Linking Fish Species Diversity to Green Crab Abundance in the Casco Bay Aquatic Systems Survey (CBASS)

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Abstract:

Invasive European Green Crab (*Carcinus maenas*) populations have been rapidly spreading in the coastal waters of Maine. Green crabs are opportunistic feeders and have been known to cause large-scale disruptions to the health and function of the benthic ecosystem. A disturbed benthic ecosystem may have cascading effects on available habitat for migrating fish species that use the coastal zone at some point during their lifecycle. Here, we used an eight year (2014-2022) nearshore dataset to analyze interactions between fish species diversity and green crab abundance. Using a generalized additive model (GAM), we found that green crab abundance had a statistically significant relationship with fish species diversity. Low green crab abundance correlated to lower biodiversity, medium green crab abundance correlated to higher biodiversity, and high green crab abundance did not significantly affect biodiversity. These results indicate that green crabs survive in a wide range of environmental conditions, but thrive in areas where fish populations are present in higher numbers because there may be more structure and plentiful resources there. However, increased interspecific competition for resources may favor green crabs, and therefore, reduce fish species diversity. Further understanding of the relationship between green crab presence and habitat change over time is necessary to generalize our findings.

Intro:

As climate change accelerates and species begin moving to new areas within their thermal tolerance, there is increasing concern about how entire ecosystems may be altered. Invasive species in particular are able to adapt to harsh conditions and spread quickly, affecting the biological community structure through both direct and indirect trophic relationships (Matheson, 2016). The European green crab *(Carcinus maenas),* is one such species that thrives in a wide range of environments and has been expanding its range northward since its first introduction to North America in 1817 near Long Island, NY. Green crabs were first spotted in Casco Bay, Maine in 1900 and their populations are increasing as the waters around Maine continue to warm (Neckles, 2015).

Many migratory fish species utilize the coastal zone at some point during their lifecycle as spawning ground, feeding ground, or as refuge, and thus, overlap with areas inhabited by green crabs. Previous research has examined the potential effects of green crab populations on coastal fish species abundance by observing their indirect effects, such as disturbances to the benthic environment, as well as looking at direct effects, such as predation or competition for resources (Matheson et al., 2016; Neckles, 2015; Taylor, 2005).

Previous work has supported the hypothesis that green crabs are agents of disturbance in benthic environments. Intermediate levels of disturbance may be beneficial to diversity (Hughes, 2010). However, it is difficult to quantify benthic disturbance and explain how much of the disturbance is due to green crabs especially in areas where the introduction of green crabs preceded scientific record keeping (Hughes, 2010). Green crabs are known to damage and uproot eelgrass shoots while scavenging the benthic environment for prey and burrowing from predators. In 2013, scientists noted a dramatic loss of eelgrass in Casco Bay. The reduction in eelgrass habitat was correlated with a reduction in fish and wildlife populations, degraded water quality, erosion, and less carbon dioxide uptake in the coastal ecosystem (Neckles, 2015). In a 2016 study, Matheson et al. observed experimental eelgrass removals in Newfoundland led to declines of up to 80% in fish abundance and biomass (Matheson et al., 2016). However, here in Casco Bay, there is a lack of historical monitoring of green crab densities, making it difficult to attribute eelgrass declines and fish abundance declines directly to green crab presence (Neckles, 2015).

Other studies have examined the more direct impacts of green crabs on migratory fish species such as predation or competition for resources. In a 2005 study, Taylor found that green crabs may account for on average 2.2% of the daily mortality in winter flounder from immunological dietary analysis. While crabs predate on some migratory coastal fish species, other migratory fish are out of their reach until they can be scavenged post-mortem (Taylor, 2005). However, green crabs may still have direct impacts on fish abundance through competition. The coastal zone is a preferred habitat overlap for both green crabs and migratory fish species and so they may be competing for niche space and resources (Matheson et al., 2016).

Since 2014, the Gulf of Maine Research Institute has been collecting seine, eDNA, zooplankton, and environmental data from early June to late August for the Casco Bay Aquatic Systems Survey (CBASS) to assess the long-term ecosystem health of the Casco Bay region (*Casco Bay Aquatics Systems Survey,* 2018). Utilizing this dataset is beneficial for this study in which we examine trends in fish species biodiversity in relation to green crab presence in Casco Bay. Green crabs are expected to negatively impact fish diversity and benthic community biodiversity due to direct competition for resources and indirect effects on benthic habitat structure. This study has implications for understanding the impact green crabs have on overall ecosystem health. Further, environmental regulators may be able to use this information to help establish long-term ecosystem management goals and draw attention to the issue of invasive green crabs in local fishing communities.

Methods:

We analyzed data from seine sampling at 12 different nearshore sites in Southwestern Casco Bay over an eight year period between 2014 and 2022. No data was collected in 2018. A total of approximately 543 seine hauls were completed, of which 509 had fish and/or crabs present. Seining protocol was consistent at each site. The seine net was 150 feet long and four feet tall with a mesh size of 3/16 square inches. One person on shore held the net at one end while another person guided the net out from the deck of a small boat. As the net was deployed, the boat backed out and the other side of the net was brought to land to complete a semi-circle. The people at both ends of the net pulled it in and the contents of the bag were examined. For each species caught, the first 25 individuals were measured to the nearest millimeter while the rest were counted for total species abundance. Other environmental measurements (temperature, salinity, dissolved oxygen, benthic substrate type, tide, and weather conditions) were recorded. The seine data was compiled, organized, and cleaned for analysis. To quantify fish species diversity, we used the Simpson's biodiversity index (relative abundance) at each site for each trip. The formula for Simpson's Index is:

$$D=1- (\Sigma\, n(n-1)/N(N-1))$$

The index value is indicated by D, the number of individuals of a single species is indicated by n, and the number of individuals in the total population is indicated by N. All data was analyzed using R studio.

Results:

To investigate differences in green crab abundance at each of our 12 sites, we ran a Kruskal-Wallis test using the natural log transformation of green crab abundance ($p<0.001$; df=11). This test demonstrated that there was enough evidence that at least one pair of sites had a statistically significant different mean green crab abundance to each other. To determine which sites these were, we ran the Dunn Test with Bonferroni's correction for multiple comparisons. Pairwise comparisons using the Dunn test indicate statistically significant differences in median green crab abundance between sites with different letters (a, b, c, d, e, f) (figure 1). To investigate the differences in relative species abundance using the Simpson's index at each of our 12 sites, we repeated the statistical tests from above ($p<0.001$; df=11). Pairwise comparisons using the Dunn test indicate statistically significant differences in median fish species diversity (Simpson's Index) between sites with different letters (a, b) (figure 2).

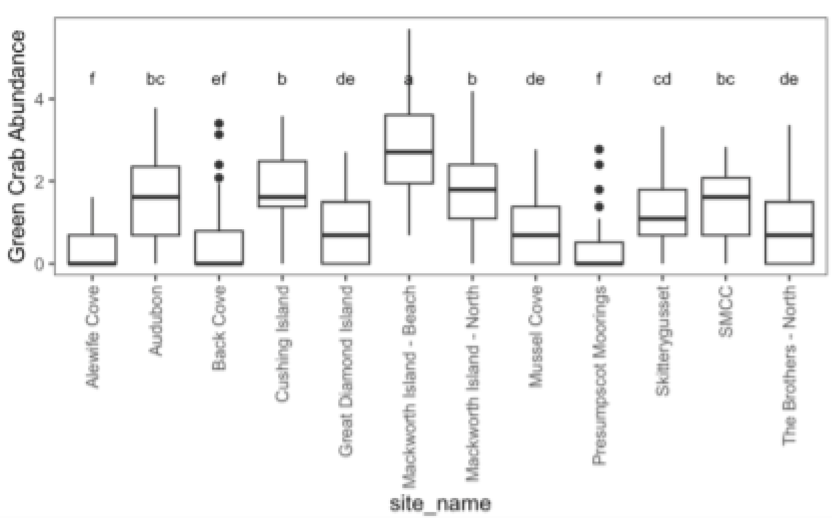

Figure 1: Box plot of green crab abundances at each of the 12 sites. The letters indicate statistically significant differences in green crab abundance between sites according to the Dunn Test.

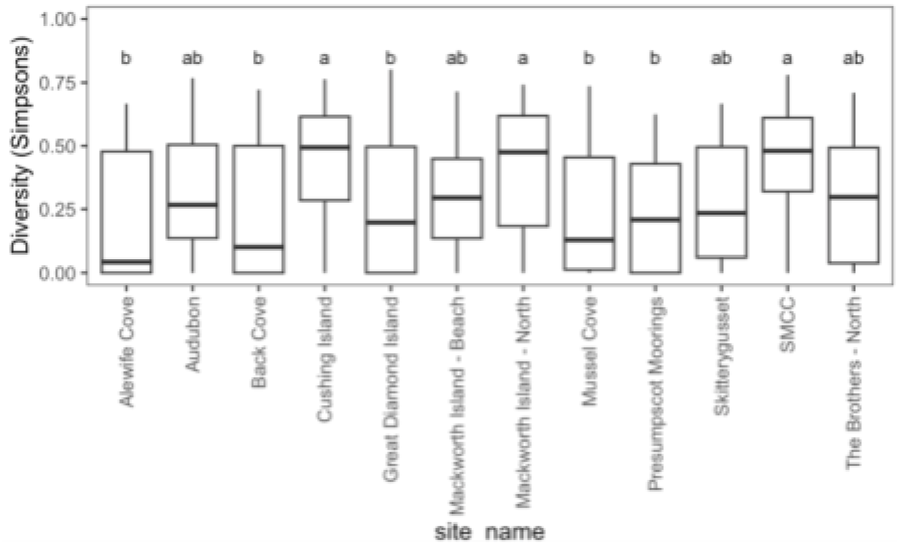

Figure 2: Box plot of Simpson's Index at each of the 12 sites. The letters (a, b, ab) indicate statistically significant differences in diversity between sites according to the Dunn Test.

To observe the general trend between green crabs and diversity, we plotted the log of green crabs against the Simpson's index (figure 3). There is no clear linear trend and we fail to meet the assumption of equal variance, so we did not proceed with a linear model.

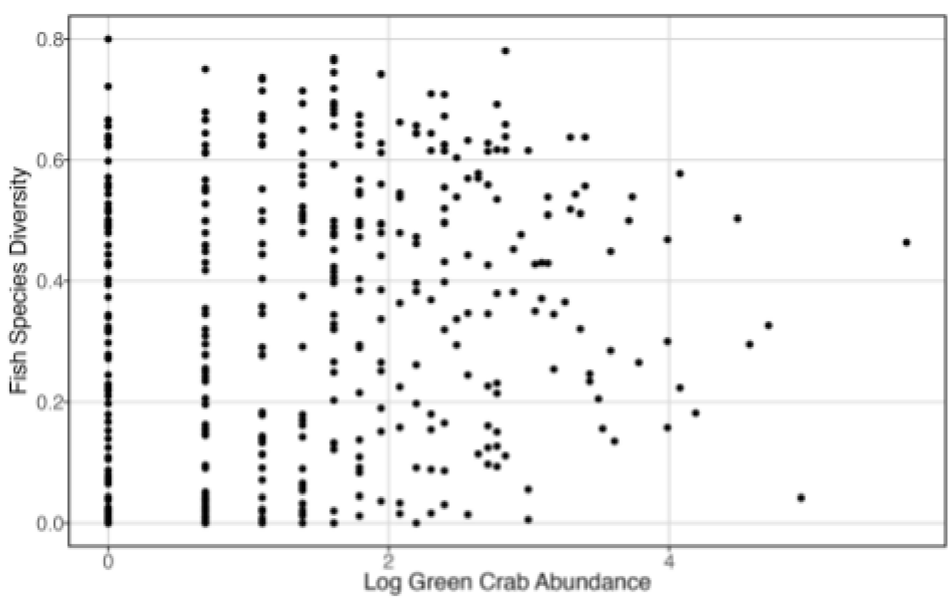

Figure 3: Scatterplot of the log of green crab abundance and fish species diversity calculated using the Simpson's Index.

We decided to proceed with a generalized additive model (GAM) to determine what, if any, relationship exists between green crab abundance and fish species diversity using the Simpson's Index. Generalized additive models are able to quantify non-linear relationships between one or more explanatory variables (quantitative or categorical) and a response variable. We thought to include temperature, salinity, tide height, numeric tide, bay location, weather, substrate, and dissolved oxygen as potential explanatory variables. Numeric tide was calculated by attributing a number between 0 (dead low tide) and 1 (dead high tide) regardless of the height for that day. These variables are all expected to impact fish abundance, and therefore biodiversity. We also included temporal variables (week and year) to account for temporal autocorrelation.

To test for collinearity prior to including all terms in the model, we used a correlation matrix which determined that temperature and salinity were correlated as well as tide height and numeric tide. We removed salinity and kept temperature because temperature is more spatially distinct. We removed tide height and kept numeric tide because we were more interested to see if high, medium, or low tides, regardless of height, affected diversity. To make sure we could continue with this model, we determined there were not any outliers in the response variable (Simpson's Index). Using a Gaussian distribution, with the restricted maximum likelihood method, we ran a GAM to determine what variables may be affecting the Simpson's index.

Previous research has identified tides to have significant effects on the biodiversity of organisms collected in coastal seine nets (Morrison et al., 2002). Studies have also found that fish diversity and abundance has both inter-annual and intra-annual variability, especially as the Gulf of Maine is rapidly warming (Staudinger et al., 2019). We ran an ANOVA on the variables and removed variables that were not significant one at a time until we were left with green crab abundance, numeric tide, and the interaction term of week/year as explanatory variables. Our results were consistent with previous studies, and so, we can feel comfortable proceeding with this model. Aikaike Information Criterion (AIC) was used to check model performance after every non-significant term was excluded. AIC results indicated that even though water temperature did not significantly affect Simpson's index, excluding it decreased model performance. Therefore, even though it has no significant effect on fish species diversity, it is an important factor to include.

The black line on each of the GAM outputs indicate the relationship between each explanatory variable (green crabs, tides, temperature, week/year) and its effect on the Simpson's index, all other variables held equal. The outputs center the mean response variable value at 0, so the horizontal blue line on each graph indicates the mean Simpson's index value for all observations of the explanatory variable. The shaded gray region is the 95% confidence interval. Confidence intervals are wider when there are fewer samples at that value of the explanatory variable because we cannot be as precise in determining the relationship to the response variable at those values. When the confidence interval includes the blue line, it indicates that the explanatory variable does not significantly affect the response variable at that particular value of the explanatory variable. The small vertical lines at the bottom of each plot indicate the raw number of samples at each value of the explanatory variable (figure 4).

Green crab abundance has a significant non-linear relationship with Simpson's index. When crab abundance is low (<5 individuals) Simpson's index is significantly lower than mean Simpson's index for all observations of crab abundance. Simpson's index at medium crab abundance (>5 and <40 individuals) is significantly higher than the mean Simpson's index for all observations of crab abundance, and there is no clear relationship between Simpson's index and crab abundance at high abundance (>40 individuals) (figure 4a). For numeric tide, we find a significant linear relationship with Simpson's index. When tide is low (<0.6), Simpson's index is significantly higher than expected, when tide is just above mid-tide (0.6), Simpson's index is at its expected value, and when tide is high (>0.6), Simpson's index is significantly lower than expected (figure 4b). For all temperatures, we see no divergence from expected, because as we reported in our ANOVA results, temperature has no significant impact on the Simpson's index, but was included because it helped to improve the model (figure 4c). For the week/year interaction, we see that Simpson's index is the highest at early weeks (June) and early years (2014) and is lowest at late weeks (September) and early years (2014) (figure 4d).

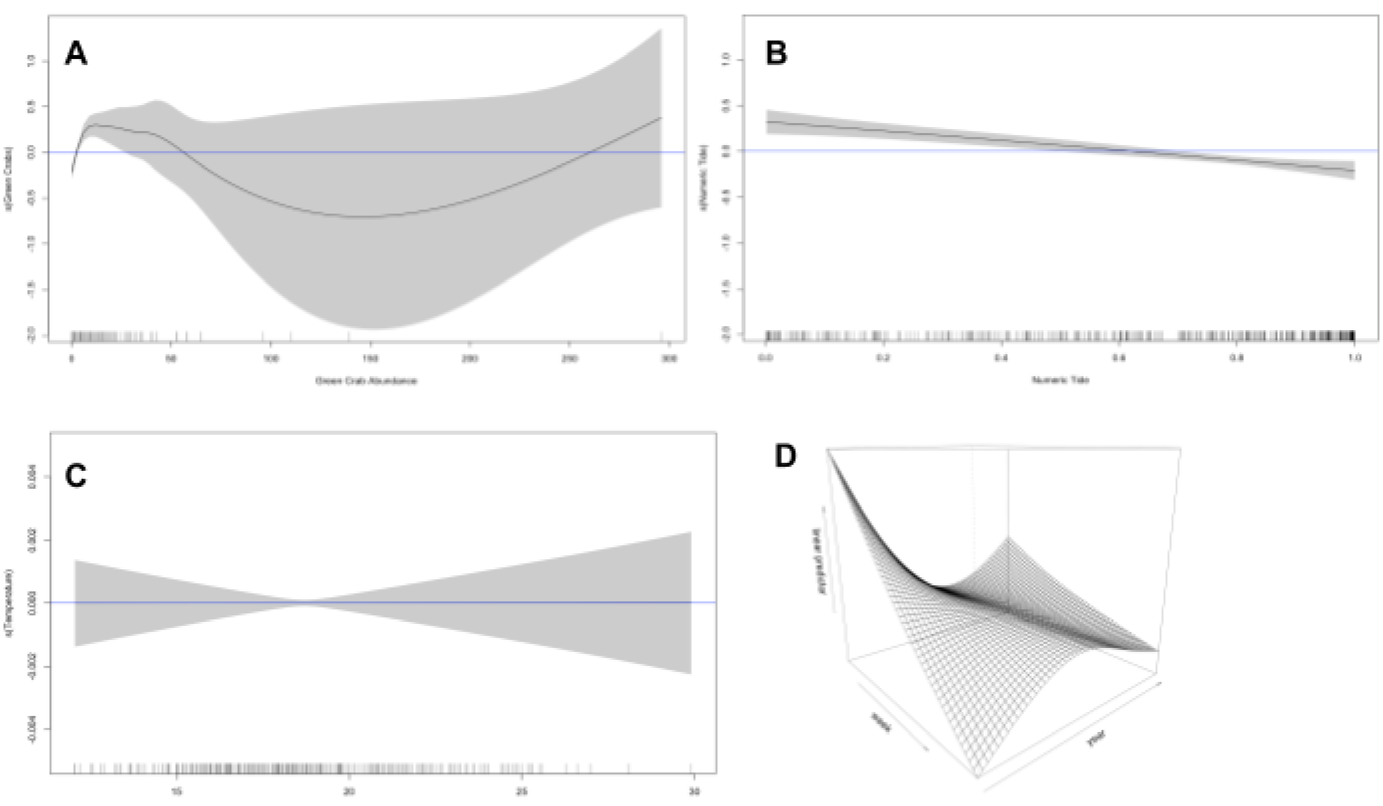

Figure 4: Generalized additive model (GAM) plots showing the partial effects of selected explanatory variables ((a)green crab abundance, (b) numeric tide, (c) temperature, (d) week/year) on fish species diversity. The tick marks on the x-axis are observed data points. The y-axis represents the effect of each variable. The shaded areas indicate the 95% confidence intervals.

Discussion:

Using the CBASS historical dataset from 2014-2022, we were able to link green crab abundances to fish species diversity. The data suggest that there were slight differences in green crab abundance and fish species diversity between sites. The results from the generalized additive model show that at low green crab abundance, fish species diversity was lower than the model expected, at mid-abundance of green crabs, fish species diversity was higher than the model expected, and at high abundance of green crabs, fish species diversity was not significantly different than expected (figure 4). Matheson et al. (2016) was able to attribute a reduction in fish species diversity to the reduction in eelgrass habitat from the invasion of green crabs. While we were unable to make connections between the direct effect of green crabs on the environment at our sites, these results may support the hypothesis that green crabs are able to survive in a wide range of environmental conditions, but they thrive more in areas where fish populations are present in higher numbers because there may be more structure and plentiful resources there. However, at high densities of green crabs, there may be more fragmented habitats which result in an increase in predation and competition for resources, and thus, fish abundances may not be supported in as high numbers (Matheson et.al, 2016; Neckles, 2015; Taylor, 2005).

We also examined trends in the effects of tides and the interaction factor of week and year on fish species diversity using the generalized additive model. We found that as the tide stage shifted from low to high tide, fish species diversity decreased. This trend aligns with previous research using beach seines, where low tide samples had substantially higher species diversity (Morrison et al., 2002). While it was found that diversity decreases with higher tides, it would be interesting to see if overall fish numbers follow this same trend as certain species may prefer to come inshore at higher tides. As species are migrating into the coastal waters of Maine, they arrive early in the summer and leave in early fall and these trends are shifting to be slightly earlier over time as the Gulf of Maine is warming (Staudinger et al., 2019). We found a similar trend when observing the interaction effect of week/year on fish diversity. At early years and later weeks, fish diversity was lowest, at early weeks and mid years, fish diversity was highest. This may be the trend because we expect inter-annual variation in diversity due to changes in species abundance caused by availability of resources, reproductive success, and long-term environmental fluctuations with changing temperatures (Staudinger et al., 2019). We also expect weekly variation due to seasonal migrations of species that are not in the coastal zone all year.

We are unable to generalize our assumptions about what is causing this observed effect of green crabs on fish species diversity because we do not have a historical understanding of the benthic disturbance and habitat types at each of the sites over time to measure and attribute disturbance to green crab presence. In the future, it may be beneficial to get a better idea of the habitat health at each site and look at changes over time. It may also be interesting to look at the effect of green crab sizes, rather than numbers, on fish species diversity. This is important for ecosystem monitoring and development of regulations because the size of green crabs may predict future harm to the environment (high numbers of smaller crabs means they are successfully reproducing, leading to more potential future destruction). Long term monitoring of species diversity and interactions with invasive species, such as this study, are important for establishing environmental mitigation and a sustainable habitat for future populations.

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