777		82.615		130.033		140.517		134.619	

Table 2. Variables selected for final sedimentology variables site level occupancy model. Values in bold denotes significance.

	Water Column Feeder								Generalist Bottom Feeder								Specialist Benthic Feeder							
	Rosefin Shiner		Satinfin Shiner		White Shiner		Rosyside Dace		Mt. Redbelly Dace		Blacktip Jumprock		Roanoke Hogsucker		Central Stoneroller		Roanoke Darter		Riverweed Darter		Johnny Darter		Glassy Darter	
	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P
Year			-4.412	0.093							-3.326	0.064					4.294	0.114					-2.895	0.114
Day			4.215	0.104					**-0.449**	**0.041**	3.466	0.054	**0.441**	**0.033**			-4.804	0.077			-0.445	0.051	2.745	0.133
Cumulative Soil Loss									-0.449	0.145											0.406	0.135		
Stream Order							0.304	0.161																
Pres Fine Sed Deposition			**-0.743**	**0.034**																			**-0.463**	**0.031**
Pres Wood							0.417	0.063					0.379	0.072			0.520	0.111						
Exposed Tree Roots	**0.448**	**0.033**																						
Pres Slump Blocks							-0.331	0.120																
Inverse Vegetation Density			0.508	0.117			-0.363	0.095													**0.485**	**0.047**		
Bank Steepness																	-0.441	0.154						
Riparian Shading Potential																			0.389	0.085				
Inverse Floodplain Erosion					0.449	0.054															0.380	0.116		
Floodplain Deposition																					**0.481**	**0.044**		
R^2	0.045		0.104		0.037		0.073		0.066		0.040		0.067		0.000		0.081		0.029		0.176		0.071	
AIC	140.545		95.766		138.365		144.184		127.810		146.597		144.091		135.668		87.588		144.618		135.792		144.951	

Table 3. Variables selected for final universal (fisheries and sedimentology) site level occupancy model. Values in bold denote significance.

		Water Column Feeder								Generalist Bottom Feeder								Specialist Benthic Feeder							
		Rosefin Shiner		Satinfin Shiner		White Shiner		Rosyside Dace		Mt.Redbelly Dace		Blacktip Jumprock		Roanoke Hogsucker		Central Stoneroller		Roanoke Darter		Riverweed Darter		Johnny Darter		Glassy Darter	
		Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P
Traditional	Year					0.352	0.123	**-0.867**	**0.005**	**-1.557**	**0.001**	-3.754	0.081	-2.930	0.156			**7.193**	**0.025**						
	Day			0.787	0.107							4.244	0.053	3.238	0.121			**-7.955**	**0.016**			**-0.611**	**0.019**		
	Slope									**0.969**	**0.011**					**-0.909**	**0.011**								
	Width					**0.532**	**0.028**			**-1.833**	**0.001**									**0.769**	**0.006**	-0.449	0.089	0.458	0.115
	Depth			**-1.722**	**0.009**					**2.084**	**<.001**			**0.659**	**0.019**										
	Depth COV	**-0.578**	**0.033**	**-1.902**	**0.008**			**-0.666**	**0.044**							**0.723**	**0.009**					**-0.727**	**0.030**	-0.423	0.150
	HabCov			-0.691	0.148					-0.765	0.101	-0.405	0.135												
	HC COV															**0.692**	**0.006**	**0.943**	**0.037**			0.438	0.079	**0.613**	**0.023**
	Silt Cover	0.493	0.237	1.006	0.102	**0.695**	**0.027**			-0.168	0.841	1.171	0.027	-0.632	0.079	-0.716	0.053			-0.348	0.433				
	SC COV					0.527	0.086			0.697	0.122					-0.521	0.070								
	Embed			**2.380**	**0.043**			**-2.094**	**<.001**	**-1.042**	**0.025**	1.228	0.043	**1.069**	**0.002**			1.104	0.254			**-0.885**	**0.005**	0.484	0.064
	Emb COV																								
	Substrate	0.089	0.829	1.678	0.266					0.827	0.197	**3.687**	**<.001**			0.680	0.148	**3.413**	**0.044**	**1.400**	**0.027**	-0.470	0.267		
	Sub COV			-0.808	0.067	-0.439	0.096	**1.083**	**0.002**											0.547	0.084			-0.455	0.085
	SC*Sub	**1.585**	**0.020**							**2.567**	**0.023**	**1.917**	**0.047**							**1.749**	**0.034**				
	Emb*Sub			3.219	0.065							**1.616**	**0.048**					2.289	0.056						
Nontraditional	CumSoilLoss			0.685	0.162			-0.573	0.064	-0.490	0.222											0.506	0.144		
	Stream Order			-1.161	0.060			**1.006**	**0.005**																
	PresFineSedDep			**-1.263**	**0.008**																			-0.474	0.059
	PresWood							0.470	0.094					0.419	0.064			**0.936**	**0.024**	0.444	0.092				
	ExpTreeRoots																								
	PresSlumpBlocks																								
	InvVegDensity			**1.123**	**0.012**			-0.629	0.029							-0.392	0.136					**0.563**	**0.031**		
	BankSteepness	**0.561**	**0.021**	-0.756	0.112					**0.778**	**0.045**							-0.693	0.073					-0.377	0.143
	RipShadingPot																			0.542	0.058				
	InvFPErosion																								
	FPDeposition															-0.498	0.074					**0.574**	**0.027**		
	R^2	0.152		0.402		0.154		0.406		0.529		0.252		0.213		0.275		0.242		0.285		0.274		0.251	
	AIC	136.101		88.170		133.901		110.522		92.898		132.965		135.041		122.037		79.396		125.637		131.189		131.900	

APPENDIX D: DENSITY MODELS

Table 1. Variables selected for final traditional fisheries habitat site level density model. Values in bold denotes significance.

	Water Column Feeder				Generalist Bottom Feeder				Specialist Benthic Feeder			
	Satinfin Shiner		Rosyside Dace		Mt. Redbelly Dace		Roanoke Hogsucker		Riverweed Darter		Johnny Darter	
	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P
Year	**-7.454**	**0.000**	-0.326	0.054	**4.555**	**0.005**	-2.474	0.057	**-0.475**	**<0.001**	**-0.470**	**0.007**
Day	**6.308**	**0.002**			**-4.957**	**0.003**	**2.752**	**0.035**				
Slope	0.689	0.094	**0.285**	**0.022**	0.231	0.133						
Depth	**0.369**	**0.030**	0.291	0.112							0.288	0.102
Depth COV	**-1.427**	**0.002**										
HabCov	**-0.613**	**0.031**	-0.292	0.059	**-0.679**	**0.029**					-0.269	0.150
HC COV							-0.213	0.127				
Silt Cover	-1.481	0.023									-0.112	0.583
SC COV	**-2.169**	**<0.001**					0.361	0.008				
Embed	-0.453	0.386	-0.496	0.061	**-0.940**	**0.008**	0.443	**0.003**	**-1.015**	**<0.001**	**-0.663**	**0.031**
Emb COV									**-0.352**	**0.008**	-0.324	0.070
Substrate	**-2.398**	**0.017**	0.706	0.105	0.600	0.307			**0.150**	**0.025**	-0.420	0.383
Sub COV	0.465	0.064	**0.361**	**0.026**			0.191	0.129			0.332	0.079
SC*Sub	**1.517**	**0.048**									**-1.080**	**0.002**
Emb*Sub	**-2.045**	**<0.001**	0.665	0.058	0.963	0.125					0.622	0.132
R^2			0.238				0.058		0.308		0.079	
AIC	155.560		496.117		295.460		339.733		354.339		430.995	

Table 2. Variables selected for final sedimentology variables site level density model. Values in bold denotes significance.

	Water Column Feeder				Generalist Bottom Feeder				Specialist Benthic Feeder			
	Satinfin Shiner		Rosyside Dace		Mt.Redbelly Dace		Roanoke Hogsucker		Riverweed Darter		Johnny Darter	
	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P
Year					3.703	0.099	0.210	0.112	**-0.550**	**<0.001**		
Day					-4.460	0.052					**-0.354**	**0.006**
Cumulative Soil Loss			**-0.254**	**0.045**	-0.422	0.152						
Stream Order												
Pres Fine Sed Deposition	**-0.715**	**0.027**	0.258	0.075	**-0.592**	**0.028**						
Pres Wood							0.184	0.134				
Exposed Tree Roots			**-0.289**	**0.043**	0.495	0.080			**0.325**	**0.042**	-0.278	0.114
Pres Slump Blocks			**-0.406**	**0.009**								
Inverse Vegetation Density	0.475	0.092									**0.329**	**0.035**
Bank Steepness					-0.423	0.069			-0.267	0.076		
Riparian Shading Potential												
Inverse Floodplain Erosion					**-0.368**	**0.047**						
Floodplain Deposition					**-0.497**	**0.049**					**0.394**	**0.017**
R^2			0.080				0.001		0.168		0.027	
AIC	156.430		518.857		310.486		348.099		378.302		425.257	

Table 3. Variables selected for final universal (fisheries and sedimentology) site level density model. Values in bold denote significance.

	Water Column Feeder				Generalist Bottom Feeder				Specialist Benthic Feeder			
	Satinfin Shiner		Rosyside Dace		Mt. Redbelly Dace		Roanoke Hogsucker		Riverweed Darter		Johnny Darter	
	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P	Coeff	P
Year			**-0.298**	**0.016**	**4.508**	**0.002**			**-0.814**	**<0.001**		
Day					**-5.138**	**0.000**					**-0.390**	**<0.001**
Slope							**-0.321**	**0.009**				
Depth	**-0.936**	**0.002**							**0.272**	**0.029**		
Depth COV	-0.654	0.174	-0.198	0.153							**-0.341**	**0.024**
HabCov			**-0.312**	**0.034**	**-0.680**	**0.022**						
HC COV									0.153	0.092		
Silt Cover	**0.978**	**0.007**					**0.555**	**<0.001**	**-0.641**	**0.001**	0.093	0.621
SC COV	**0.779**	**0.044**					**0.590**	**<0.001**	**-0.753**	**<0.001**		
Embed			**-1.062**	**<0.001**	**-1.149**	**<0.001**			**-0.774**	**<0.001**	0.215	0.499
Emb COV	**-1.089**	**0.031**					0.250	0.115			0.321	0.091
Substrate							**-0.585**	**0.016**	**0.161**	**0.004**	0.241	0.530
Sub COV	**-0.600**	**0.006**	**0.440**	**0.003**							**0.635**	**<0.001**
SC*Sub											**-1.376**	**<0.001**
Emb*Sub											**1.641**	**<0.001**
Cum Soil Loss	0.605	0.057	**-0.471**	**0.009**			-0.221	0.161	0.225	0.069		
Stream Order	**-1.202**	**0.015**	**0.684**	**<0.001**			**0.759**	**<0.001**	**-0.298**	**0.042**	**0.222**	**0.027**
Pres Fine Sed Dep	**-1.345**	**0.001**										
Pres Wood												
Exp Tree Roots									**0.355**	**0.002**	**-0.555**	**<0.001**
Pres Slump Blocks											**-0.333**	**0.015**
Inv Veg Density	**0.682**	**0.027**	**-0.275**	**0.010**	0.331	0.110	-0.207	0.092			**0.415**	**0.009**
Bank Steepness	-0.517	0.082	**-0.293**	**0.014**	**-0.489**	**0.037**	**-0.360**	**0.008**	**-0.270**	**0.009**		
Rip Shading Pot												
Inv FP Erosion									0.155	0.118		
FP Deposition					-0.316	0.149			**-0.317**	**0.017**	**0.760**	**<0.001**
R2			0.223				0.518		0.140		0.009	
AIC	145.990		488.626		291.962		325.360		350.159		413.590	

APPENDIX D: CANONICAL CORRESPONDENCE ANALYSIS BETWEEN TRAITS AND SEDIMENT DEPOSITION AT THE TRANSECT LEVEL

Table 4. Canonical Correspondence Analysis (CCA) for each combined and individual feeding and reproduction functional trait attributes at the transect level. Eigenvalues of the first two axis of each analysis and percentage of variance explained. Significance of the first canonical axis is included, * denotes significance (<0.05).

Functional Trait Group	Axis	Eigenvalue	Significance	% Cumulative Variance
All Feeding and Reproduction	I	0.002	0.07	0.5
	II	0.000	-	0.6
All Feeding	I	0.001	0.05*	0.6
	II	0.000	-	0.8
Feeding Location	I	0.001	0.02*	1.5
	II	0.000	-	1.5
Feeding Preference	I	0.001	0.29	0.4
	II	0.001	-	0.6
All Reproduction	I	0.002	0.08	0.6
	II	0.000	-	0.6
Spawning Behavior	I	0.002	0.34	0.4
	II	0.000	-	0.4
Oviposition Substrate	I	0.006	<0.01*	1.2
	II	0.000	-	1.2
Reproductive Season	I	0.001	0.65	0.2
	II	0.000	-	0.2

Table A.5. Results from significant CCA models at the transect level for the environmental variables. Eigenvalues for the first two axis and the significance of the variable in the model.

	Feeding Location			Spawning Substrate		
	Axis I	Axis II	Term Significance	Axis I	Axis II	Term Significance
Silt Cover	0.133	-0.991	0.57	0.448	-0.894	0.23
Embeddedness	0.825	-0.565	<0.01*	-0.370	-0.929	<0.01*

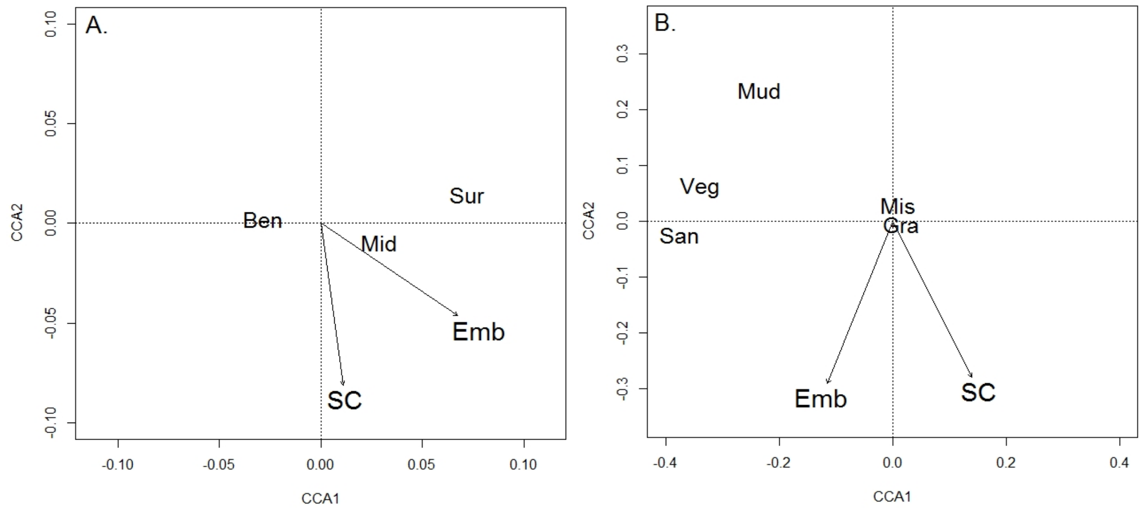

Figure A.2. Ordination diagrams from the significant CCA models at the transect level. In Figure A, feeding location: Surface (Sur), midwater (Mid), and benthic (Ben) and in Figure B, spawning location: mud (Mud), vegetation (Veg), sand (San), Gravel/Rock (Gra), and miscellaneous (Mis) are located in in relation to the influence of silt cover (SC) and embeddedness (Emb).