Spatiotemporal Dynamics of Interstitial Sediments and Mussel Populations in the South Toe River

By

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ABSTRACT

Sedimentation is widely-cited as having impacts to freshwater biodiversity but quantifying sediment composition at a scale that is meaningful to interstitial invertebrates like freshwater mussels can be challenging, especially in streams with coarse substrates. The South Toe River is a headwater of the Tennessee River in western North Carolina that supports one of only a few extant populations of endangered Appalachian elktoe mussels. As part of a larger project to assess the impacts of a highway expansion project on this stream and its mussel populations, we are monitoring surface and interstitial sediment composition using freeze-core sampling. Mussel populations, instream habitat including substrate composition and interstitial sediments were quantified at six sites in the South Toe River during spring and summer sampling. Freeze cores were collected by pounding galvanized iron tubes into the streambed and filling them with crushed dry ice. Tubes were left in place for 20 minutes before being extracted from the substrate. Sediments adhering to each tube were removed, dried, sieved and weighed. We computed the proportion of each sediment size fraction retained on sieves. We also gathered historical mussel data for each site. Interstitial sediments contained significantly more fine substrates at one site immediately downstream of Little Crabtree Creek (LCC), a sediment-impacted tributary. Elktoe populations at all sites downstream from LCC declined between 2013 and 2015 and while 2016-2017 surveys revealed that populations at two sites appear to be recovering, mussel populations at the site immediately downstream from LCC have continued to decline. These data suggest that chronic sediment impacts to mussels in the South Toe River appear localized and that populations appear to be recovering at some downstream sites. However, continued sediment inputs into LCC and the South Toe River will likely have negative impacts on mussel populations in downstream reaches.

INTRODUCTION

Sedimentation, defined as the deposit of organic and inorganic particles on a riverbed, is a natural process that may be dramatically altered by land use change and other human activities. Altering the composition of stream sediments by increasing the concentrations of fine (sand and silt) particles is widely believed to be detrimental to water quality and ecosystem health. A report released by the US Environmental Protection Agency (1990) listed sedimentation as one of the most harmful and widespread stressors in US streams (Ritchie 1972, Lemly 1982). Another EPA report (EPA 1994) found that silts (particles <0.0625mm) had the greatest negative effect on water quality in US streams.

Several physical and chemical mechanisms are involved with fine particle impacts to stream habitats and biota. Fine sediments can occlude interstitial spaces between gravel and cobble particles leading to the formation of hardpan or armored stream channels (Gordon et al. 1992). Armored channels have decreased interstitial flow rates (Brim-Box and Mossa 1999) which result in decreased interstitial DO and pH and concurrent increases to pore water ammonia concentrations (Wood and Armitage 1997, Augspurger et al. 2007). Sedimentation is typically associated with several anthropogenic activities, including livestock grazing/agriculture (Henley et al. 2000), forest clearing (Pandolfi 2016) removal of riparian vegetation (Wood and Armitage 1997) and road construction (Henley et al. 2000).

Sedimentation can impact sensitive biota in aquatic communities and has been a proposed cause of mussel population declines since the late 1800s (Kunz 1898, Henley et al. 2000). Although habitat preferences, including substrate size preferences appear variable among mussel species (reviewed in Ellis 1936 and Harman 1972),numerous studies have found that fine particles appear detrimental to mussels. Silts and clays can occlude gill surfaces, interfere with filter-feeding and stress brooded larvae (Ellis 1936, Aldridge 1987). Brim-Box and Mossa (1999) reported that sedimentation may indirectly affect mussel feeding by reducing the amount of photosynthetic food available and smaller particles may reduce mussel recruitment (Osterling et al. 2010, Kreutzweiser and Capell 2001).

The Appalachian elktoe (*Alasmidonta raveneliana*) is a freshwater mussel endemic to the upper Tennessee River drainage in western North Carolina and eastern Tennessee (Clarke 1981). The Appalachian elktoe was listed as endangered under the Endangered Species Act in November 1994 (USFWS 1994). Fewer than a dozen isolated populations occur in the Little Tennessee and Nolichucky river basins. The South Toe River in Yancey County, NC supports one of the largest remaining Appalachian elktoe populations (USFWS 2009).

Appalachian elktoe populations were not detected in the South Toe River until 1998 and based on a recent five year review for the species completed by USFWS, this stream appears to support one of the few populations that has increased (USFWS 2009). In 2012, NCDOT began a project to expand US Highway 19E between Spruce Pine and Burnsville, North Carolina from a two-lane to a four-lane highway. Highway 19E crosses the South Toe River near the upper range limits for Appalachian elktoe in this stream and thus sediments originting from highway construction activities have the potential to affect downstream populations. A recent analysis of Appalachian elktoe habitat associations in the Nolichucky River Drainage found that abundance was negatively correlated with the proportion of fine particles (i.e., sands and silts) at a site (Pandolfi 2016).

METHODS

Study Sites

The South Toe River is a tributary of the Toe and Nolichucky rivers that begins on the eastern slope of Mount Mitchell (elevation 2,037 m) the highest point in the Eastern United States. The right and left prongs of the South Toe join near Celo, North Carolina. The river then flows north through Yancey County before joining the North Toe river near Kona, NC. The South Toe is considered one of the most pristine rivers in the Southeastern United States and is classified an outstanding resource water (ORW) due to its location in Mt. Mitchell State Park and the Blue Ridge Parkway (NCDEQ 1987). The South Toe river supports a number of sensitive species including the Appalachian elktoe, the Blotchside logperch (*Percina burtoni*) and the Eastern hellbender (*Cryptobranchus alleghеniensis*, NCWRC Strategic Wildlife Action Plan 2015).

My study examined six sites in the South Toe River where USFWS and NCWRC have been regularly monitoring Appalachian elktoe populations since 2003 (Figure 1). Each site is 150 m long and all sites are ~1000 m apart. Sites 1 and 2 are located upstream of the US Highway 19E bridge and sites 3-6 are located downstream of the US Highway 19E bridge. Site 4 is located downstream of Little Crabtree Creek, a third order tributary that flows parallel to the highway cut for several hundred meters before joining the South Toe River. Site 5 is located ~500 m downstream of the new Yancey County Wastewater Treatment Facility and Site 6 is located another 2 km downstream of Site 5.

Freeze Cores

I collected freeze cores at each site seasonally starting in May 2017 and ending March 2018. At each site, I collected six cores within the 150 m study reach, with the general location of the cores within the reach remaining consistent across seasons. I modified Marchant and Lillywhite's (1989) freeze coring technique. I filled galvanized iron pipes (19.05 mm internal diameter) but used solid CO_2 (dry ice) instead of liquid CO_2. I pounded tubes into the substrate using a post-pounder and filled each of them with ~2.3kg. of dry ice over a 20-minute period (Adkins and Winterbourne 1999). Packing dry ice firmly into the tubes using wooden dowel rods ensured that blockages did not form near the top of the tubes and appeared to greatly increase success rates. After 20 minutes cores were removed from the substrate and I used a butane torch to remove frozen sediment from tubes. Sediments were retained in freezer bags and returned to the laboratory for analysis.

Processing

In the lab, we quantitatively analyzed the sediment samples using a series of sieves and a shaker table. Before we could do anything else, we calculated the average dry weight of our aluminum pie plates, 17.47g for the first two rounds and 17g for the last two, which we used to hold the sediment during weighing. Each sample was placed in a drying oven set at 180^{o}F for ~48 to 72 hours. Once the samples were dry, we ran each sample through sieves, sizes:3.35mm, 2mm, 500µm, 250µm, 125µm, and <125µm, on a shaker table for one minute. Each size category was weighed using an Ohaus 6000g x 1g scale (being sure to subtract the weight of the aluminum plate). The total weight of the sample was calculated and used to determine the percentage of each size category within the sample.

Statistical Analysis

I used the particle grading scale from Gordon et al. (1992) to determine the cuttoff point for fine sediments. I defined fines as particles <125µm which includes very fine sand as well as all silts and clays. I calculated the percentage of fine sediment (percent fines) in each freeze core sample at each site for each season. Because GLMs revealed significant interactions between site and season I used 1-way ANOVAs to determine whether fines differed among sites and seasons. I used an LSD post hoc test to determine whether sites and seasons differed from one another. I also computed the coefficient of variation for interstitial fines at each site for the period of record by dividing the standard error of mussel abundance by the mean abundance.

I gathered PAWS data dating back to 2003, to examine changes in mussel abundance at each site. I examined temporal trends in total and site-scale mussel abundance in the South Toe River. Additionally, I used regression analyses to generate a slope for the mussel population growth trend at each site by regressing mussel abundance on year. I also used correlations to examine the associations between interstitial fines and mussel abundance and growth trends. All analyses were conducted in SPSS (Version 24, IBM).

RESULTS

Composition of interstitial gravel substrates across site and season revealed significant differences in the proportion of fine substrates in freeze core samples. The site directly downstream from the confluence of Little Crabtree Creek had the highest proportion of fine substrates. ANOVA revealed that while among-site variability was significant both among and within seasons. Comparisons across all sites and seasons indicate that site 4 had a significantly higher proportion of fine substrate compared to all other sites ($p = <0.001$) (Figure 2).

Seasonal changes to substrate composition were variable among sites (Figure 3). At Site 1 (the upstream-most site) the percentage of fine particles decrease from Spring to Summer 2017 and then increased during Fall 2017 and Winter 2018. At Site 2 fines increased from Spring to Summer 2017 and remained stable through Winter 2018. Just downstream from the 19E crossing at Site 3 fines increased from Spring to Fall 2017, and then decreased during Winter 2018. Fines at Site 4 were relatively high in Spring 2017, but then increased during Summer and Fall 2017, before decreasing in Winter 2018 to near Spring 2017 levels. The interstitial fines at Site 5 remained stable from Spring to Summer 2017, then increased in Fall 2017, and were stable through Winter 2018. At Site 6, the downstream most site, I observed a decrease in the proportion of fines from Spring to Summer 2017, which then increased during Fall 2017 and Winter 2018.

Examination of the number of Appalachian elktoe collected during the past 15 years shows an oscillating trend for the period of record (Figure 4). The mean abundance of mussels was variable among sites, with site 2 having the highest (61.45 per survey) and Site 1 having the lowest (8.75 per survey, Figure 5). The mean mussel abundance at each site was also variable between years (Figure 6). Mussel abundance at Site 1 was relatively low and stable but increased dramatically in 2014 and 2015. Although catch rates have fluctuated at Site 1, abundance during the last survey in Fall 2017 found that abundance at Site 1 remained higher than pre-2015 levels. The exact same trend was found as site 2, with relatively low but stable numbers dramatically increasing in 2014 and 2015, before fluctuating slightly, but maintaining abundance higher than pre-2015 levels. Downstream of 19E, Appalachian elktoe abundance increased from 2005 to 2008 but declined in 2014. Mussel abundance at Site 3 then increased in 2015 before declining slightly in 2016 and finally increasing in 2017. At Site 4, immediately downstream of Little

Crabtree Creek, mussel numbers remained relatively high through 2012 but have declined through 2017 (Figure 7). Just downstream at Site 5 mussel numbers were relatively low in 2012, increase sharply in 2014, declined in 2015 and 2016 and then increased in 2017 to levels greater than those observed in 2012. Site 6 supported relatively high numbers of mussels but abundance sharply decrease in 2015. Although abundance at Site 6 has increased steadily since 2015, numbers remain below pre-2015 estimates.

Although comparisons of fine substrate data with mussel abundance did not reveal any statistically significant trends, however trends were likely biologically meaningful. Regression analysis found that the slope of mussel abundance trends at my study sites showed a strong negative association with increased concentrations of interstitial fine sediments ($R^2 = 0.46$; $P = 0.10$; $F = 4.674$; DF =1, 5; Figure 8). Additionally both the mean percentage of interstitial fines at each site (mean of all seasonal measurements) and the variability of interstitial fines appear to be reasonably strong (given the small sample size) predictors ($R^2 = 0.46$; $P = 0.14$; $F = 3.39$; and $R^2 = 0.48$; $P = 0.13$; $F = 3.68$ respectively, both DF = 1, 5; Figures 9 and 10) of mean mussel abundance at study sites in the South Toe River.

DISCUSSION

The proportion of fine particles in interstitial substrate samples was generally low (<5%) at sites in the South Toe River and showed minimal seasonal variability. However, the concentration of interstitial fines was significantly higher at Site 4 compared to all other sites. Site 4 is located immediately downstream of the Little Crabtree Creek confluence. This sediment-impacted stream transports fines from both the highway corridor and an active pasture to the South Toe River. Mussel abundance at Site 4 has declined for the period of record, possibly in response to interstitial fines, however populations at sites further downstream appear to be recovering following declines observed in 2014-2016 suggesting sediment impacts may be transitory.

Interstitial Fine Substrates

Blue Ridge streams are characterized by naturally low levels of fine substrates (Glenn 1911). The South Toe River is a classic Blue Ridge stream in that fine substrates typically comprise < 10% of surface substrates and <5% of interstitial substrates (Pandolfi 2016, Figures 2 and 3). Changes to the composition of both surface and interstitial fine substrates have been shown to negatively affect freshwater mussel populations. At extreme levels, Vannote and Minshall (1982) showed that bedload movements in Rocky Mountain streams can burry entire mussel beds and Tucker (1996) showed that shifts in channel morphology can result in large-scale mussel strandings. Additionally, Gangloff et al (2009) studied the effects of chronic bedload impacts and water quality impairment and found that sentinel mussels placed downstream of urbanized Piedmont tributaries exhibit reduced survival compared to upstream controls.

Although mussel populations appear to have declined in response to fine sediment inputs at sites downstream of Little Crabtree Creek confluence, the mechanism for these declines remains unclear. It is possible that any combination of: decrease in substrate stability (Arbuckle and Downing 2002, USFWS 2011), increase in stream temperature (Pandolfi 2016), burial (Vannote and Minshall 1982), and interference of filter feeding (Aldridge et al. 1997), among other possibilities, could be the mechanism driving these population declines. Experiments are needed to determine whether fine sediments directly or indirectly impact mussel survival downstream of Little Crabtree Creek.

My research in the South Toe River found trends that were parallel to published studies that examined effects of surface substrate conditions (Brim Box and Mossa 2002). However, few published studies have examined mussel interstitial habitat use and no prior studies have used freeze-cores to quantify interstitial substrates in mussel habitat. More work using this methodology is needed to better understand the applicability and relevance of freeze core data to freshwater mussel population and life history dynamics.

Appalachian Elktoe Abundance

Overall, Appalachian elktoe abundance in the South Toe River appears to be increasing. Although catch rates exhibited some among and within year variability between 2003 and 2017, the mean mussel abundance for each study year gradually increases. Additionally, although the CV of Appalachian elktoe abundance was similar among sites it was highest at Site 1 suggesting that this population has changed the most, relative to its median size, over the period of record. This may be explained by the location of the site- Site 1 is the farthest upstream site and survey data suggest this is the upper edge of the Appalachian elktoe's range in the South Toe River. In contrast Site 5 had, for the period of record, the highest median mussel abundance and the lowest CV.

Mussel abundance at sites upstream of the US Highway 19E bridge (Sites 1 and 2) appears to have increased relative to historical numbers. Although Site 2 currently has the largest Appalachian elktoe population, this is likely due to the fact that mussels were relocated from the footprint of the Highway 19E bridge and translocated to this reach beginning in 2013. Examination of population trends at sites downstream of the Highway 19E crossing revealed a similar trend for site 3, the site directly downstream of the bridge. Sites further downstream, however, reveal contrasting trends. Although populations at sites 5 and 6 increased during recent surveys, populations crashed at these sites sometime between 2008 and 2013-15 surveys. Additionally, Site 4 experienced a similar crash subsequent to 2012 surveys but that population has not yet shown signs of rebounding.

Conclusion

Taken together these data suggest that Appalachian elktoe populations in the South Toe River are sensitive to changes in interstitial substrate composition or some other factor associated with highway construction in the 19E corridor. Although there was relatively little evidence of fine sediment loading at the site 500 m downstream of the 19E crossing (Site 3) the concentrations of fine sediments were much higher at Site 4 located just downstream of the Little Crabtree Creek confluence. Site 4 provides a textbook example of stream substrates that have been heavily impacted by sedimentation.

On a more hopeful note, the temporal trends in fine substrate abundance suggests that habitat conditions at most sites in the South Toe River will likely return to pre-construction conditions. Interstitial fine sediments appear to be variable among sampling events and may track seasonal flow conditions. However, the timing of mussel recovery in the South Toe is unclear and will likely depend on the duration of activities in the 19E corridor and the extent to which legacy sediment exports by Little Crabtree Creek can be mitigated. Despite elevated levels of interstitial fines at sites downstream of 19E mussel abundance appears stable at most sites that experienced declines between 2012 and 2015.

Site 4 may be an exception. The proportion of fine particles was significantly higher at this site during all seasons. Moreover, freeze cores collected at this site are visually striking and have the appearance of concrete due to the high levels of fines in the samples (Figure 11). Upstream of its confluence with the South Toe, Little Crabtree Creek flows for ~10 km through the Highway corridor and then through an active cattle pasture, therefore compounding the amount of sedimentation (Wood and Armitage 1997). These sediments have not only altered interstitial substrates at Site 4 but they have also altered the hydro-morphology of the channel by expanding the extent of the run habitat at the upstream end of this site through large amounts of deposition of sand and other sediments, which is consistent with deposition patterns found in other south Appalachian streams (Price and Leigh, 2006). This deposition of sand and other fine particles is detrimental to Appalachian elktoe, as they prefer coarser, relatively silt free, stable habitats (USFWS 2011). Sediment deposition has also altered the geomorphology at the midpoint of the reach through the formation of a large point bar, which decreases the channel size and increases the flow on the outer bank (Thorne and Furbish 1995), and routes sediment around the upstream end of the bar (Legleiter et al. 2011). Most of the mussels found at this site are found on the outer bank of the river, where bedrock stabilizes their habitat and protects from high flows, whereas Sediment deposition and shifting substrates prevents the mussels from inhabiting the inner bank.

The findings of this study will be important for furthering the discussion of environmental disturbances on freshwater mussels and their habitat. Important questions including what composition of interstitial sediments is optimal for mussels and how are interstitial habitats impacted by environmental disturbances cannot be answered using traditional habitat surveys. My findings suggest there is a relationship between mussel populations and interstitial fines and that freeze cores are an effective method for examining freshwater mussel habitats, however many important questions associated with freshwater mussels and interstitial habitat remain unanswered.

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Tables and Figures:

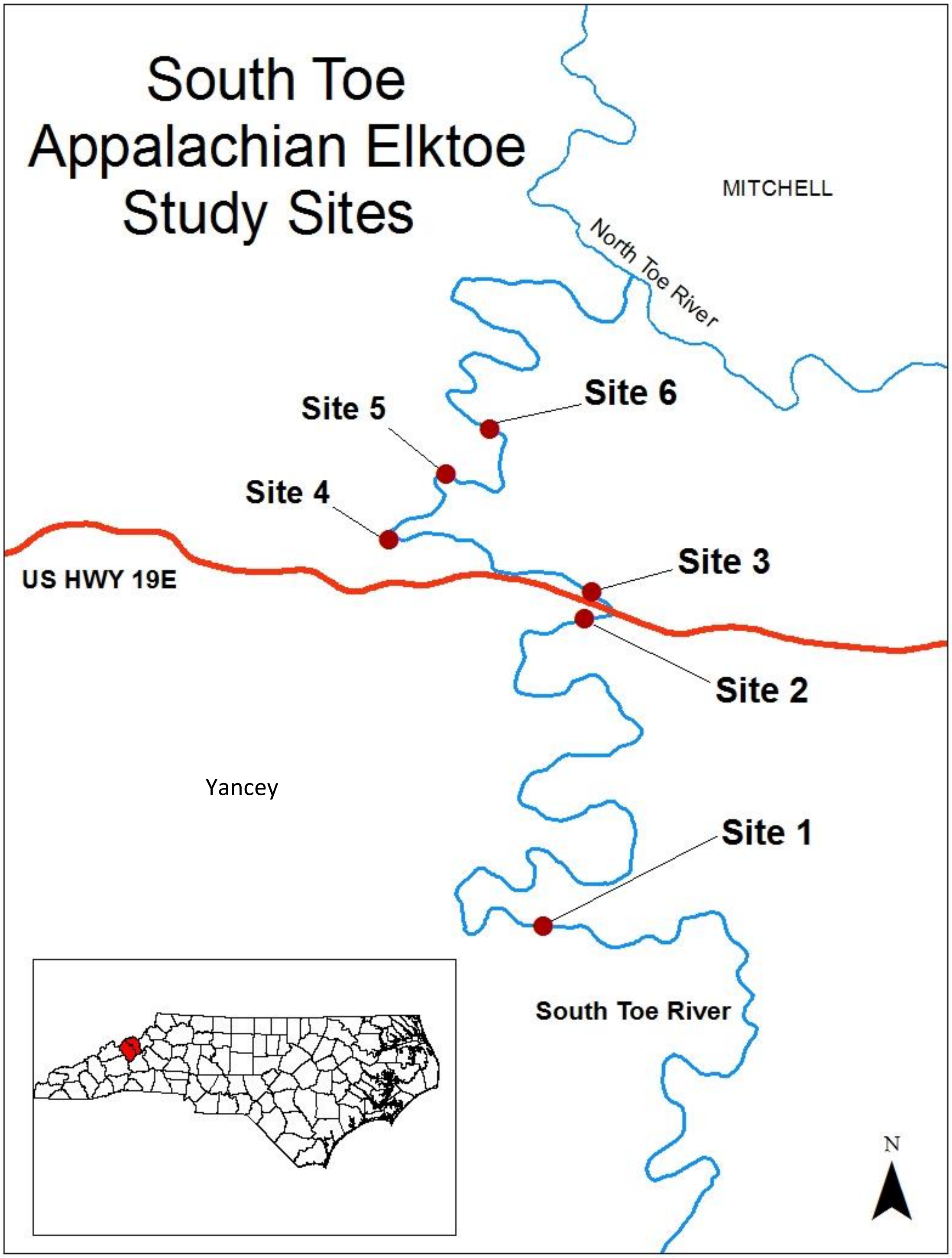

Figure 1: A map of our study sites in the South Toe River, Yancey Country, NC. The six sites and labeled and US HWY 19E is highlighted. *Map credit: Vincent Santini*

Table 1: Particle size grading scale *Credit: Gordon et al. 1992*

Class (Wentworth)	mm	ϕ
Very large boulder	4096-2048	-12 to -11
Large boulder	2048-1024	-11 to -10
Medium boulder	1024-512	-10 to -9
Small boulder	512-256	-9 to -8
Large cobble	256-128	-8 to -7
Small cobble	128-64	-7 to -6
Very coarse gravel	64-32	-6 to -5
Coarse gravel	32-16	-5 to -4
Medium gravel	16-8	-4 to -3
Fine gravel	8-4	-3 to -2
Very fine gravel	4-2	-2 to -1
Very coarse sand	2-1	-1 to 0
Coarse sand	1-0.5	0-1
Medium sand	0.5-0.25	1-2
Fine sand	0.25-0.125	2-3
Very fine sand	0.125-0.0625	3-4
Coarse silt	0.0625-0.0312	4-5
Medium silt	0.0312-0.0156	5-6
Fine silt	0.0156-0.0078	6-7
Very fine silt	0.0078-0.0039	7-8
Coarse clay	0.0039-0.0020	8-9
Medium clay	0.0020-0.0010	9-10
Fine clay	0.0010-0.0005	10-11
Very fine clay	0.0005-0.00024	11-12

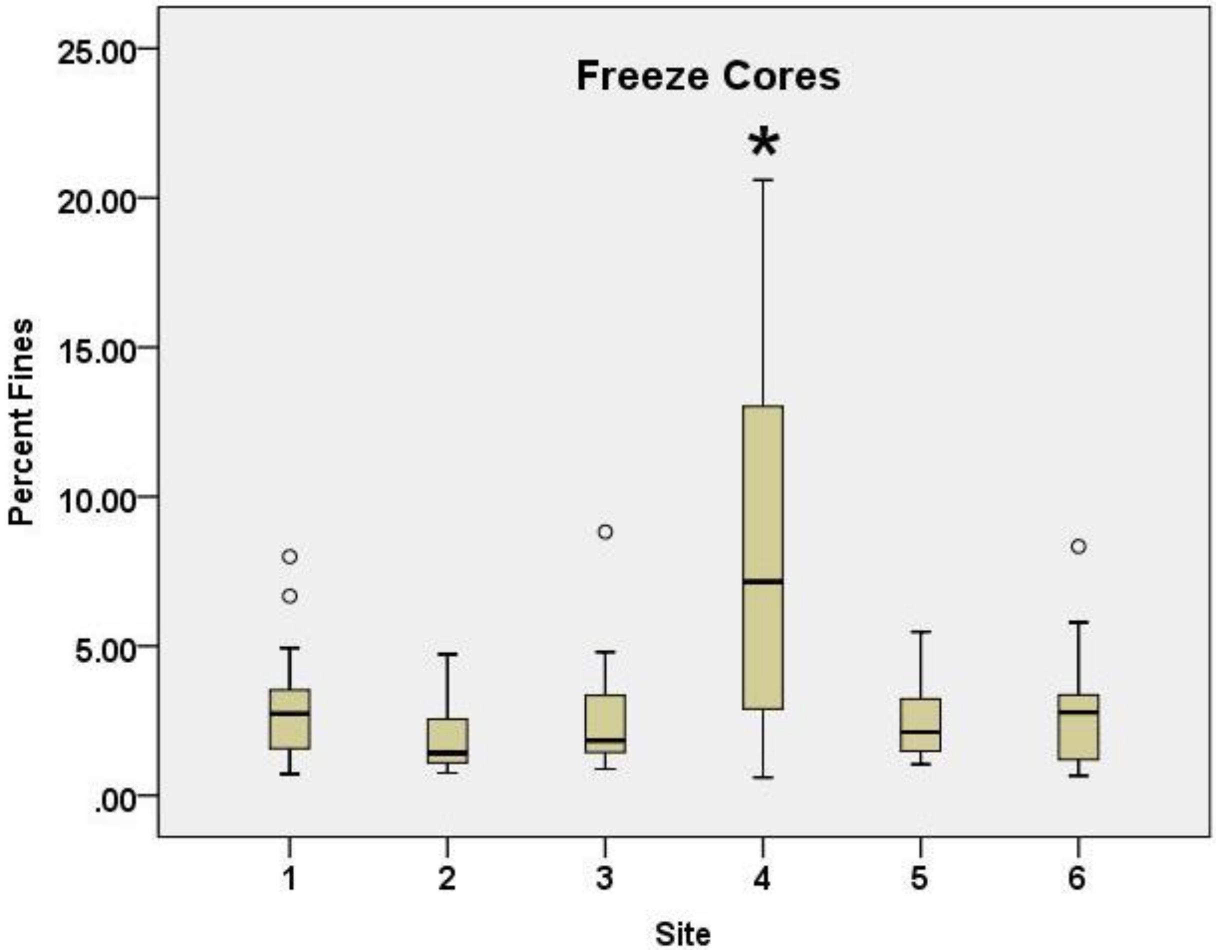

Figure 2: Boxplot displaying the proportion of fine sediment particles (<625 um) in freeze core samples collected at six sites in the South Toe River during 2017-2018. Site with the asterisk above the bar is significantly different from the others (1-way ANOVA, LSD post hoc test).

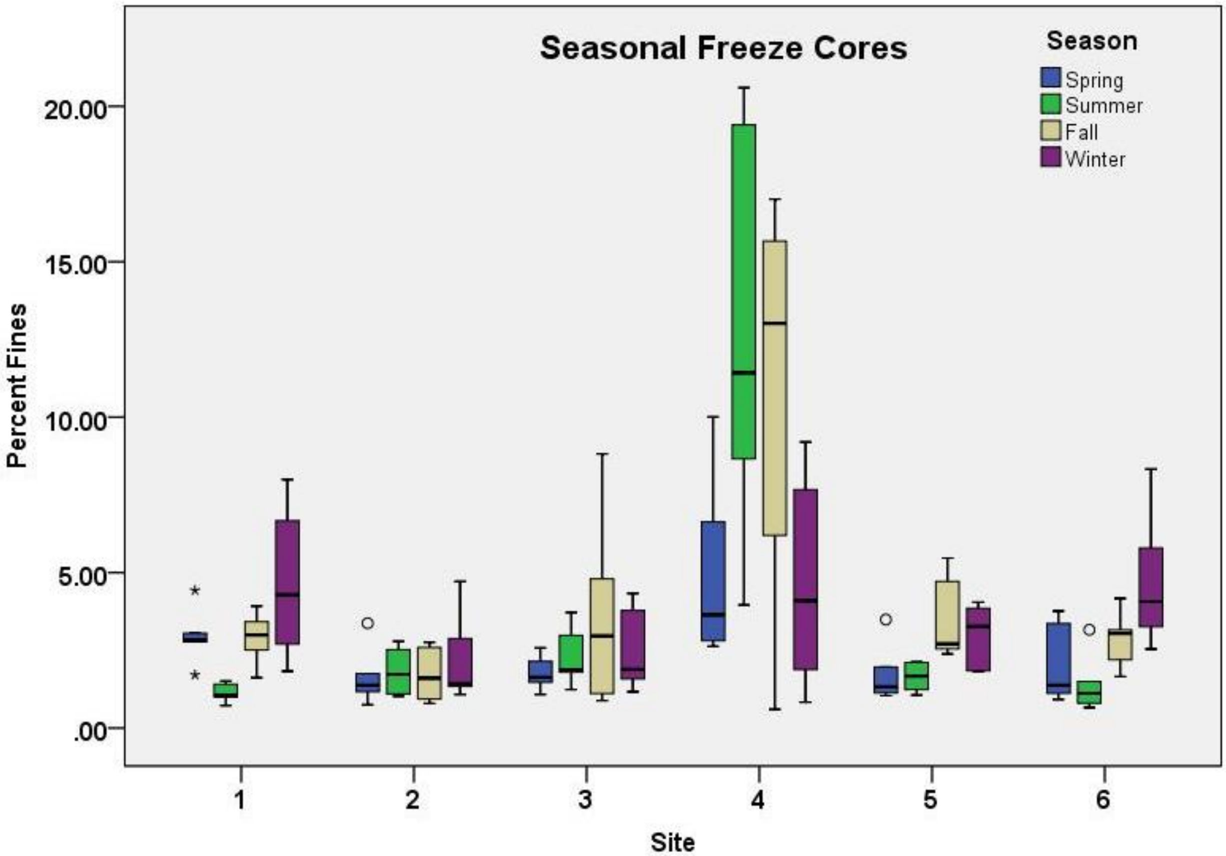

Figure 3: Boxplot displaying the seasonal proportion of fine sediment particles (<625 um) in freeze core samples collected at six sites in the South Toe River during 2017-2018.

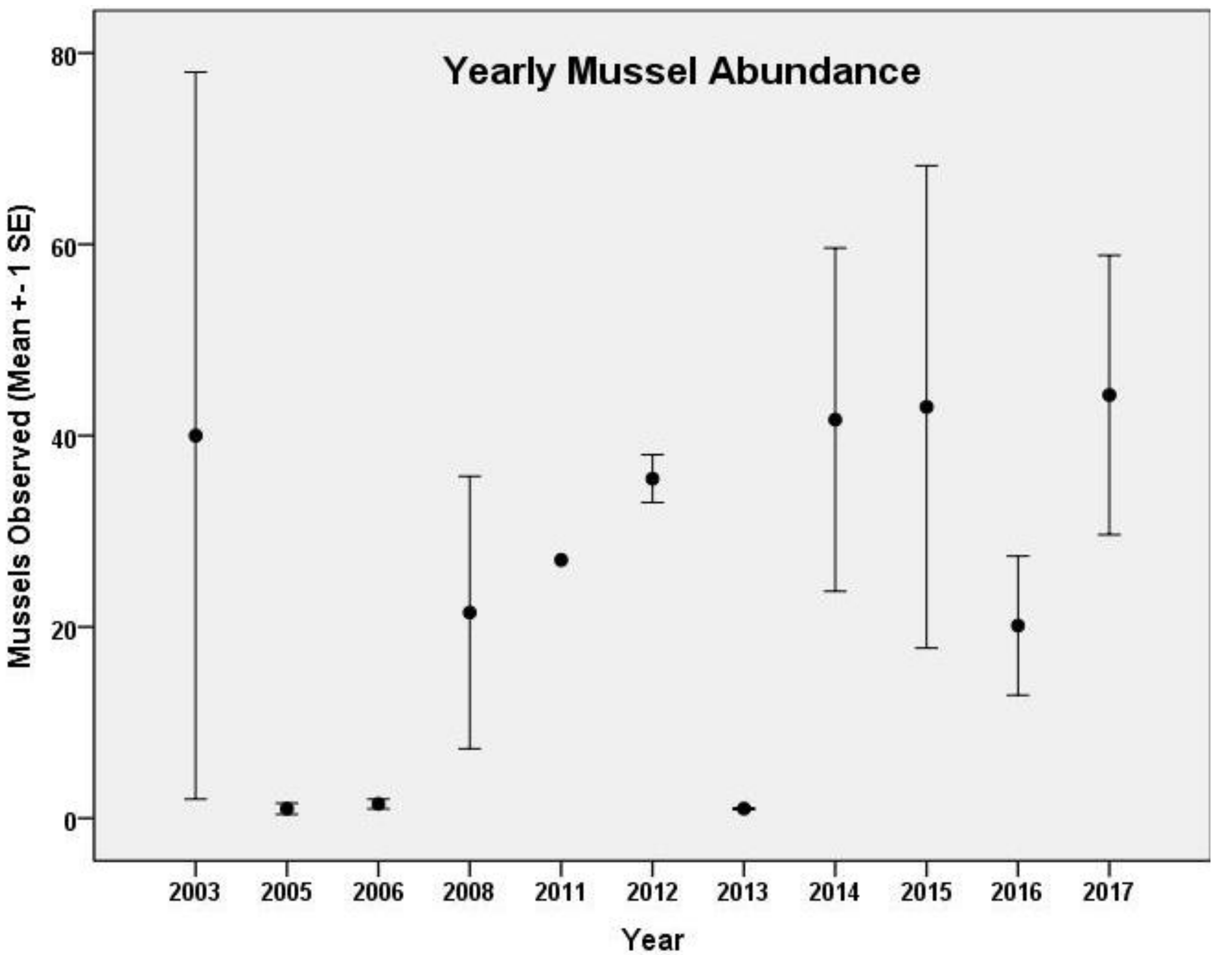

Figure 4: Error bar chart displaying the number of *A. raveneliana* observed each year data was collected between 2003 and 2017 at six sites in the South Toe River. Centroids are site means and bars represent 1 standard error from the mean.

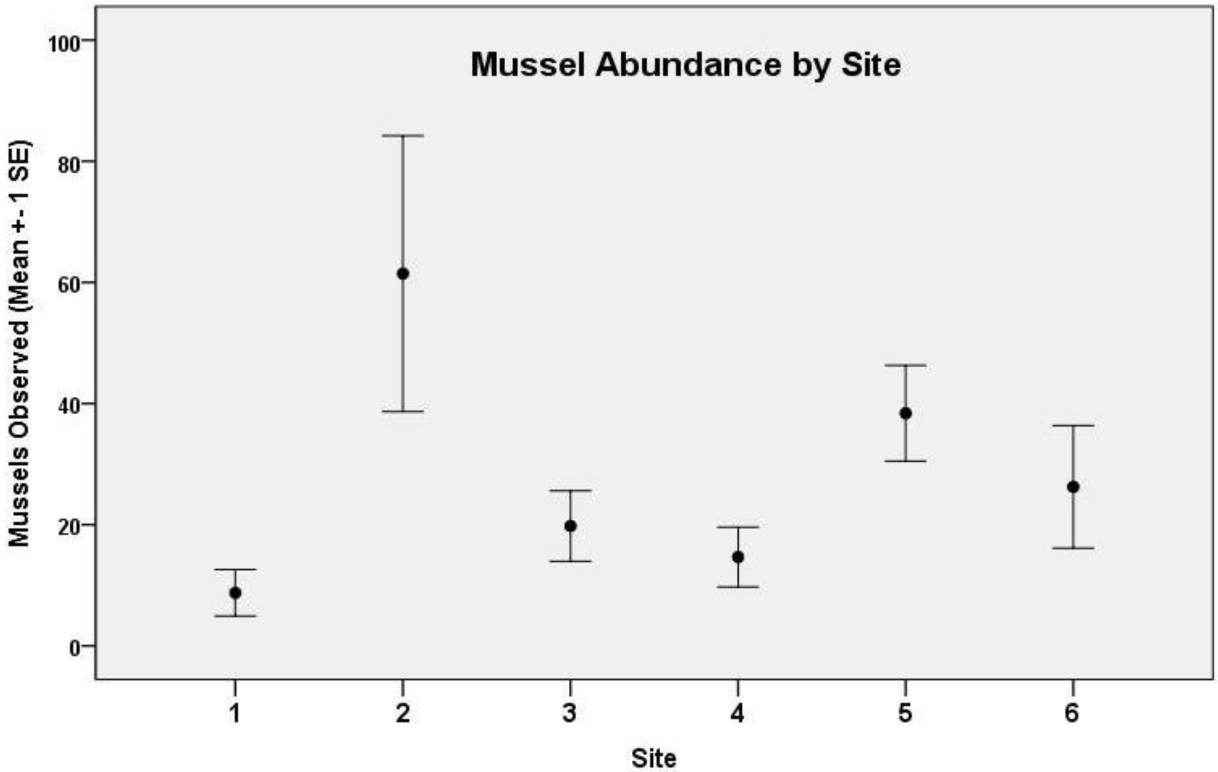

Figure 5: Error bar chart displaying the number of *A. raveneliana* observed at six sites in the South Toe River between 2003 and 2017. Centroids are site means and bars represent 1 standard error from the mean.

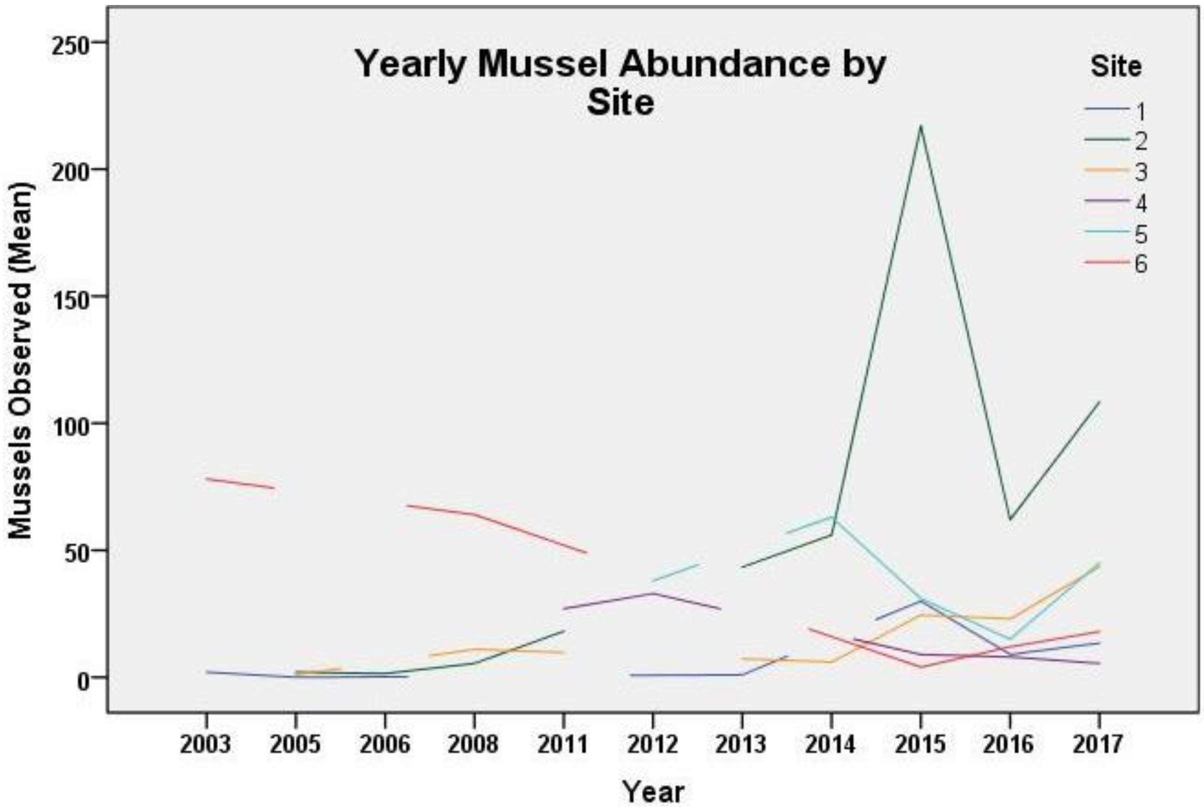

Figure 6: Line graph displaying the mean number of *A. raveneliana* observed at six sites in the South Toe River each year data was collected between 2003 and 2017.

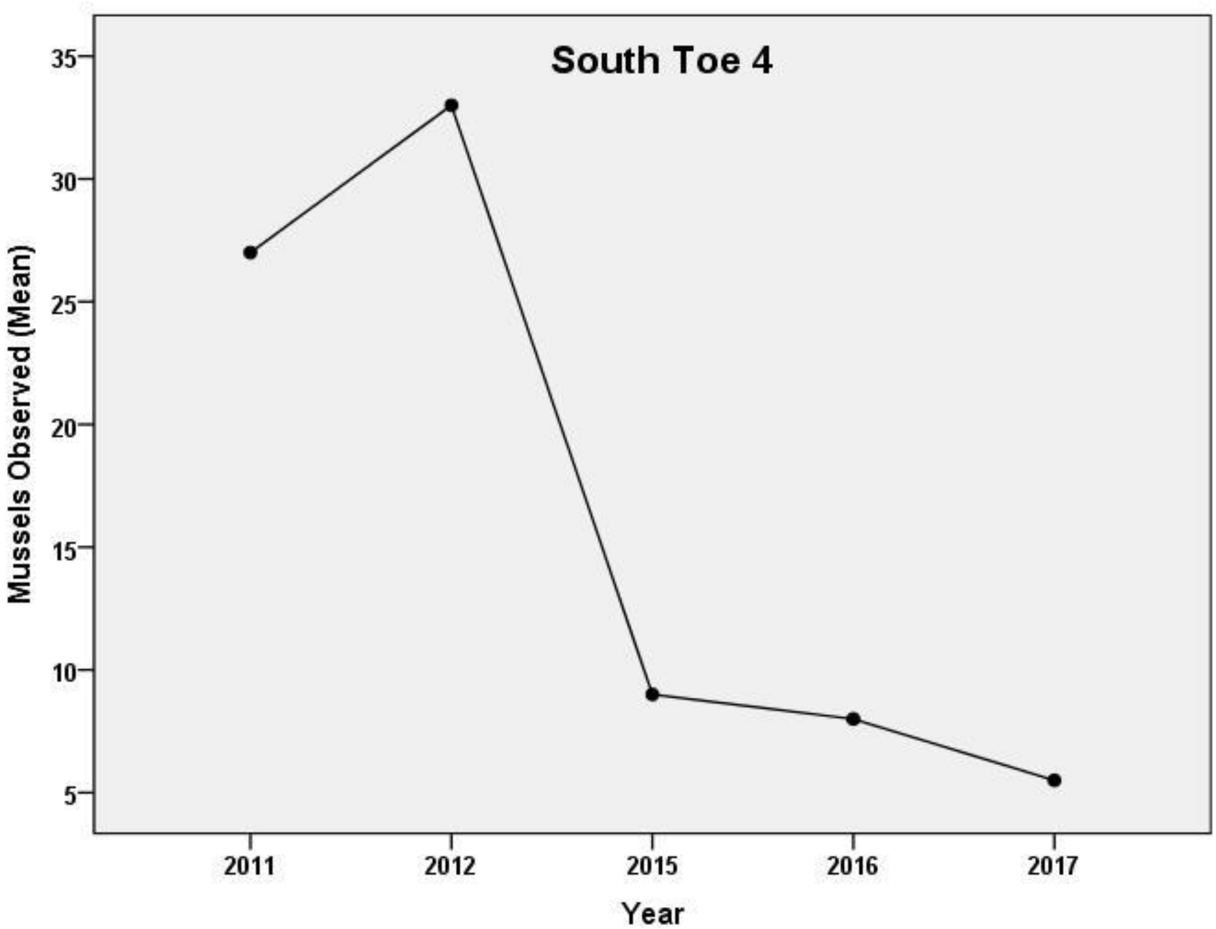

Figure 7: Line graph displaying the mean number of *A. raveneliana* observed at site 4 in the South Toe River each year data was collected between 2011 and 2017.

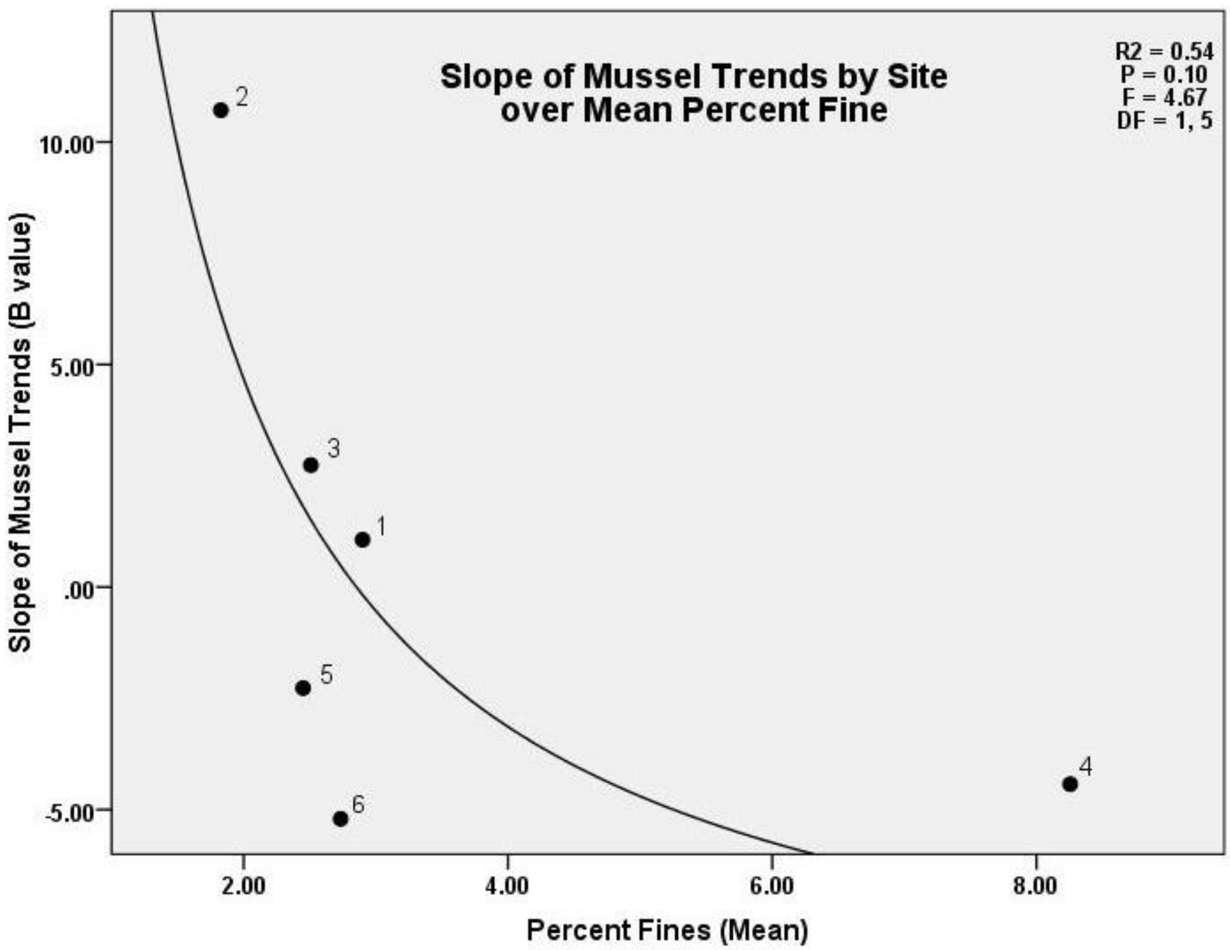

Figure 8: Scatter plot displaying the slope of the changes in yearly mussel abundance over the mean percent fine values at six sites in the South Toe River. An inverse curve was used to display the trend.

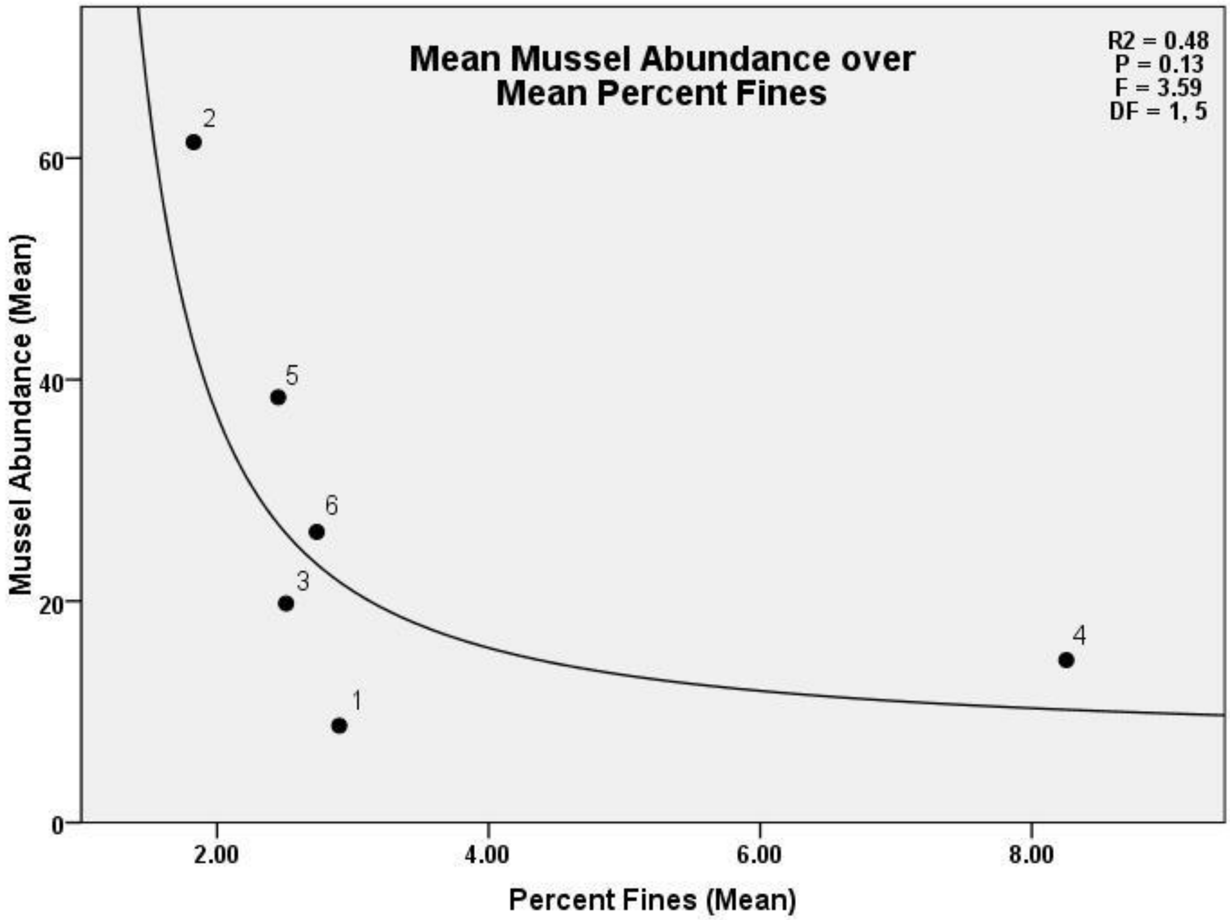

Figure 9: Scatter plot displaying the mean mussel abundance over the mean percent fine values at six sites in the South Toe River. An S curve was used to display the trend.

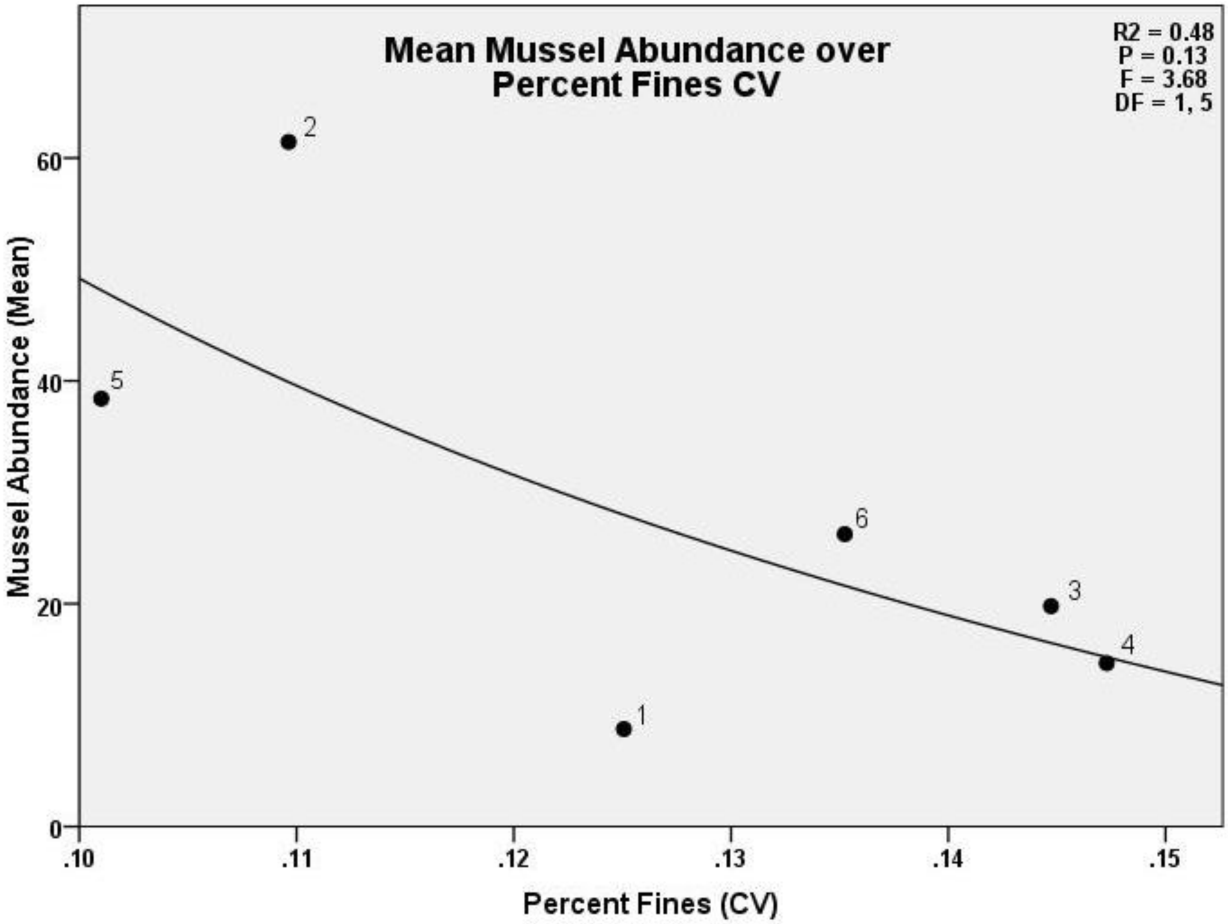

Figure 10: Scatter plot displaying the mean mussel abundance over the coefficient of variation for percent fine values at six sites in the South Toe River. An inverse curve is used to display the trend.

(A) (B)

Figure 11: A) Cores resembling concrete collected at Site 4 in the South Toe River compared to B) Core collected at site 5 in the South Toe River exhibiting traits consistent with cores collecting in this river.