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Range Extension Parameters of the Opportunistic Bivalve Corbicula fluminea (Müller, 1774) in New Jersey

Katie Elizabeth Vazquez

Abstract:

The invasive freshwater bivalve *Corbicula fluminea* has gained notoriety as a macro-fouler of industrial waterways across the United States. Little is known about the specific habitat requirements that contribute to its successful colonization of riverine systems. Small, often immature clams (shell length $\leq$ 14 mm) passively drift downstream. Settlement in unsuitable habitat can limit burrowing, growth and reproduction, and lead to juvenile mortality. Settlement in suitable habitat however can result in population densities in excess of 10,000 ind./m^2. Sampling was conducted in diverse Northern New Jersey waterways between May and mid-October 2008 to assess the habitat conditions conducive to establishment of new populations. Within these sites there was a significant correlation between clam density and both dissolved oxygen level and Ambient Biological Monitoring Network EPT scores. There was no correlation between clam density and dominant grain size, substratum organic content or turbidity. It appears stochastic events largely governed the dispersal and settlement of juvenile and small mature Asian clams while microhabitat conditions can be associated with population density. Live specimens of *C. fluminea* were collected at 8 sites half of which appear to house stable reproducing populations of *C. fluminea.* The remaining sites could represent interim "stops" likely containing specimens that entered as a result of downstream drift. Anthropogenic disturbance regimes in New Jersey waterways may contribute to the successful invasion by the Asian clam. An understanding of the habitat and physicochemical characteristics associated with the spread of juvenile *C. fluminea* is crucial to predictive modeling of dispersal patterns.

Keywords: Corbicula, aquatic invasive, dispersal behavior, opportunism, anthropogenic disturbance

MONTCLAIR STATE UNIVERSITY

RANGE EXTENSION PARAMETERS OF THE OPPORTUNISTIC BIVALVE *CORBICULA FLUMINEA* (Müller, 1774) IN NEW JERSEY

by

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Introduction:

The invasive Asian clam *Corbicula fluminea* (Müller 1774) is found in every major river basin in the United States (Britton rand Morton 1979). Asian clams possess a suite of characters typical of aquatic invasive species that allow for survival in diverse and often, fluctuating conditions. In particular, the modes of dispersal and relative physiological tolerance to disturbance have contributed to the rapid spread across the United States. While native freshwater mussel dispersal is restricted to obligate parasitic larvae on host organisms, small Asian clams ($\leq$ 14 mm shell length (SL)) can extend mucosal drogue lines and drift passively downstream (Prezant and Chalermwat 1984). Kraemer (1979a) examined the role of *Corbicula* as a competitor to the indigenous freshwater lampsiline mussels after authors had correlated the presence of the invasive bivalve to the decline of native species (Fuller and Richardson 1977). The fused mantle and siphonal pocket of the Asian clam was deemed more "conservative" than the mantle flaps specialized for reproductive purposes exhibited by lampsiline mussels (Kraemer 1977). It has been suggested (Kraemer 1979a, Vaughn and Spooner 2006) that *C. fluminea* is not a fierce competitor of freshwater bivalves but an opportunistic invader of disturbed habitats where native bivalves are typically absent. Within 10 years of its introduction in the heavily managed Arkansas River, *C. fluminea* had become the most abundant macrobenthic animal (Kraemer 1979a, b). Freshwater mussels remained dominant in the substratum of the more pristine Buffalo River despite the presence of the invasive bivalve in limited numbers (Kraemer 1979a). With the subsequent North American invasion by the zebra mussel (*Dreissena polymorpha*) and its contribution to the decline of freshwater mussels (Strayer and Smith 1996, Ricciardi et al. 1998, Strayer and Malcom 2007), public attention has shifted away from the range extension of the

Asian clam. In their discussion of the potential dispersal of the zebra mussel in the United States, Drake and Bossenbroek (2004) identified the issue of achievement of maximum dispersal potential as the most critical piece of information toward management. Based on the occurrence of Asian clams in unexpected habitats and the high population densities observed at previously unreported locations, it is likely *C. fluminea* has not yet achieved its maximum dispersal potential in New Jersey. Riverine habitats once suitable for native pearly mussel populations are shifting (Stanford et al. 2005) to the more disturbed and often biologically impaired areas associated with clam settlement (Kraemer 1979a, b, Boltovskoy et al. 1997). If a relationship exists between organismal life-span and recurrence intervals of suitable flow conditions as Strayer (1999) has suggested, the increased frequency and intensity of aquatic disturbance may favor communities dominated by the invasive bivalves.

Adult clams are typically more tolerant of physical disturbance and environmental contaminants than larval and juvenile clams (Harrison et al. 1984, Boltovskoy et al. 1997). In order to develop predictive models for dispersal of *C. fluminea* the habitat conditions suitable to settling clams (< 14 mm) must be established. Williams and McMahon (1986) found the majority of clams entrained in the water column of a Texas power station intake were small, malnourished and most abundant just prior to reproductive periods. Malnourished migrant clams likely experienced increased fitness after migration and settlement (Williams and McMahon 1989). The observed increase in downstream drift suggests upstream conditions, while not immediately lethal, were not conducive to long-term settlement and establishment of populations. Identification of specific habitat parameters where migration has resulted in establishment of a population can lead to predictive modeling of dispersal and interspecific interactions with native freshwater bivalves.

Fuller and Powell (1973) were the first to discover the invasive bivalve in New Jersey in the Upper Delaware River near Trenton. Since the early 1990s specimens of *C. fluminea* have been reported by the USGS at 48 stations of the Ambient Biological Monitoring Network (AMNET) seen in Fig 1. The NJDEP pursues quarterly macroinvertebrate sampling at these sites in order to establish the biological conditions of each stream segment. Over 850 AMNET stations have been established as seen in Fig. 2. The vast majority of AMNET sites where Asian clams have been reported were moderately biologically impaired at the time of specimen collection (Fig. 1). Among the biometrics assessed for New Jersey Impairment Scores (NJIS) are both the abundance and overall diversity of pollution sensitive and insensitive invertebrates. Kraemer (1977; 1979a) attributed the invasive species's success in the heavily managed Arkansas River to hardy shell construction, mantle fusion, alternative reproductive strategies, and dispersal abilities. She (Kraemer 1977) found the gill/mantle complex in *C. fluminea* to be more generally tolerant of myriad stressors in contrast to the more specialized native freshwater bivalve species evolutionarily derived for riverine environments. My observations of populations in 2008 suggest that the dispersal behavior and physiology of *C. fluminea* has led to an opportunistic invasion of moderately disturbed areas in Northern New Jersey.

Analyses of physicochemical properties affecting benthic macroinvertebrate community composition (Kraemer 1979b, Poff and Ward 1990) can lead to identification of potential hot spots for establishment of new Asian clam populations. The presence of

C. fluminea has typically been documented in coarse, gravelly to medium sand (Fuller and Powell 1973, Sickel 1986, Poff et al. 1993). I predicted clam density would be positively correlated with the coarse sand fraction of substratum core samples as this is likely most suitable to settling and bysally attached juvenile clams (Kraemer 1979a, b). Hakenkamp and Palmer (1999) found that in high densities, Asian clams dominated benthic metabolism and respiration and contributed to a net gain of organic matter in the substratum. Based upon this study I expected to observe a positive relationship between substratum organic content and clam density. Sensitivity to prolonged hypoxic periods has been correlated with decreased density in the field (Belanger 1991) and has induced density dependent mortality in laboratory populations (Cherry et al. 2005). Furthermore, water column entrainment can increase after sags in dissolved oxygen (DO) concentrations (Williams and McMahon 1986). I expected clam density to be positively correlated with DO and the organic content of the substrata as a result of this well-documented relationship. Densely populated areas must be sufficiently oxygenated to support high respiration rates. The high metabolic demands and variable filtration rates (Way et al. 1990) allow for rapid seston removal from stream segments where clam beds are present and can lead to an observable increase in water clarity (Phelps 1994) and organic accumulation in the substratum (Hakenkamp and Palmer 1999). I predicted clam density would be negatively correlated with turbidity. Clam size distribution allows for a rough estimation of the number of recent recruits and potential migrant clams in an area. The presence of only individuals ~14 mm SL suggests a recent opportunistic drift event as opposed to the presence of individuals > 30 mm SL who have likely been settled for over 2 y (McMahon and Williams 1986). Environmental parameters were assessed at 19 sampling sites in Northern New Jersey in two rounds of sampling between May and mid-October of 2008.

Methods:

Site selection:

Seventeen sites were selected in Arcview GIS based on their proximity to sites sampled by NJDEP for the Fish Index of Biotic Integrity (FIBI) currently restricted to Northern New Jersey as seen in Fig 2. FIBI habitat reports were particularly relevant as they included substratum grain size distribution. Sites were within 16 km of an AMNET station reported by the USGS to have *Corbicula fluminea* present. To maximize the likelihood of sampling populations of *C. fluminea*, substrata dominated by boulder or bedrock were avoided. Habitat conditions at each site were determined through field sampling and literature surveys of FIBI and AMNET reports. All GIS data were obtained from the NJDEP GIS downloadable database. In order to map the sites reported by the USGS to contain *C. fluminea* specimens since 1990, the relevant AMNET stations were selected by the station number attribute in Arcview GIS version 9.2. A 16 km buffer around each AMNET station was created. Geocodes and maps from FIBI reports were used to locate sites for field sampling. The sampling sites in order of sampling date were located in Deepavaal Brook (N 40°53.045', W 74°16.68') the Pequannock River (N 41°00.113', W 74°19.049'), the Wanaque River (N 41°00.157', W 74°17.546'), Beaver Dam Brook (N 40°55.434', W 74°17.991'), the Rockaway River (N 40°53.474, W 74°22.548'), Troy Brook (N 40° 51.33, W 74°23.495'), Green Brook (of Green Brook Park)(N 40°36.43' W 74°26.926'), the Passaic River (N 40°44.03', W 74°22.631'), Sidney Brook (N 40°36.998' W 74°55.807'), Mile Run (N 40°30.271', W 74°28.145'), Green Brook (Milford Twp.) (N 40°33.957', W 74°31.516'), Six Mile Run (N 40°28.180', W 74°32.620'), Ireland Brook (N 40°25.026', W 74°29.115'), Shabakunk Creek (N 40°15.071', W 74°44.877'), Heathcote Brook (N 40°22.184', W 74°36.966'), Beden's Brook (N 40°24.956', W 74°39.946'), and Pike's Run (N 40°26.739', W 74°38.750'). Habitat variables assessed in FIBI include substratum composition: epifaunal substratum/available cover, embeddedness of larger particles and sediment deposition; habitat regimes within the stream: velocity/depth regimes, frequency of riffles, channel flow status and alteration. The bordering terrestrial environment is included by assessment of bank stability, vegetative protection and riparian vegetative zone width. Stream habitat parameters are ranked from 1–20 where 20-16 is considered optimal for fish assemblages, 15-11 is suboptimal, 10–6 is marginal and 5–0 is poor. The terrestrial parameters rank each bank of a scale of 1-10 similarly with 10-9 as optimal, 8–6 as suboptimal, etc. For instance, substratum considered optimal for epifaunal substrate/available cover must consist of at least 70% stable colonizable particles.

Field sampling procedures

An initial rough survey of an approximately 50 m stream segment was conducted at each site. During this survey the presence of live specimens or empty shells was noted. Substratum with burrowing individuals was further sampled. In streams where no live *C. fluminea* specimens were initially seen but empty shells were present, we chose to sample in sandier areas to maximize the chance of recovering live specimens. Sites where live clams and valves were entirely absent were also sampled in relatively sandy areas that appeared suitable for clam settlement based solely on this parameter. A GPS reading was taken at each sampling site. Turbidity was measured with a turbidity meter. Dissolved oxygen and water temperature were measured with a YSI 85 dissolved oxygen meter. pH was measured by an IQ Scientific Instruments pH Meter. Ambient shade air temperature was also recorded.

Four 0.25 m^2 quadrats were taken at each site. Three substratum core samples with a three centimeter diameter were taken from each quadrat. The top three centimeters of substratum were separated from each core sample and bagged separately. All substratum samples were kept on ice for the duration of sampling and transport back to the laboratory. Samples were stored in a freezer until samples were analyzed and substratum composition was determined. Also, within each quadrat 3 subsamples were taken using a box-corer of 225 cm^2 in order to determine clam density at each site. Each subsample was carefully sorted and all live clams removed and immediately preserved in 70% ethanol. At sites dominated by larger substratum particles it was necessary to remove a substantial amount of the larger cobbles in order to verify that clams were not present in underlying finer substrata. The occurrence of dead clams or unpaired valves was also noted. Hinged valves counted as one individual and two unhinged/unpaired valves also represented a single clam. These specimens were not included in the final tally used to estimate live clam density.

Core sample analysis

Substratum samples were dried at 100° C for approximately 12 h. Dried samples were weighed and transferred to crucibles. Crucibles were combusted at 550 °C for 1 h. Samples remained covered and were allowed to cool for 20 min. Baked samples were then weighed. The pre- and post-combustion weights were used to determine percent organic content. A standard series of geological sieves (Wentworth scale) was used to determine relative grain size of each substratum sample.

NJDEP Environmental Data

Information regarding clam presence/habitat and dominant invertebrate populations was taken from USGS records, FIBI and AMNET reports respectively. Parameters used to assess the presence of pollution sensitive benthic invertebrate taxa, namely EPT score, are especially pertinent. The EPT score is an index scoring the sum of the number of families present from the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) (NJDEP 2008). The NJDEP recognizes these species' sensitivities to low dissolved oxygen, ammonia, biocides, and heavy metals (NJDEP 2008). The presence of greater than 5 families receives a score of 6, 5-3 families receives a score of 3 while fewer than 3 families receives a 0. The EPT is one of several biometrics considered in biological assessment of a waterbody. Other biometrics include taxa richness, percent dominance, the percentage of the community represented by EPT families, and modified family biotic index. Biologically unimpaired sites score from 24-30 while moderately impaired sites score from 9-21 and severely impaired sites score from 6-0. FIBI habitat parameters and scores described above were taken from 2002-2005 reports. FIBI sampling sites are typically within 3.2 km of AMNET stations and consist of 150 m stream segments.

Second Round Sampling

The status of the populations at Beaver Dam, Green, Troy and Bedens Brooks was unclear during the first round of sampling. Clams were present in moderate densities in the expected suitable habitats in Beaver Dam Brook and Green Brook and conspicuously present in the presumed unsuitable habitat at Troy Brook and Beden's Brook. The Beaver Dam Brook and Green Brook sites were re-sampled. Troy Brook (N 40°51.248', W 74°23.744') and Beden's Brook (N 40°24.923', W 74°40.127') sampling sites in round 2 were new locations upstream of first round sampling sites, as only dead specimens were recovered during the first round of sampling and observed preliminarily in the second. Sampling was conducted upstream in an attempt to locate the populations and assess environmental parameters. All second round sampling was conducted in October 2008.

<u>Results</u>

There were no significant correlations between clam density and substratum grain size (coarse sand, $p = 0.238$; medium sand, $p = 0.228$; fine sand, $p = 0.138$; fine silt and clay, $p = 0.093$), turbidity ($p = .679$), or organic content ($p = .055$). There was a significant relationship between clam density and both DO ($p = 0.013$) and EPT values taken from the most recent round of AMNET sampling ($p = 0.038$). Of the 19 different sites sampled live specimens of *C. fluminea* were collected at 8 different sites depicted in Fig 3: Beaver Dam Brook, Beden's Brook, Deepavaal Brook, Green Brook, the Passaic River, Six Mile Run, Troy Brook and the Wanaque River. Table 1 contains the measured environmental and habitat parameters for each of these sites. Figure 4 provides a complete look at size distribution of clams collected from sampling sites. All but two of these sites contained individuals likely older than 1 y with exceptions during the first round of sampling in the Wanaque and Passaic Rivers. These sites had the smallest average densities and shell lengths. The Wanaque River was a fast flowing stream with substratum dominated largely by boulders. Clams were only recovered from a single quadrat. Weathered hinged specimens were scarcely seen along the banks. Due to these factors and the apparent unsuitability of this habitat for long-term settlement by migrant clams this site was not re-sampled. In Deepavaal Brook clam density was low and 62% of the clams sampled were smaller than 14 mm. Evidence at the remaining sites suggested clams were either abundant or altogether absent. Eleven sites contained no live specimens of *C. fluminea*: the Pequannock and Rockaway Rivers, first round sampling sites in Troy and Beden's Brooks, Mile and Pike's Runs, Sidney, Ireland and Heathcote Brooks, Shabakunk Creek, and Green Brook (within Green Brook Park). The assessed parameters are presented in Table 2.

Clam collection sites with stable populations

Stable populations were observed at Six Mile Run, Green Brook and the second round sampling sites in Troy and Beden's Brooks [see Figs 3 and 4]. All 4 populations contained both individuals less than the 14 mm maximum SL and larger individuals incapable of drogue-line drift. Maximum shell lengths reached nearly 40 mm. Re-sampling was conducted at the sites in Beaver Dam Brook and Green Brook in October to assess the possibility of late reproduction and growth. The possibility of pseudoreplication exists as these data were treated independently of each other during statistical analyses. Resampling of the same site was conducted in order to assess the variability of a population persisting at a site, and the possibility of additional clam settlement between sampling periods. During the first round of sampling at Beaver Dam Brook in May, clams were present at an average density of 22 clams/m^2. The mean shell length of 13.09 mm was below the presumed maximum shell length of drifting individuals (Prezant and Chalermwat, 1984). A single clam 14.7 mm long was the only exception. When the site was re-sampled in October 2008 the average density had increased to 296 clams/m^2. Twenty nine percent of the collected clams were between 5 and 10 mm in shell length, while no individuals this small were recovered during sampling in May. The presence of these small individuals reduced the mean shell length of clams collected in October to 11.76 mm. There were no drastic environmental differences between the two rounds of sampling at Beaver Dam Brook: slight reductions in DO levels and increased organic content are seen in Table 1.

Green Brook was sampled in June and October 2008. Fifty percent of the clams collected in June were larger than 14 mm in shell length: 22% were less than 10 mm and 28% were between 10 and 14 mm. The presence of both pre-reproductive (<10 mm SL) (Williams and McMahon 1986) and mature individuals exceeding 20 mm SL suggested that clams had been present for perhaps a year at this site (McMahon and Williams 1986). Re-sampling was conducted to obtain more information on the *C. fluminea* population dynamics at this site. In addition to an increase in population density from 67 to 126 clams/m^2, 53% of the clams collected in October were greater than 14 mm in shell length a slight increase from the 50% in June. While clams were abundant, the population was again nearly evenly composed of potentially drifting and relatively recently settled individuals.

The two highest documented clam densities were 885 and 593 clams/m^2 at Troy Brook and Beden's Brook, respectively. No live clams were collected during the first round of sampling at either site. The first sampling site in Beden's Brook was dominated by bedrock coated with some periphyton and grazing snails (*Goniobasis, Helisoma,* and *Physa spp.*). Upstream, individual clams were spotted very sparingly along the channel.

This site was proximal to a gravel bar where hinged and unhinged specimens had accumulated, however no live clams were found in any of the four quadrats. The second round sampling site was located approximately 75 m upstream of the round 1 site in an effort to examine the source of the few individuals downstream. There was a densely populated area with 593 clams/m^2 in a relatively slow moving gravelly area. Individuals ranged in size from 6.3 to 29.3 mm in SL. The smallest of these individuals are likely new recruits as individuals can grow up to 5 mm in their first month (McMahon and Williams, 1986) while larger individuals likely had been settled for at least 2 y.

In June 2008 no live clams were recovered from Troy Brook but, hundreds of dead specimens littered both banks of a stream segment dominated by boulders and fast flowing water. A few live individuals were seen wedged between boulders throughout the riffles. The numerous dark, weathered valves present suggested successful drift was possibly occurring in the area with subsequent mortality or mass die-offs in the population upstream with subsequent deposition of empty shells. A densely populated clam bed was found approximately 80 m upstream at the second round sampling site. Further exploration upstream revealed the presence of agricultural areas draining into Troy Brook at times of high flow. Sixty five percent of the clams sampled in October at Troy Brook exceeded a shell length of 14 mm. Individuals ranged in size from 8.5 to 39.4 mm in shell length. Two individuals present had reached shell lengths in excess of 35 mm indicating they were likely present at the site for several years while the small individuals were likely in their first year

Habitat criteria

Tables 1 and 2 show that nearly all substrata samples had a substantial portion of coarse sand/gravel. The only exceptions to this were Deepavaal Brook in May and Beaver Dam Brook in both May and October. Clams were present at both sites. Figure 5 shows there was no correlation between clam density and the substratum percent coarse sand and gravel (a), medium sand (b), fine sand (c), or fine silt and clay (d). There was a positive correlation between clam density and the percent coarse sand and gravel (R^2 = 0.16, p = 0.238) and fine silt and clay (R^2 = 0.31, p = 0.093) in core samples as can be seen in Figs 5a and 5d. A negative correlation existed between clam density and the medium (R^2< 0.18, p = 0.228) and fine sand (R^2 = 0.25, p = 0.138) components as shown in Figs 5b and 5c. Figure 6 shows clam density was positively correlated with the amount of organic content in the substrata with a nearly statistical significane (R^2 = 0.39, p = 0.055). The correlation between clam density and DO was significantly positive (R^2 = 0.56, p = 0.013) as can be seen in Fig. 7. The weakest correlation existed between turbidity and clam density (R^2 = .02, p = 0.679) where there was virtually no relationship as seen in Fig 8.

The EPT values used were reported for the AMNET stations nearest to each FIBI station as reported in each sites' FIBI report. The values of all sites ranged from 0-12. The EPT index scoring goes as high as 35 members of designated taxa. Of the sites proximal to those reported to house clam populations the highest reported EPT value was only 5. Despite this relatively small range of values Fig. 9 shows a significant positive correlation between EPT indices and clam density (R^2 = 0.43, p = 0.038). It should be noted that DO levels and EPT scores are not independent of each other as the presence of sensitive taxa is impacted by DO levels at the time of AMNET sampling.

Discussion

It appears that stochastic events coupled with dispersal behavior exhibited by juvenile and small adult clams result in at least temporary settlement in a wide range of habitats. The physical and chemical characteristics of freshwater microhabitats are a result of natural and anthropogenic disturbance regimes in the surrounding watershed. The most frequent element of disturbance to rivers and streams is flooding (Fisher et al. 1982). Flooding and flash flooding occur more often in more developed areas where impervious surfaces are most prevalent. Flooding can lead to the sudden influx of massive amounts of water and downstream transport of benthic and pelagic biota, nutrients, and sediment. Severe disturbance such as substratum scouring can remove virtually all taxa from a reach of stream severely reducing biodiversity and species abundance. *Corbicula fluminea* and other successful invaders rapidly recolonize disturbed areas because of high mobility, short life-spans associated with rapid growth and maturation, and high fecundity (Fisher et al. 1982, Morton 1996). Opportunistic dispersal facilitated by the drogue line drift behavior of *C. fluminea* into areas subject to both natural and anthropogenic disturbance is the most likely explanation for the current distribution of the Asian clam in New Jersey.

In agreement with past rounds of AMNET sampling, the majority of sampling sites where live specimens of *C. fluminea* were recovered were at least moderately disturbed with the exceptions of Troy and Beden's Brooks where the two highest population densities were observed [Fig 3]. The sampled sites were both located upstream of their respective AMNET stations. Despite the high densities observed upstream, clams have yet to be documented by AMNET sampling as of 2004. The presence of multiple size cohorts [Fig 4] and individuals exceeding 35 mm in SL suggest these populations have been established for at least two years and maximally five years (Britton and Morton 1979, McMahon and Williams 1986). These sites were among the highest in coarse sand content of sites where live clams were collected. These values were not as high when considered across all sites as several sites where clams were entirely absent had a larger fraction of coarse sand in the substrata [Table 2]. As Kraemer (1979a, b) has suggested homogeneous sandy channels prone to frequent disturbance can be dominated by juvenile clams. Further analyses of substratum homogeneity could refine our estimation of substratum deemed suitable for colonization by *C. fluminea*

The presence or absence of an organism in a reach is largely dependent on the physicochemical characteristics of patchily distributed microhabitats (Poff and Ward, 1990). Dissolved oxygen levels were relatively high throughout both rounds of sampling, never dropping below 4 mg/L, well above the minimum DO levels tolerable to *C. fluminea* (Williams and McMahon 1986). Nevertheless there was a significant correlation between DO levels and clam density. Troy Brook and Beden's Brook had the highest observed DO levels 17.7 and 14.19 mg/L, respectively although this is likely related to the lower air temperatures observed in October. Both sampling areas were quite shallow (< 10 cm) and varied in velocity with Beden's Brook being relatively slow and Troy Brook more moderate. The associated EPT parameter also was significantly positively correlated with clam density. As stated previously, collection sites were typically moderately biologically impaired and scored within a small range of low EPT values. These results suggest that while clams may be patchily distributed along a stream, higher population densities are more likely to occur in stream segments that are at least periodically well-oxygenated and tolerable to pollution sensitive taxa. Further studies could examine the co-occurrence of *C. fluminea* with specific ecologically indicative taxa. Of particular interest may be the relationship between clam density and population density of documented hypoxia intolerant species given the relationship between clam density and DO levels.

Lack of any further correlation between clam density and measured environmental parameters at the remaining collection sites indicates these factors may be more accurately linked to temporal variability and physical characteristics of the stream. While the number of AMNET stations throughout New Jersey has impressively increased over the years since its conception, the distribution and range extension of *C. fluminea* in New Jersey has been poorly monitored. The presence of even a single clam recovered in AMNET grab sampling can be indicative of an established population upstream and perhaps the source of significant future populations downstream. A single gravid individual either used as live-bait or simply discarded into the stream can release hundreds of pediveligers. These pediveligers drift planktonically and individuals ≤ 14 mm in length are capable of passive downstream drift with the assistance of mucosal draglines (Prezant and Chalermwat 1984). Migration can be completely passive as described in the case of individual dislodgment, but Williams and McMahon (1986) found that small individuals collected floating in the water column were often malnourished. They suggested these drifting malnourished individuals would have access to unexploited resources and so gain a selective advantage over non-migratory individuals remaining in areas of poor food availability. A population could be quickly established if settlement occurs in suitable habitat for growth and reproduction.

The population at Troy Brook sampled in October has been established for at least 2 years. Regardless of any ambiguity surrounding the introduction of the invasive bivalve to the brook, *C. fluminea* achieved the maximum density observed in this study of 885 clams/m^2 and dominated the macrofauna there. As Poff and Ward (1990) suggested, the physicochemical parameters of a microhabitat suitable for settlement can act as a marker for that species. These characteristics are difficult to discern for *C. fluminea* and other invasive species adapted to unpredictable environments in a wide range of habitats (Strayer et al. 2006). The substratum at Troy Brook in October was relatively homogeneous. The DO at this time was the highest reported of all sites 17.7 mg/L. The minimum shell length of 8.5 mm suggests the presence of individuals born in the spring, but very small individuals released during a characteristic fall spawning period (McMahon and Williams 1986) were absent. The possibility exists that these individuals dispersed downstream away from the area densely populated by adult clams passively or in response to adult chemical cues (Werner and Rotthaupt 2007). The round 1 sampling site located downstream of the round 2 site was littered with thousands of weathered valves ranging from 5 mm to $\geq$ 25 mm SL. This area was very fast flowing and dominated by large boulders with gravelly banks evidently unsuitable for long-term settlement. During times of high-flow it appears individuals of all-sizes can be dislodged and become deposited on the banks of the stream reach sampled in round 1. The empty shells downstream in round 1 could also be a result of mass die-offs in the population upstream and subsequent drift of the shells downstream during a flood. The next round of sampling at the AMNET station in Troy Brook could reflect the high population densities observed upstream if the boulder dominated substratum of the round 1 site is not a significant barrier to dispersal.

Odum (1969) described community succession in terms of a natural progression toward ecosystem stability achieved through the replacement of "developmental" species with "mature" ones, but invasive species such as *C. fluminea* violate such models. Stability can be achieved relatively rapidly because of rapid colonization/recolonization rates and resistance to various forms of disturbance. The invasive bivalve has at least achieved the "pulse stability" ascribed by Odum (1969) to an ecosystem existing at an intermediate point along the succession model maintained by regular disturbance. Our sites in northern New Jersey were moderately disturbed in terms of macroinvertebrate community composition as determined by the diminished presence of pollution sensitive taxa and had fractions of gravelly sand and moderately high dissolved oxygen levels. Aside from these broad criteria finer distinctions between the sites did not emerge from subsequent sampling. Habitat conditions vary according to natural lotic disturbance and anthropogenic influence over the surrounding watershed (Fisher et al. 1982, Poff and Ward 1990, Stanford et al 2005)). Natural flooding and sediment disturbance are amplified by the presence of impervious services while the natural input of allochthonous material is supplemented by residential use of fertilizer and agricultural runoff. Physical disturbance of rivers in the form of dredging, channelization, and impoundment drastically increase the scale and degree of lotic disturbance. Poff and Ward (1990) argued that organismal behavior and preadaptedness to disturbance would influence recolonization rates and patterns as opposed to the unidirectional mode of succession described by Odum (1969). More recently, Strayer (1999) has suggested a relationship between organismal life-span and the recurrence interval of the flow regimes they inhabit while Stanford et al. (2005) assert that aquatic microhabitats are more like shifting mosaics. *Corbicula* and other invasive species can be placed on an r-k continuum varying with environmental fluctuations as indicated by shifts in filtration rates (Way et al. 1990) and life history strategies (Hedtke et al. 2008). With increased frequency of large-scale disturbance rivers and streams have shifted to habitat conditions more favorable to *C. fluminea* and other invasive species. This may help explain the increased population densities observed at Beaver Dam Brook between rounds 1 and 2 [Fig 4].

The populations of *C. fluminea* sampled in this study have achieved the stability attributed to organisms in higher succession levels by Odum (1969) and at a minimum the pulse stability found at intermediate levels. Relatively dense populations can be maintained indefinitely representing a stasis along Odum's succession progression. In high densities Asian clams can have a significant impact on organic matter dynamics in river substratum (Hakenkamp and Palmer 1999) through a combination of both pedal- and filter-feeding. Poff (1993) hypothesized that clam removal from a Piedmont stream segment it dominated in terms of benthic biomass and metabolism by an Asian clam population would drastically alter the system's biodiversity and open the possibility of colonization by unionid mussels. While the invasive bivalves are adapted for relatively short-term existence in generally unpredictable environments (Kraemer 1977) native unionids exhibit behavior and physiology evolved for long-term survival in riverine systems (Strayer 1999). Historical commercial harvests, impoundments, pollution, channel alteration, and the invasion of the zebra mussel have been associated with the decline and impending extinction of native freshwater mussel species (Bogan 1993, Ricciardi et al. 1998,Vaughn and Taylor 1999, Strayer 2006). Conservation efforts toward preserving native unionid species habitat and diversity can be compromised in rivers and streams with dense populations of Asian clams. Native bivalves were not present in more disturbed stream segments densely populated by *C. fluminea* despite dense mussel assemblages elsewhere in the river (Kraemer 1979, Vaughn and Spooner 2006) while in the past Fuller and Richardson (1977) reported dislodgement of mussels by invasive clams. In order to maximize the NJDEP's efforts toward mussel conservation and preservation of biodiversity the continued range expansion of *C. fluminea* and the likely possibility of its macrobenthic dominance in colonized rivers should be addressed. The current range of *C. fluminea* in New Jersey is likely under appreciated as these and other benthic invertebrates are often patchily distributed along rivers and streams (Strayer 1999). The majority of the most recent AMNET reports cite the presence of only a single clam at an AMNET station as part of their 100-specimen index. It is more likely that a population exists upstream as was likely the case in Troy Brook where the likely source of the individual collected during AMNET sampling in 2004 was discovered upstream during sampling in 2008. The single clam could very well have come from the population of over 800 clams/m^2 upstream or an intermediate suitable reach of stream also containing individuals/offspring from the upstream population.

In the future, populations and environmental parameters should be monitored in the long-term at a site or sites known to have an established population of *C. fluminea*. Furthermore, adjacent downstream stretches could be monitored for juvenile clam settlement and periodic drift events. An understanding of the dispersal patterns of *C. fluminea* in New Jersey rivers and streams is most crucial to preventing further range expansion and preserving native freshwater mussel habitat and diversity. Naturally unpredictable riverine environments are increasingly subject to disturbance of greater scale and intensity with increased anthropogenic influence over the surrounding watershed (Poff and Ward 1990, Strayer 2006) with repercussions in aquatic invertebrate communities (Carlisle et al. 2008, Palmer 1996). The exacerbated disturbance has allowed the invasive Asian clam to persist in temporally variable habitats and artificially maintained systems. It appears repeated sampling at a single site can best indicate the relationship between population dynamics and specific environmental variables, particularly dissolved oxygen. This information coupled with documentation of dispersal in specific stream segments can aid in the development of predictive models of *C. fluminea* dispersal.

Figure 1: The distribution of *C. fluminea* in New Jersey's macroinvertebrate monitoring network as of 2004 with round 2 biological impairment values indicated by color. The majority of these sites (>70%) were moderately impaired during the second round of AMNET sampling. Elevation contours (m) are also displayed.

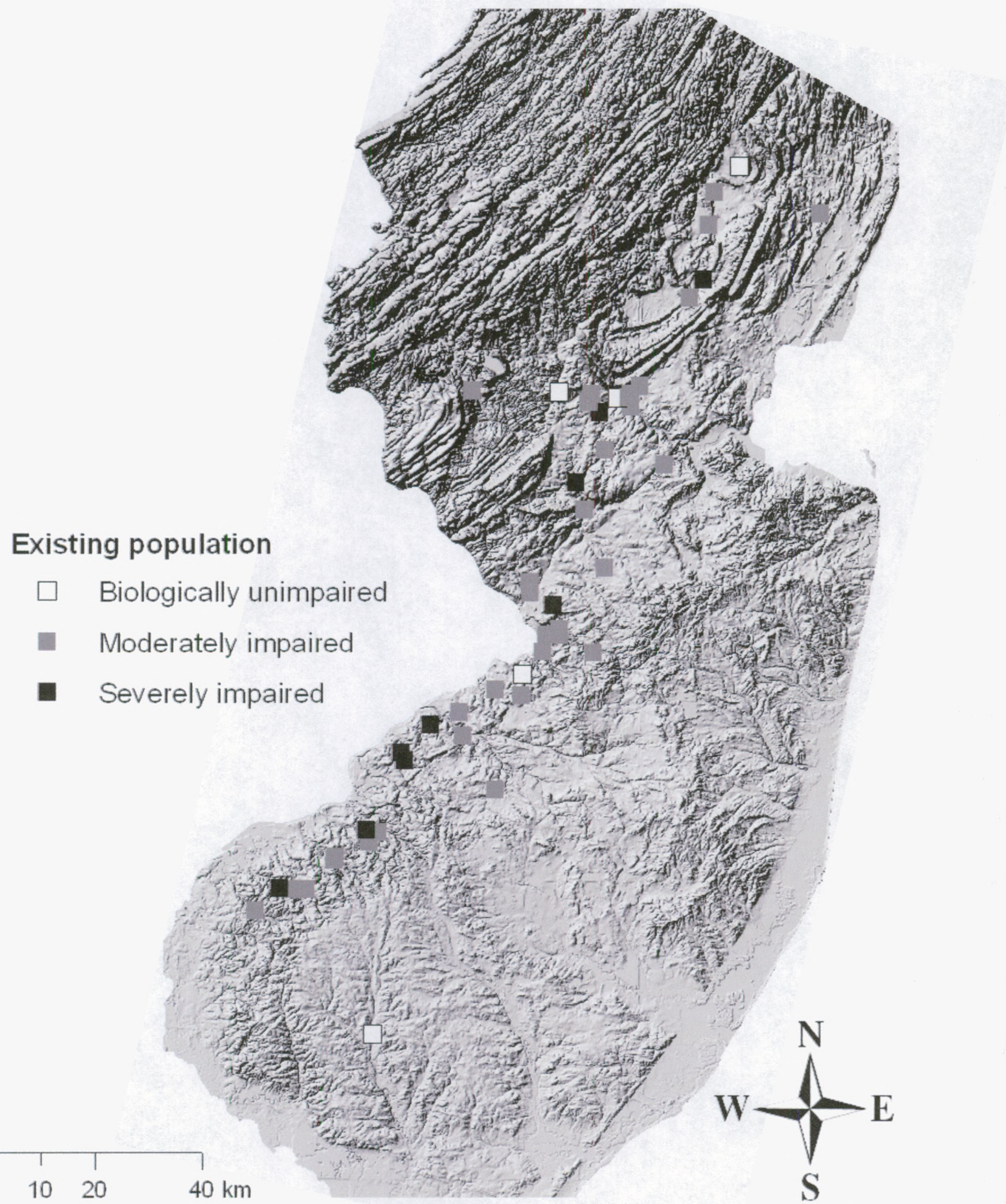

Figure 2: Stations in New Jersey AMNET as of 2004 and FIBI stations in northern New Jersey. FIBI stations in the Atlantic coastal plain are reportedly being established.

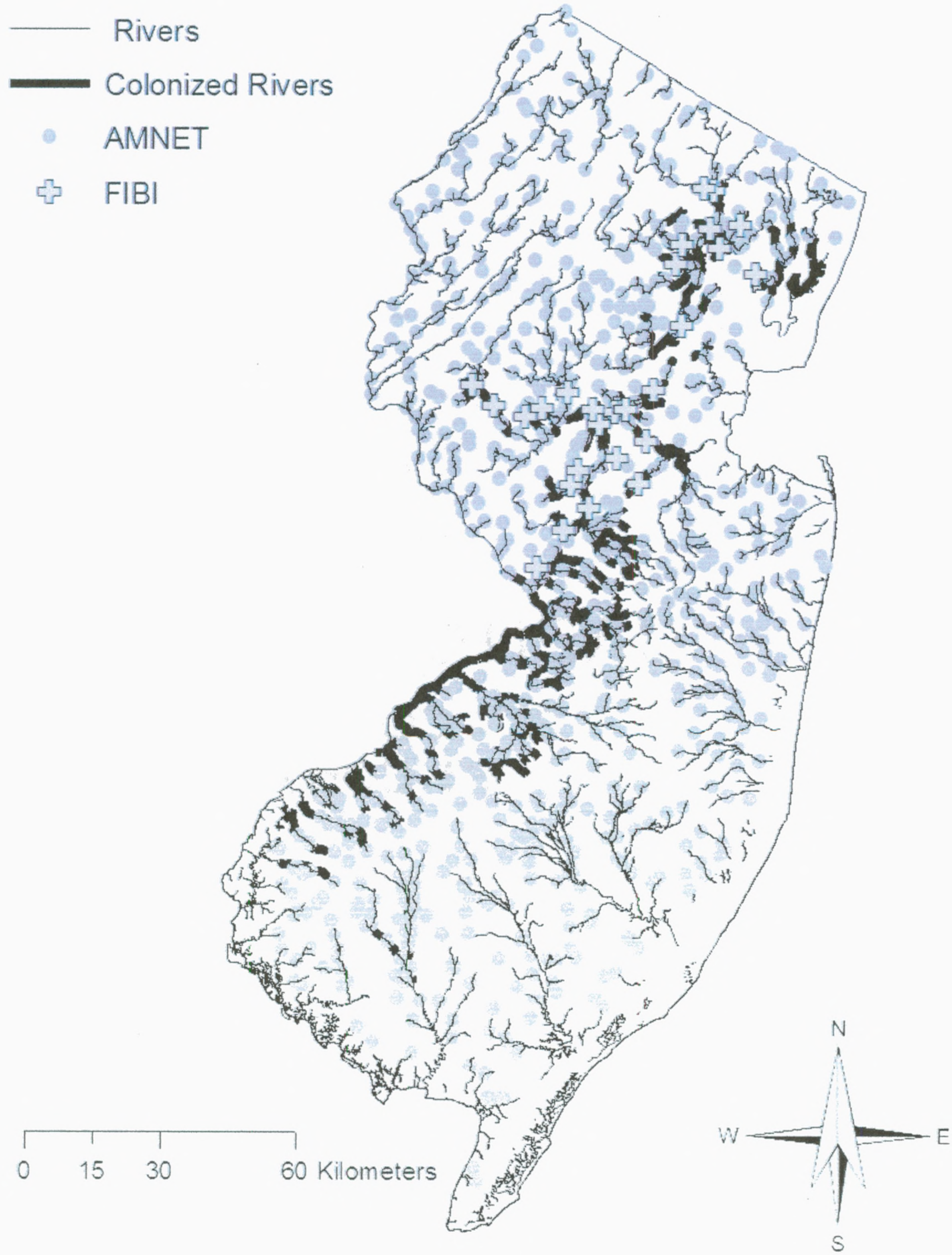

Figure 2: Stations in New Jersey AMNET as of 2004 and FIBI stations in northern New Jersey. FIBI stations in the Atlantic coastal plain are reportedly being established.

Figure 3: Sampling sites with and without clams between May and October, 2008. Clam density (m^{-2}) is indicated by marker size.

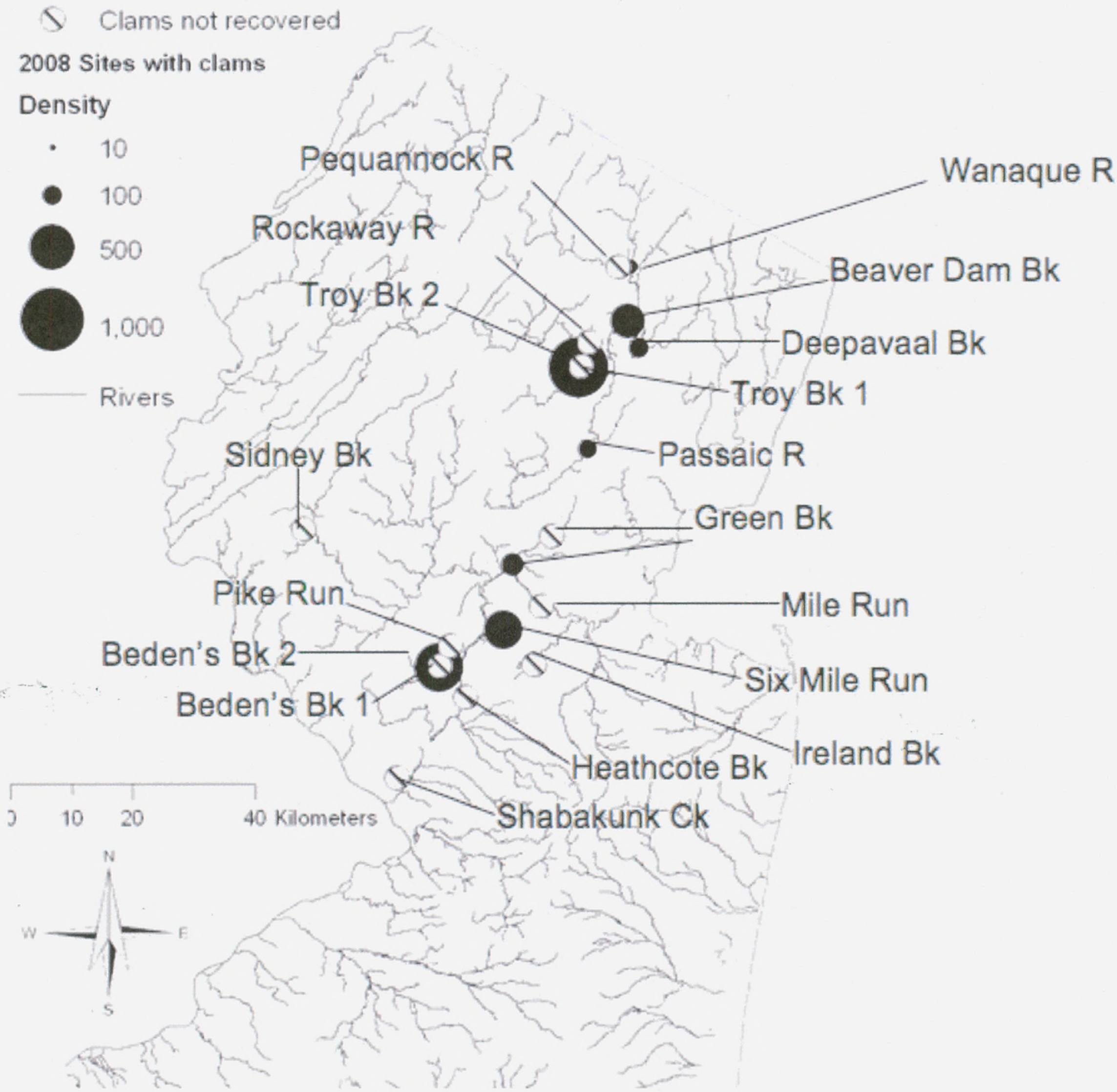

Figure 4: Shell length distributions of clams collected between May and October 2008. The Beaver Dam and Green Brook sites were sampled in both rounds denoted by the numbers 1 and 2.

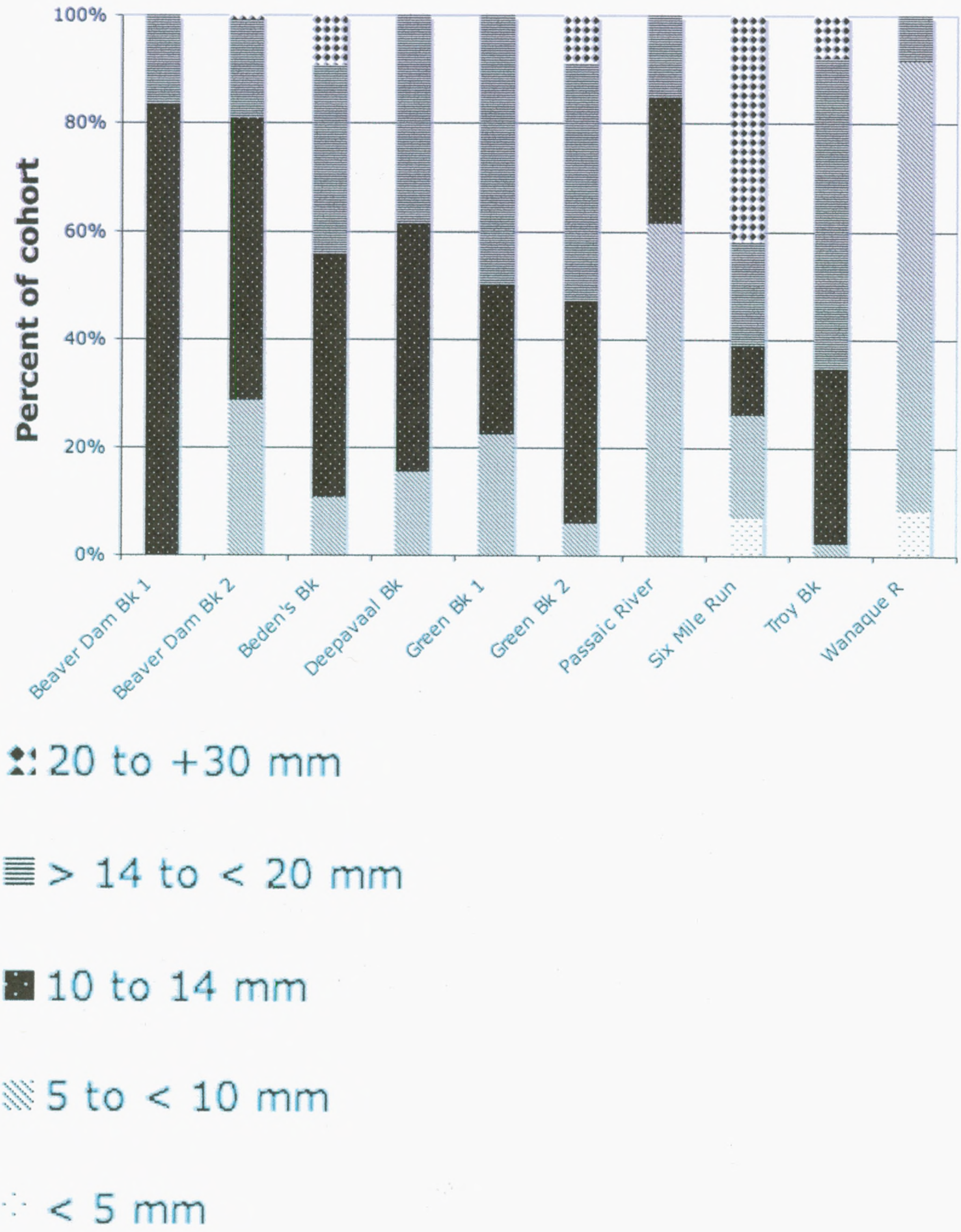

Figure 5: Substratum fractions are classified according to the Wentworth scale. No significant correlation was observed between density (m^{-2}) and (a) coarse sand and gravel ($p = 0.238$), (b) medium sand ($p = 0.228$), (c) fine sand ($p = 0.128$), and (d) fine silts and clay ($p = 0.093$).

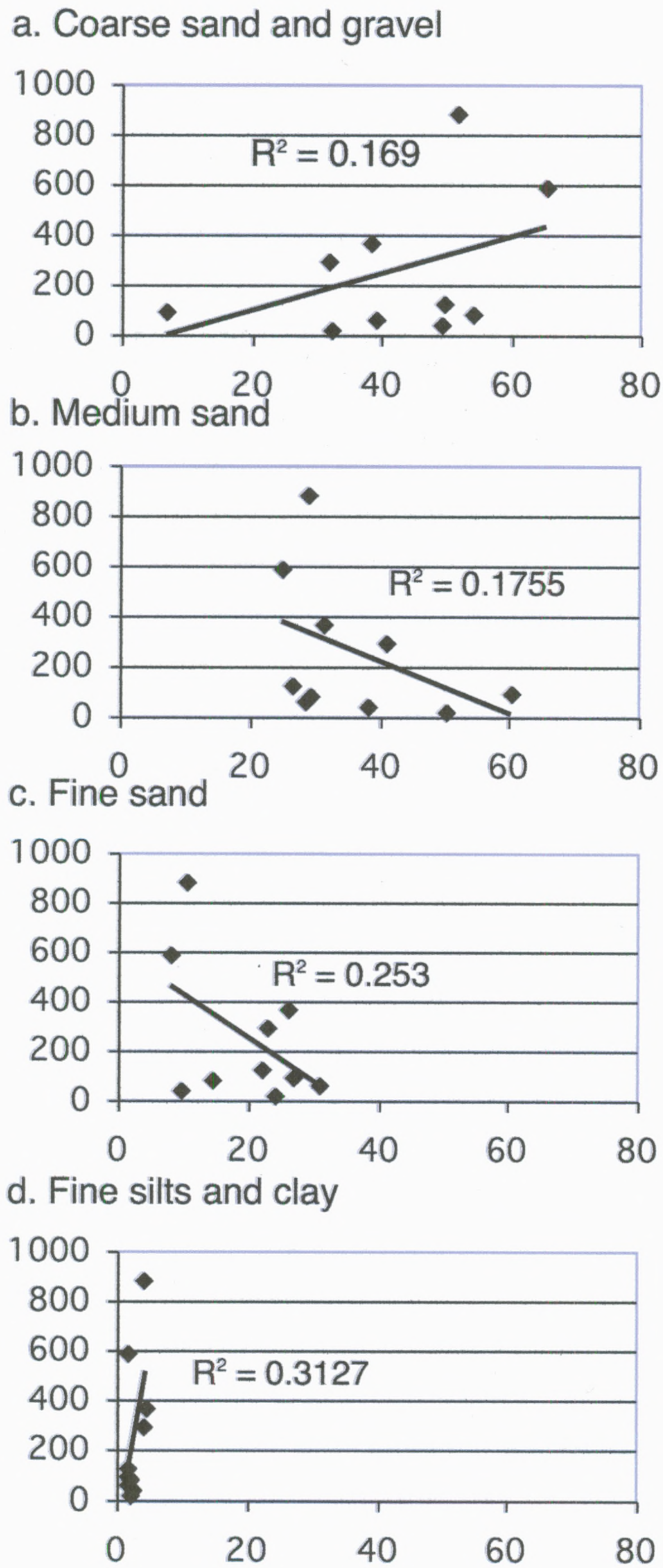

Figure 6: The relationship between substratum organic content (%) and clam density was nearly significant ($p = 0.055$) suggesting a possible positive correlation.

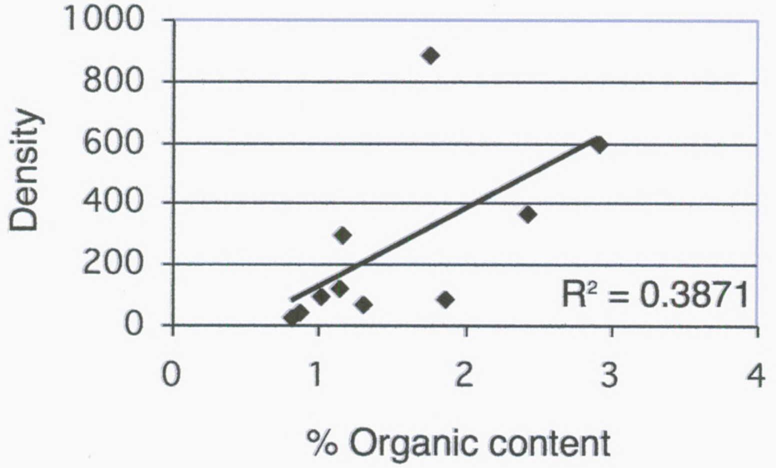

Figure 7: The correlation between DO levels and clam density (m^{-2}) was significant ($p = 0.013$). This relationship was expected as sensitivity to hypoxic conditions has been well documented in *C. fluminea* .

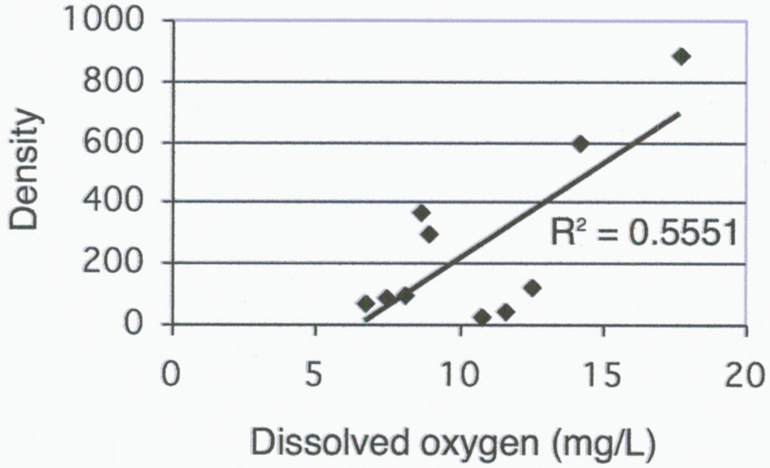

Figure 8: There was virtually no correlation ($p = 0.679$) between turbidity and clam density (m^{-2}) despite past demonstrations of the invasive bivalves' impact on water clarity. Turbidity varies greatly across stream width and a larger temporal scale as well. The relationship here is likely a dynamic one if present at all.

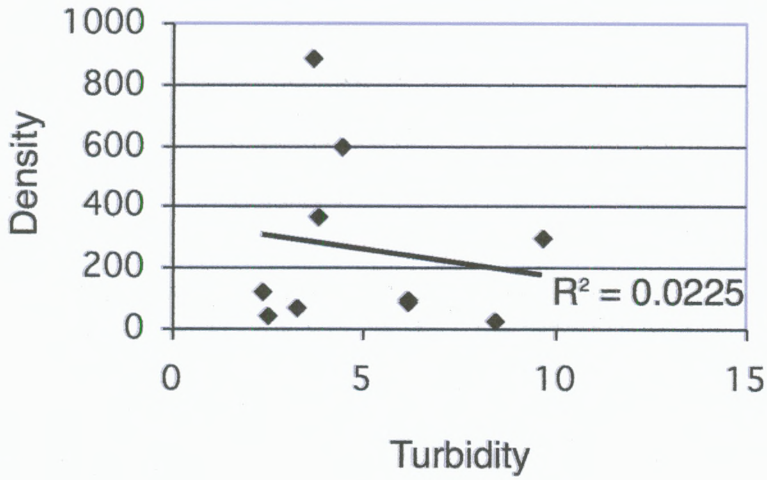

Figure 9: There was a significant relationship ($p = 0.038$) between the EPT values taken from the most recent round of AMNET sampling at stations closest to sampling sites and clam density (m^{-2}). It is important to remember EPT values are simply a reflection of the presence of pollution sensitive macroinvertebrates and are dependent upon assessed environmental conditions. Dissolved oxygen is a particularly important factor, and is likely responsible for some of the correlation observed between clam density and EPT score

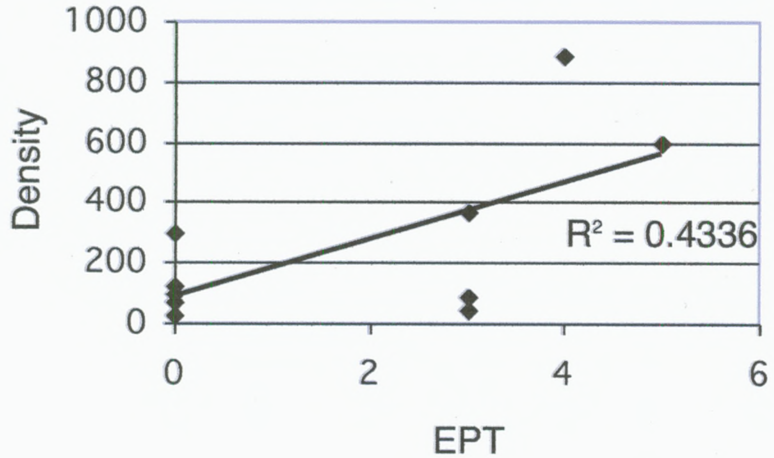

Table 1: Clam collection sites

Site	Date	Density (ind./m^2)	Max size range (mm)	Mean SL (mm)	Dominant substrata type (%)	Substrata organic content (%)	DO (mg/L)	EPT index	Turbidity
Deepavaal Bk	15 May	96	18.0 – 19.8	13.3	Med. sand (60.22)	1.02	8.09	0	6.12
Wanaque R	24 May	44	18.9	8.34	Coarse sand (49.36)	0.87	11.61	3	2.51
Beaver Dam Bk 1	30 May	22	14.7	13.08	Med. sand (50.2)	0.82	10.8	0	9.69
Passaic R	8 June	89	15.3 – 15.7	9.15	Coarse sand (54.17)	1.86	7.5	3	6.15
Green Bk 2A	14 June	67	14.1 – 19.7	14	Coarse sand (39.08)	1.31	6.7	0	3.28
Six Mile Run	27 June	370	14.3 – 31	16.43	Coarse sand (38.25)	2.42	8.7	3	3.8
Troy Bk 2	4 Oct	885	14.1 – 39.4	14.87	Coarse sand (51.67)	1.75	17.7	4	3.68
Green Bk 2B	5 Oct	126	14.3 – 20.4	14.68	Coarse sand (49.56)	1.14	12.5	0	2.35
Beaver Dam Bk 2	7 Oct	296	15.2 – 21.2	11.76	Med. Sand (41.14)	1.15	8.9	0	8.45
Beden's Bk 2	11 Oct	593	14.1 – 29.3	14.81	Coarse sand (65.55)	2.92	14.19	5	4.41

Table 2: Sites where clams were not recovered during 2008 sampling

Site	Sampling Date	Dominant substrata type (%)	Substrata organic content (%)	DO (mg/L)	EPT index	Turbidity
Pequannock R	24 May	*	*	12.68	12	2.25
Rockaway R	7 June	Coarse sand (74.33)	1.07	10.0	2	2.18
Troy Bk 1	7 June	*	*	7.0	4	8.81
Green Bk 1	8 June	Coarse sand (67.44)	1.13	8.05	2	1.8
Sidney Bk	13 June	Coarse sand (56.37)	2.5	9.9	10	9.08
Mile Run	14 June	Coarse sand (63.37)	2.54	7.2	1	6.92
Ireland Bk	28 June	Coarse sand (45.53)	0.61	8.5	2	0.52
Shabakunk Ck	25 July	Coarse sand (55.67)	1.12	6.67	3	5.37
Heathcote Bk	25 July	Coarse sand (57.18)	0.79	7.8	3	2.82
Beden’s Bk 1	26 July	Coarse sand (82.49)	2.23	9.9	5	4.51
Pike’s Run	26 July	Coarse sand (92.47)	3.68	8.9	2	25.84

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Appendix A

Current distribution of *Corbicula fluminea* in New Jersey documented by the USGS. This table was sent in a personal communication from USGS Fisheries Biologist, Amy J. Benson. The majority of specimens were reported to the USGS by the NJDEP Bureau of Freshwater and Biological Monitoring (BFBM). Where specimen collection years did not match AMNET sampling rounds, data from the subsequent round of AMNET sampling was supplemented.

AMNET Station Number	Spec ID	Site	Year	Clams collected	Impairment
AN0114	155806	Shabakunk Ck	1998	6	Moderate
AN0116	155807	Assunpink Ck	1992	8	Moderate
AN0117	155808	Pond Run	1992	2	Severe
AN0125	155809	Crosswicks Ck	1998	9	Moderate
AN0125	155810	Crosswicks Ck	1998	2	Moderate
AN0126	155812	Crosswicks Ck	1993	1	Moderate
AN0126	155811	Crosswicks Ck	1998	4	Moderate
AN0126	154653	Crosswicks Ck	2002		Moderate
AN0130	155813	Doctors Ck	1998	5	None
AN0131	155815	Crosswicks Ck	1993	2	Moderate
AN0131	155814	Crosswicks Ck	1998	18	Moderate
AN0131	154654	Crosswicks Ck	2002		Moderate
AN0134	155817	Blacks Ck	1993	6	Moderate
AN0134	155816	Blacks Ck	1998	25	Moderate
AN0134	154655	Blacks Ck	2002	29	Moderate
AN0137	155819	Crafts Ck	1993	18	Severe
AN0137	155818	Crafts Ck	1998	5	None
AN0137	154656	Crafts Ck	2002		None
AN0141	155820	Assiscunk Ck	1993	16	Moderate
AN0142	155821	Assiscunk Ck	1998	1	Severe
AN0167	155822	Barton Run	1998	6	Moderate
AN0169	155823	SW Br Rancocas Ck	1993	3	Moderate
AN0174	155825	Parkers Ck	1993	12	Moderate
AN0174	155824	Parkers Ck	1998	28	Moderate
AN0174	154657	Parkers Ck	2002		
AN0175	155826	Mill Ck	1998	2	Moderate
AN0176	155827	Swedes Run	1993	16	Severe
AN0184	155828	S Br Pennsauken Ck	1998	2	Moderate
AN0184	155829	S Br Pennsauken Ck	1998	4	Moderate
AN0185	155830	S Br Pennsauken Ck	1998	3	Moderate
AN0229	155831	Passaic R	1998	1	Moderate

AN0231A	155832	Passaic R	1998	1	Severe
AN0238	155833	Whippany R	1998	2	None
AN0268	155834	Pompton R	1998	3	None
AN0274A	155837	Passaic R	1998	10	Moderate
AN0291	155838	Saddle R	1998	2	Moderate
AN0326	155840	S Br Raritan R	1994	34	None
AN0326	155841	S Br Raritan R	1994	13	None
AN0326	155839	S Br Raritan R	1995	62	
AN0374	155843	N Br Raritan R	1994	7	None
AN0374	155844	N Br Raritan R	1994	1	None
AN0374	155842	N Br Raritan R	1995	2	
AN0375	155845	Dukes Bk	1993	1	Moderate
AN0376	155846	Peters Bk	1998	2	Moderate
AN0383	155848	Big Bear Bk	1993	13	Moderate
AN0383	155847	Big Bear Bk	1998	1	Moderate
AN0383	154658	Big Bear Bk	2002		Moderate
AN0397	155850	Millstone R	1993	3	Moderate
AN0397	155849	Millstone R	1998	1	Moderate
AN0405	155851	Pike Run	1994	4	Moderate
AN0410	155853	Millstone R	1984	1	
AN0410	155852	Millstone R	1988	33	
AN0413	155855	Royce Bk	1993	11	Moderate
AN0413	155854	Royce Bk	1998	3	Severe
AN0420	155859	Middle Bk	1994	5	None
AN0420	155858	Middle Bk	1994	5	None
AN0420	155856	Middle Bk	1995	5	
AN0420	155857	Middle Bk	1995	12	
AN0424	155861	Bound Bk	1992	9	Moderate
AN0424	155860	Bound Bk	1999	6	Moderate
AN0424	154659	Bound Bk	2002		Moderate
AN0425	155863	Ambrose Bk	1992	2	Moderate
AN0425	155862	Ambrose Bk	1999	6	Moderate
AN0425	154660	Ambrose Bk	2002		Moderate
AN0426	155865	Green Bk	1992	1	Moderate
AN0426	155864	Green Bk	1999	4	Moderate
AN0427	155867	UT Raritan R	1993	6	Moderate
AN0427	155866	UT Raritan R	1998	2	Moderate
AN0427	154660	UT Raritan R	2002		Moderate
AN0434	155869	Lawrence Bk	1993	2	Moderate
AN0434	155868	Lawrence Bk	1998	2	Moderate
AN0434	154662	Lawrence Bk	2002		Moderate
AN0659	155870	S Br Big Timber Ck	1995	4	Moderate
AN0663	155872	N Br Big Timber Ck	1995	30	Moderate
AN0663	155871	N Br Big Timber Ck	2000	1	Moderate
AN0665	155873	Almonesson Ck	1995	1	Severe
AN0671	155874	Chestnut Br	1995	13	Moderate
AN0672	155875	Mantua Ck	1995	11	Moderate
AN0680	155876	Raccoon Ck	1995	16	Moderate
AN0682	155878	S Br Raccoon Ck	1995	3	None

AN0682	155877	S Br Raccoon Ck	1995	58	None
AN0684	155879	UT Raccoon Ck	1995	21	Moderate
AN0688	155880	Oldmans Ck	1995	2	Moderate
AN0740	155881	Maurice R	1995	3	None

Appendix B:

Granulometric analyses of 2008 sampling sites.

Site	Quadrat	Coarse sand	Medium sand	Fine sand	Silts and clay
Deepavaal Bk	1	8.41	51.67	31	1.7
	2	7.68	67.76	23.48	1.1
	3	9.79	60.74	27.33	2.14
	4	1.11	60.71	26.31	1.91
Wanaque R	1	71.17	19.91	4.97	3.96
	2	40.35	42.98	11.16	5.03
	3	42.22	46.73	9.86	0.58
	4	43.69	43.11	12.63	0.46
Beaver D Bk. 1	1	38.92	57.45	36.97	1.69
	2	30.15	43	23.71	3.13
	3	26.48	50.62	21.24	1.66
	4	33.83	49.74	14.87	1.56
Beaver D Bk 2	1	42.09	38.12	16.67	3.17
	2	37.25	39.15	22.53	1.41
	3	29.03	34.07	28.49	8.41
	4	19.99	53.2	24.27	2.54
Rockaway R	1	80.56	14.57	3.79	1.3
	2	71.41	21.97	5.65	0.96
	3	65.15	29.82	3.48	1.56
	4	80.21	15.06	7.03	2.15
Green Bk A	1	54.31	32.87	0.88	1.2
	2	68.39	20.49	1.93	1.73
	3	99.83	73.66	2.78	4.39
	4	47.23	41.51	1.06	1.42
Passaic R	1	64.78	20.79	11.94	2.49
	2	50.07	32.85	15.43	1.64
	3	57.38	30.64	10.22	1.8
	4	44.45	33.27	20.9	2.58
Sidney Bk	1	42.92	32.61	14.13	10.35
	2	67.11	19.34	9.63	3.93
	3	69.44	19.48	7.97	3.11
	4	46.02	30.75	13.71	9.51
Mile Run	1	66.83	24.58	7.77	0.83
	2	64.86	27.3	6.45	1.36
	3	61.44	29.64	7.44	1.47
	4	60.36	30.1	8.51	1.03
Green Bk B1	1	43.9	27.74	26.55	1.8
	2	52.31	30.06	16.96	0.9
	3	23.47	41.53	33.55	1.5
	4	36.64	14.87	47.05	1.6
Green Bk B2	1	19.38	41.68	37.1	1.85
	2	57.74	25.96	14.59	1.71
	3	63.25	18.43	15.92	2.39
	4	57.86	20.59	20.33	1.23

Six Mile Run	1	24.71	45.61	26.12	3.69
	2	31.17	26.22	37.18	5.43
	3	49	21.02	24.22	5.76
	4	48.11	31.98	17.13	2.78
Ireland Bk	1	29.83	45.89	22.46	1.81
	2	69.49	24.65	3.5	2.34
	3	23.1	44.7	29.91	2.29
	4	59.71	29.36	9.94	0.984
Shabakunk Ck	1	55.28	21.79	16.5	6.43
	2	61.37	26.19	11.26	1.17
	3	64.11	20.16	14.96	0.78
	4	41.91	28.23	22.33	7.53
Heathcote Bk	1	52.88	23.98	21.62	1.52
	2	59.45	21.09	17.32	2.15
	3	53.88	25.08	19.88	1.16
	4	62.49	26.23	10.16	1.18
Bedens Bk 1	1	79.88	16.11	2.63	1.57
	2	93.57	2.87	2.09	1.47
	3	74.03	16.51	5.95	3.51
Bedens Bk 2	1	75.65	20.24	2.83	1.27
	2	53.31	30.4	14.29	2
	3	58.28	26.96	12.79	1.97
	4	74.96	21.32	2.4	1.32
Pike's Run	1	94.02	4.81	1.45	0.22
	2	90.91	6.02	1.04	2.39
Troy Bk	1	54.69	25.55	14.19	5.57
	2	47.4	35.81	13.22	3.57
	3	48.88	36.39	12.05	2.68
	4	55.72	18.64	2.07	4.92