A population study of the Asian shore crab, *Hemigrapsus sanguineus*, at Point Judith Pond, RI

The Asian shore crab, *Hemigrapsus sanguineus* (De Haan), has recently invaded the Atlantic coast of the United States. Its large populations and continued fecundity are indicative of its successful establishment. Competitive interaction with other coastal crab species has been a subject of many studies. For example, in *ex situ* experiments, *H. sanguineus* has been shown to be superior to a long-established invader: the green crab, *Carcinus maenas*. Because *H. sanguineus* has been found in such great density on some shorelines, it has been postulated that it poses an ecological threat due to its potential to disrupt native and established species. However, many investigators have noted the invasive crab's limiting habitat requirement for complex, rocky shorelines. After observation of Point Judith Pond, RI, we assessed whether there were enough rocky areas to support significant populations of *H. sanguineus* that might be disruptive to *C. maenas*. Using a photo-quadrat system alongside software analysis, transects were laid across areas of interest. *H. sanguineus* were collected and counted in each quadrat, allowing habitat metrics obtained from the photographs, such as rock size and cover, to be correlated with the density of crabs, their size, and sex. These data, paired with the observation that Point Judith Pond has ample habitat for *C. maenas* to be displaced to, led us to conclude that the *H. sanguineus* population in Point Judith Pond, RI, is likely not capable of causing severe disruption of the native *C. maenas* population as it currently stands, and that this trend may extend to other estuarine systems.

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INTRODUCTION: *Carcinus maenas* has been established in New England for approximately two centuries (Kraemer et al. 2007). Subsequently, it has become an integral part of the ecology in estuarine environments, such as Point Judith Pond, Rhode Island, where it now cohabitates with the blue crab, *Callinectes sapidus* and several other crustaceans across rocky shorelines, salt marshes, and various benthic substrata (Mosknes & van Montefrans 1998). The preferred habitat of *C. maenas* appears to be rocky shores (Epifanio et al. 1998). In the late 1980s, the Asian shore crab, *Hemigrapsus sanguineus*, was able to establish a foothold in New England, and it has since expanded its distribution and population along rocky shorelines from Pamlico Sound, North Carolina, to Cape Cod, Massachusetts (Williams & McDermott 1990; McDermott 1991; Lafferty & Kuris 1996). *H. sanguineus* is highly mobile as well as reproductively successful (Fukui 1998; McDermott 1998); it can thus spread aggressively. In some areas, it has become the most abundant intertidal crab (Ahl & Moss 1998; Lohrer & Whitlatch 1997), reaching densities of >300 individuals/ m^2 in extreme cases (McDermott 1998). *H. sanguineus* strongly prefers rocky substrate (MacDonald et al. 2007; Lohrer et al. 2000; McDermott 1998; Ledesma & O'Connor 2001), so much so that it displaces *C. maenas* from beneath cover (Jensen et al. 2002). This exploitative competition exposes *C. maenas* to predators as well as harsher abiotic conditions. *H. sanguineus* appears to be much less plastic in its tolerance for alternative habitats, though recent observations have found them in marsh environments (Peterson et al. 2014).

Additionally, laboratory manipulations have demonstrated that *H. sanguineus* will win a competition over a food item against *C. maenas* (Jensen et al. 2002). The fact that the larger constituents of both crabs' diets are the mussel *Mytilus edulis* and algae, such as *Enteromorpha* and *Ulva*, further suggests that *H. sanguineus* could have an influence on *C. maenas* (Ropes 1968; Brousseau & Baglivo 2005; Bourdeau & O'Connor 2003). The *in-situ* confrontations are likely non-agonistic, as it has been shown that green crabs that coexist with *H. sanguineus* have adapted subordinate behavior (Jensen et al. 2002). This means that *C. maenas* must continue foraging, expend more energy, and possibly lose out on food items. Additionally, *H. sanguineus* often co-occurs with juvenile *C. maenas* (Lohrer & Whitlatch 1997; McDermott 1998), which closes the gap in size difference, thereby conferring *H. sanguineus* further advantage.

When these points are considered, it may seem as if *C. maenas* is bound to be negatively influenced by the invasive crab. However, at some sites, like Point Judith Pond, rocky shores are limited, and *C. maenas* has other habitats in the vicinity within which they do not face competition with *H. sanguineus*. Beyond conducting a population survey and correlating crabs to rock metrics, we tested the hypothesis that an estuary with few rocky shores cannot sustain *H. sanguineus* in great enough numbers to significantly adversely influence the *C. maenas* population, due to the alternative habitats for *C. maenas* offered by an estuary.

A unique aspect of this study is the inclusion of a photo-quadrat system paired with image analysis. Our study used the software photoQuad (Trygonis & Sini 2012), which is for advanced image processing of 2D photographic quadrat samples. This provides a much more exact degree of measuring rock metrics and correlating them to *H. sanguineus* populations. Previous studies (Ledesma & O'Connor 2001) measured rock cover by eye estimation. The methods in this study create more rigorous and set definitions while beginning to point towards a predictive model for *H. sanguineus* populations, as well as possibly other intertidal species dependent on rock metrics.

MATERIALS & METHODS: Two sites were sampled on Point Judith Pond in Rhode Island over the course of July and August 2013. Point Judith Pond is a brackish estuary, with salinity varying from approximately 26 ppt at the northern end to oceanic levels at the southern portion, which connects to the ocean past an artificial harbor (for more on the pond, see Stout 2006). The sites sampled were Gardner Island and Beach Island (41° 24' 22.83" N, 71° 30' 21.40" W). The two islands at their closest points are 100 meters from each other, whereas the sample sites were no further than 300 m from each other. Both sites have rocky shores; these were where transects were laid because *H. sanguineus* was not found in the sandy areas, as is noted by both personal observation and other investigators. Both islands were easily accessible via pontoon boat from Camp Fuller, the main base of the study. Each time an area was sampled, time and date was recorded as well as height up from the waterline.

Collecting fully submerged crabs was not carried out; upon investigation, these crabs were sparse, if at all present, and would have been near impossible to collect in a consistent and reliable fashion (McDermott 1998). This was of little concern, however, as the crabs are only reported to be subtidal in the winter months (Takahashi et al. 1985). Distance up from the waterline varied from 3-12 feet, depending on the slope of the shoreline, but modally was 3 feet.

The camera used for photo acquisition was a Nikon D40 (Nikon, Chiyoda, Tokyo). The photographs were analyzed using the software photoQuad (Trygonis & Sini 2012). The photo-quadrat system was mounted on a tripod, and a ½ meter PVC quadrat was used. One hundred foot transects were laid out along the shoreline at an appropriate height, between 3 and 12 feet up from the water line. Each transect was carried out while the tide was low but still receding. Quadrats were laid every five feet. The quadrat's picture was taken first, and then the rocks were flipped over in the quadrat. Crabs were collected by hand and placed in a bucket to be processed. Large rocks that were partially (1/3rd or more) in the quadrat were flipped; any rocks outside this were not turned over, and any crabs outside the quadrat were not counted.

Once collected, we measured the carapace width of each crab with vernier calipers to the nearest millimeter. *H. sanguineus* has three anterolateral teeth on each side of the carapace; the width of each crab was measured from the middle teeth. Previous work validated the need to only measure carapace width, as both weight and carapace length are related in a near exact fashion to the width (McDermott 1998). The crabs are sexually dimorphic and therefore could be easily and reliably sexed visually. Males possess a fleshy bulb at the base of the dactyl of the cheliped and the claws are larger than those of females (Sakai 1976). The crabs were then be moved to another bucket and released at the conclusion of the transect, so that no crabs could be counted twice.

RESULTS: A total of 268 *H. sanguineus* crabs were collected over the month-long period of sampling (see Table 1**)**. The population was found to have a sex ratio of 1:1. Sexual dimorphism in the current sampling was limited only to apron shape and cheliped size, as the average width of both males and females was not significantly different. The difference between gravid females and non-gravid females, however, was noticeable. On average, a gravid female was 2.27 mm wider than a given female, which likely reflects the required energetic cost of carrying eggs. Another interesting point regarding gravidity was the identification of *H. sanguineus*' egg bearing period. Not a single gravid female was found in July; all were found in August (Tables 2a & 2b).

The crab density did correlate positively with the different metrics of rock cover (Figs. 1-4). Out of all the quadrats, the greatest density of crabs/ half meter^2 was 14 individuals, found on three occasions. These quadrats had a significant amount of large rock cover. In no instance were crabs found in an exclusively sandy area.

Other measurements of note included that the largest female collected was 28 mm wide, while the largest male was significantly larger at 36 mm. *H. sanguineus* rarely attains carapace sizes wider than 40 mm (Fukui 1998, pers. obs., Jouett). The widest found at the current locale, but not included in the data, was 40.5 mm. The smallest gravid, and therefore mature, crab was 11 mm wide.

The photoQuad analysis involved five different methods of analysis. Crabs were compared to: the number of cobble sized rocks (defined as having an area ≥68 cm^2) (Fig. 1); the area of the largest rock in an individual quadrat (Fig. 2); the area of the average rocks size in the quadrat (of rocks that were larger than 16 cm^2) (Fig. 3); and the total coverage of rocks in the quadrat (also of rocks ≥16 cm^2) (Fig. 4). The strongest correlation among these individual components was seen when crabs were measured as a function of the total coverage. It was found that the smallest rock that had a crab underneath it had an area of 68 cm^2 (this was the justification for determining the definition of cobble sized rocks). The correlation shows that the larger the rock is past this threshold, the more crabs there are likely to be. The maximum amount of crabs found in any one quadrat was 14, which was on three occasions. For these quadrats, the smallest largest rock was 236 cm^2, which describes the highest *possible* observed density of the crabs. There were only two other cobble sized rocks in this particular quadrat, making it likely that most, if not all, crabs came from beneath this rock, as the next biggest rock was 84 cm^2. As far as density is concerned, the current study's quadrat size was half a square meter. If this is scaled up to a square meter, the highest density of *H. sanguineus* that the current study found was 56 individuals/ m^2.

Using a multiple linear regression in the statistical software package PAST (Version 3.02, Hammer et al. 2001), a more exact relationship linking all of the rock metrics to the abundance of crabs was found (see Table 3), demonstrating that multivariate analysis better describes the relationship of crabs to rock metrics than the analysis of any individual components.

DISCUSSION: McDermott's 1991 study reported a mean carapace width of 17.2 mm for males and 17.6 mm for females. The current study reports a mean carapace width of 15.4 ± 5.26 mm for males and 15.5 ± 4.95 mm for females. This is smaller than McDermott's study; however, when only the crabs collected in August from the current study are considered, the mean increases to 19.6 mm for males and 17.9 mm wide for females. These notable differences are likely attributable to the variations in locale and timing; this can be said with confidence because the size ranges of the current study were drastically different. The maxima for both males and females of McDermott's 1991 study were no larger than 24.5 mm, whereas the maxima for males and females in the current study were 36 mm and 28 mm, respectively.

H. sanguineus rarely attains carapace sizes wider than 40 mm (Fukui 1998, pers. obs., Jouett). The widest found at the current locale, but not included in the data, was 40.5 mm. The smallest gravid, and therefore mature, crab was 11 mm wide. This is significantly smaller than the smallest mature female in McDermott's 1991 study, which was 15.2 mm. However, the 2001 study by Ledesma & O'Connor was carried out in several, more proximal locales of southeastern Massachusetts and Rhode Island, and the smallest mature female that they found was 12 mm, which is much closer to this study's finding. This measurement is also corroborated by later findings, where 12 mm is approximated to be the smallest possible size of maturity. It was determined that sexual maturity in *H. sanguineus* is attained at 14 mm wide (Fukui 1998); however, this was for Japanese shorelines, and it is clear that this size is smaller for New England shores. Comparing Pacific and Atlantic shores is useful, and it is important to note the differences. *H. sanguineus*' range currently is thought to be no further south than North Carolina, and it has consistently been found to be no further north than Cape Cod (McDermott 1998). This makes its latitudinal distribution a fifth of its Pacific range. It is thought that, provided the necessary substrate, *H. sanguineus* therefore has the potential to expand further south.

In August, the percent of gravid crabs out of the entire female population sampled was 66% (n= 44/56). In Japan, *H. sanguineus*' native range, the period of egg bearing in the north is from March to October, with the peak being in May-June (Fukui 1998). In the south of Japan, however, the egg bearing period is shortened to 3 months (Takahashi et al. 1985). It has been suggested that the period is dependent on water temperature, and the period in New Jersey has been found to last from late April to September (McDermott 1991 & 1998). Other studies describe New England as facilitating a 4 month period for egg bearing (Epifanio et al. 1998). Though the current study did not span this long, all gravid crabs were found in August, while none were found in July. This curiously was also the case in McDermott (1991); this may be because the time of sampling was between broods in both instances, suggesting great similarity in the environments sampled.

Ledesma & O'Connor (2001) linearly correlated rock cover, estimated via eye by two observers, to *H. sanguineus* abundance. The R^2 value of their results was 0.534. While this is a strong relationship and does accurately describe what is found *in-situ*, it could be described in a better way, though far more difficult to calculate. Percent cover of rocks is not the most important factor; rather, it is the space between the rocks that the rocks create. This is referred to as structural complexity (Lohrer et al. 2000). The space between rocks helps reduce desiccation (also asserted by Grant & McDonald 1979), which is important for *H. sanguineus*. It also allows for mobility to different areas and evasion of predators, likely increasing foraging proficiency (Lohrer et al. 2000). More importantly, small shelters also serve as a buffer against temperature changes (Taylor 1981; Abele et al. 1986), to which *H. sanguineus* is sensitive (Epifanio et al. 1998). However, measuring structural complexity is difficult to do in the field, and thus measuring rock cover has been developed as a proxy for structural complexity. Our study shows that this has its faults, as we did not produce as tight a correlation as has been found previously while using a more precise method (Ledesma & O'Connor 2001). The multiple linear regression produced an adjusted R^2 value of 0.29992, which is stronger than any relationship generated with our univariate linear comparisons. Additionally, the ANOVA's p value (5.7169E-11) strongly suggests that the trends observed are not due to random sampling. Therefore, it appears that this study's analysis is not only objective (free of estimation), but also relatively robust and may have applications to other intertidal species dependent on rock metrics.

In terms of density, although potential estimates have put maximum *H. sanguineus*/ m^2 at 320 individuals (McDermott 1998), this is likely an overestimation. The current results are the same as actual previous results (Takahashi et al. 1985; McDermott 1998).

As far as competition with *C. maenas* is concerned, at both sites sampled in the current study, few *C. maenas* were observed. While some individuals present were indeed juveniles, as could be predicted by previous studies (MacDonald et al. 2007; Lohrer & Whitlatch 1997; McDermott 1998), no clear affiliation between site and size was observed. By personal observation, *C. maenas* is very abundant in Point Judith Pond; however, it seems to thrive in epibenthic environments and is less often found emerged. In fact, *C. maenas*' biggest competitor may be itself; the species is cannibalistic, and this causes a constant juvenile bottlenecking pressure. Juvenile *C. maenas* are more successful at surviving to adulthood when in a nursery habitat, such as eelgrass (Mosknes & van Montfrans 1998). Due to the crab's cannibalism, this also makes eelgrass meadows ideal habitats for adults. Point Judith Pond has an extensive bed of eelgrass in the middle of the main body of the pond as a result of dredging out the channel. The deposits were simply displaced to the center of the pond, and the decreased depth allowed eelgrass to grow in large beds (Stout 2006). When searching through these beds of eelgrass, *C. maenas* is found in abundance (pers. obs. Jouett).

However, there appears to be no doubt that *H. sanguineus* is having some effect on *C. maenas*. In its native waters, juvenile *C. maenas* often occur under rocks and shells in the intertidal zone (Crothers 1968; Klein-Breteler 1976; Thiel & Dernedde 1994). In Maine, which is too far north for *H. sanguineus*, *C. maenas* are also found under rocks in the intertidal zone (Epifanio et al. 1998). This therefore appears to be their preferred habitat, but they are seemingly displaced by *H. sanguineus* in New England rocky shores. Competitively inferior species may not necessarily be found in their preferred habitat if they are displaced by competitive superiors (Lohrer et al. 2000). However, *C. maenas* does not appear to be too adversely affected, as there are apparently numerous other habitats that they can thrive in (pers. obs. Jouett; Moksnes & van Montfrans 1998).

Additionally, significant amounts of the black fingered mud crab, *Panopeus herbstii*, were found to co-occur, in terms of proximity, with *H. sanguineus*. These individuals are significantly smaller, especially at more northern latitudes (Hines 1989), and are often found embedded in the mud underneath rocks. This proximity and habitat is described in the literature (Ledesma & O'Connor 2001; Epifanio et al. 1998) and is agreed upon in regards to the current study. While the overlap and competition between these two crabs cannot be commented on in the current study in regards to foraging, it is possible that these two crabs are competitors. Rock and shell substratum, as well as the presence of *Fucus vesiculosus*, is critical in the maturation of *P. herbstii* megalopae (Weber & Epifanio 1996), and the megalopae could be vulnerable to the various pressures of established *H. sanguineus*. Both crabs likely exploit the same benefits of the habitat because *P. herbstii* has the same stringent temperature requirements for juvenile development as *H. sanguineus* (Costlow et al. 1962). Additionally, it is well documented that *P. herbstii* is vulnerable to desiccation (McDonald 1977).

After a review of the various literatures on the subject, attempting to define *H. sanguineus* residence in terms of the tidal levels appears to be a fruitless task. The crab is, during the non-winter months, certainly intertidal. Because the goal of the current study was to correlate *H. sanguineus* individuals and their traits with rock metrics, areas of the shoreline could be selected where it would be thought many crabs could be found. However, this is not to say that crabs were not found significantly higher up. They could be found as high up as the tide went, though the upper limits often had fewer members presumably due to the degree of desiccation. By personal observation, these crabs were often larger (>25 mm) than their lower shoreline counterparts. All in all, conflicting consensuses exist concerning *H. sanguineus*. It has been characterized as a high intertidal crab in some studies (Takada & Kikuchi 1991; Lafferty & Kuris 1996; McDermott 1998) and as a low or mid-intertidal crab in others (Depledge 1984; Lohrer & Whitlatch 1997; Saigusa & Kawagoye 1997). The crabs seem to be solely dependent on the rock cover, so long as it is located within the intertidal zone (Hwang 1993; Lohrer et al. 2000). Finally, in accordance with the authors' view, *H. sanguineus* is characterized as being present throughout the intertidal (Lohrer & Whitlatch 1997). Wherever cobble sized rocks are deposited in the intertidal zone is therefore where these crabs will be found.

We conclude that at the Point Judith Pond locale, there is not enough structurally complex rocky shoreline available to support an amount of *H. sanguineus* that could be truly disruptive to *C. maenas*. Additionally, Point Judith Pond's shoreline perimeter to area ratio appears to favor *C. maenas*' relocation/displacement to shallow epibenthic areas. It seems that because an estuary has numerous habitat types, such as eelgrass beds, salt marshes, rocky shorelines, sediment flats, and sandy shorelines, competitive inferiors have many places to which they are able to relocate. In our study, the areas that contain a high enough cobble sized rock cover are limited: there are the two islands sampled, two other islands on the pond, and a few select portions of the shoreline, which overall make up a small portion of the estuary.

For example, if *C. maenas* were living on a rocky shoreline that was exposed to a large body of water, such as a large bay or the ocean, then *H. sanguineus*' effect would likely be much more profound. In this instance, the only habitat *C. maenas* could relocate to is deeper water, where it could be put into competition with *Cancer* or *Libinia* species. It may not be able to successfully compete with these new pressures or cope with the environmental differences. As traditionally noted, *C. maenas* may have its lower limit set by other crab species. Interestingly, this may also be the case for its upper limit in rocky shoreline areas, as traditionally opposed to abiotic factors. Upper and lower biotic limits are a widely studied phenomena in intertidal areas, and it would be of no surprise if this concept applied heavily to sympatric crab species.

Future work should emphasize developing a method to identify areas of *H. sanguineus* refuge from aerial imagery. By eye, it is relatively simple to (successfully) suppose where *H. sanguineus* may be located. If a program or analysis could be developed that could determine this from mass image data, population characteristics could be quickly deduced with relative accuracy. The methods and results of this study could serve as a starting point and may have applications for other intertidal species. These factors could then be compared to the amount of other habitats available to *C. maenas*, and if the amount of displaceable habitat is too low, then it could be postulated that *H. sanguineus* has the potential to adversely affect *C. maenas*. It is almost certain that in the absence of other competitive crabs, *C. maenas* would spread throughout the intertidal, epibenthic, and benthic environments. However, at Point Judith Pond, it is typically confined to the epibenthic because of food sources, acceptable substrate, and competitive superiors such as

H. sanguineus.

ACKNOWLEDGEMENTS: The authors would like to thank Prentice K. Stout for his wisdom, Nikki Sabatino for assistance in the field, and Camp Fuller for its facilities and materials. The manuscript benefited greatly from the suggestions of Dr. Graham Forrester. Last but not least, the authors would also like to thank the eager young minds and hands of all the campers at Camp Fuller who assisted in field collection of specimens, especially Jaydon Gianfrancesco, who also took a majority of the photographs.

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Table 1 (on next page)

Table 1 - Data for all H. sanguineus sampled

Data grouping all crabs logged. Measurements are in millimeters. See Tables 2a and 2b for temporal differences

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Table 1	Non-Gravid	Gravid	All Females	Males	All
Mean	14.39326	17.79545	15.5188	15.43704	15.47761
Mode	11	15	15	14	15
Std. Dev.	4.564233	3.897403	4.627981	5.259827	4.947237
Range	21	16	21	30	30
Min	7	11	7	6	6
Max	28	27	28	36	36
Total Count	89	44	133	135	268

Table 2 (on next page)

Table 2a - Data for H. sanguineus in July

Temporal data for crabs in July. Measurements are in millimeters. No gravid females were found

Table 2a	Females July	Males July	All July
Mean	13.75325	12.90476	13.31056
Mode	11	14	14
Std. Dev.	4.280174	3.137872	3.740381
Range	19	19	20
Min	7	6	6
Max	26	25	26
Total Count	77	84	161

Table 3 (on next page)

Table 2b - H. sanguineus data for August

Temporal data for crabs in August. Measurements are in millimeters

Table 2b	Non-Gravid Aug	Gravid Aug	All Females Aug	Males Aug	All Aug
Mean	18.5	17.79545	17.94643	19.60784	18.73832
Mode	16	15	15	18	18
Std. Dev.	4.337993	3.897403	3.965394	5.41139	4.760958
Range	17	16	17	23	25
Min	11	11	11	13	11
Max	28	27	28	36	36
Total Count	12	44	56	51	107

Table 4(on next page)

Table 3 - ANOVA of multiple linear regression

Multiple linear regression with crab count per quadrat as the dependent variable and rock metrics as the independent variables.

N	N=155
Multiple R	0.54765
Multiple R^2	0.29992
Multiple R^2 adjusted	0.28125
ANOVA	
F	16.065
df1, df2	4,150
p	5.7169E-11

Figure 1

Crabs versus cobble

Number of crabs as a function of cobble sized rocks. "Cobble sized rocks" were defined as rocks that had an area of 68 cm² or higher in photoQuad analysis.

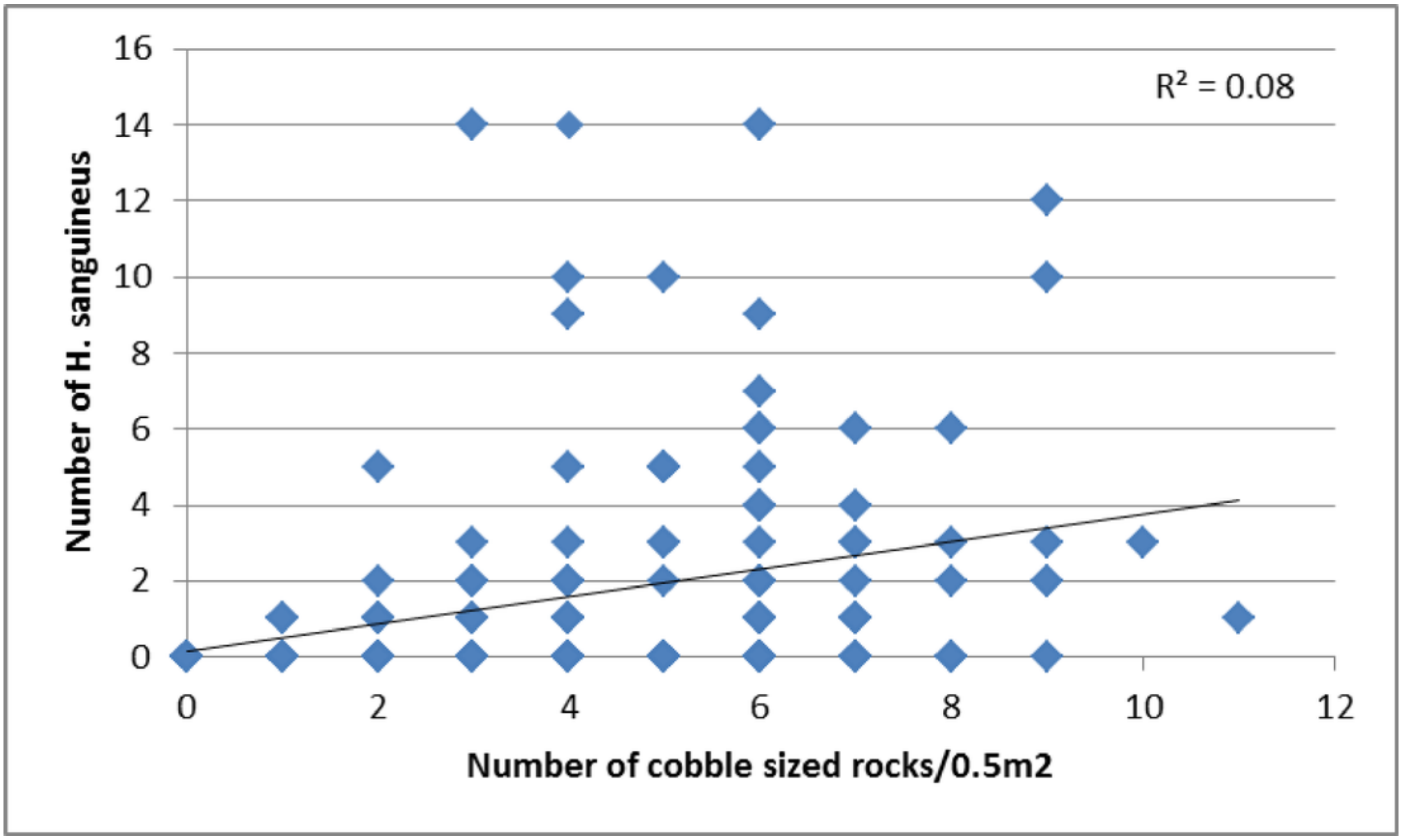


Figure 2

Crabs versus average rock

Number of crabs as a function of the average individual rock area.

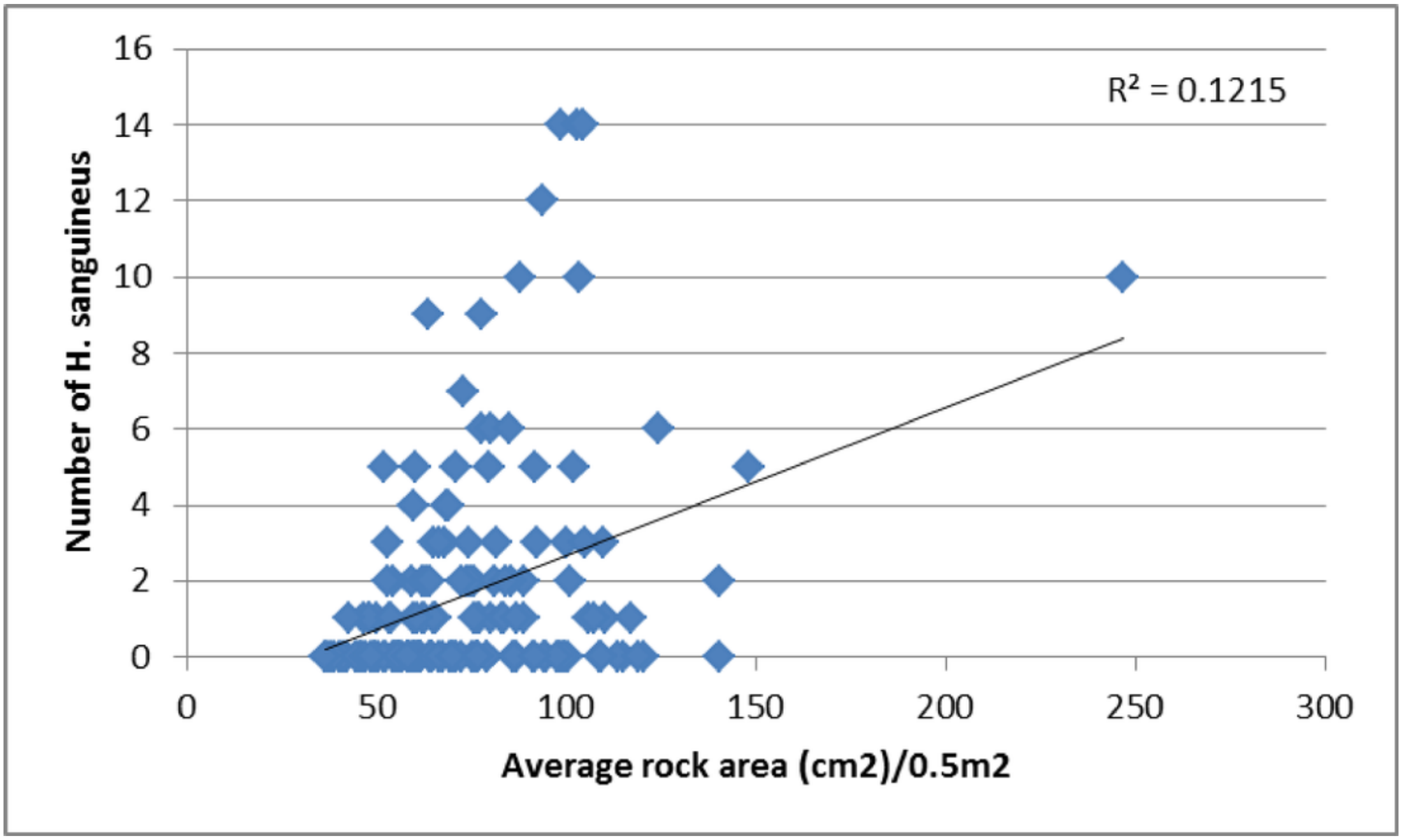


Figure 3

Crabs versus largest rock

Number of crabs as a function of the largest rock's area per quadrat.

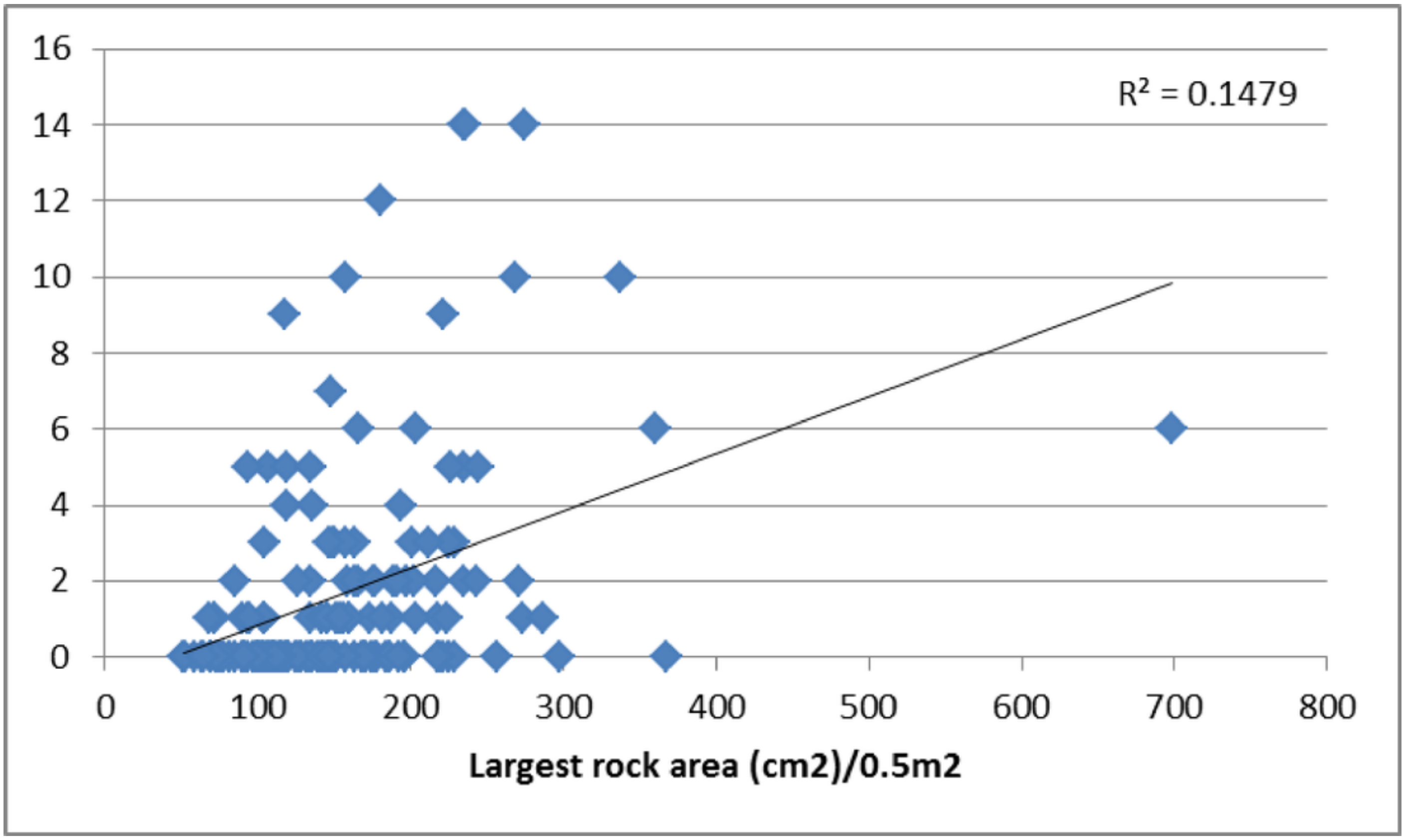
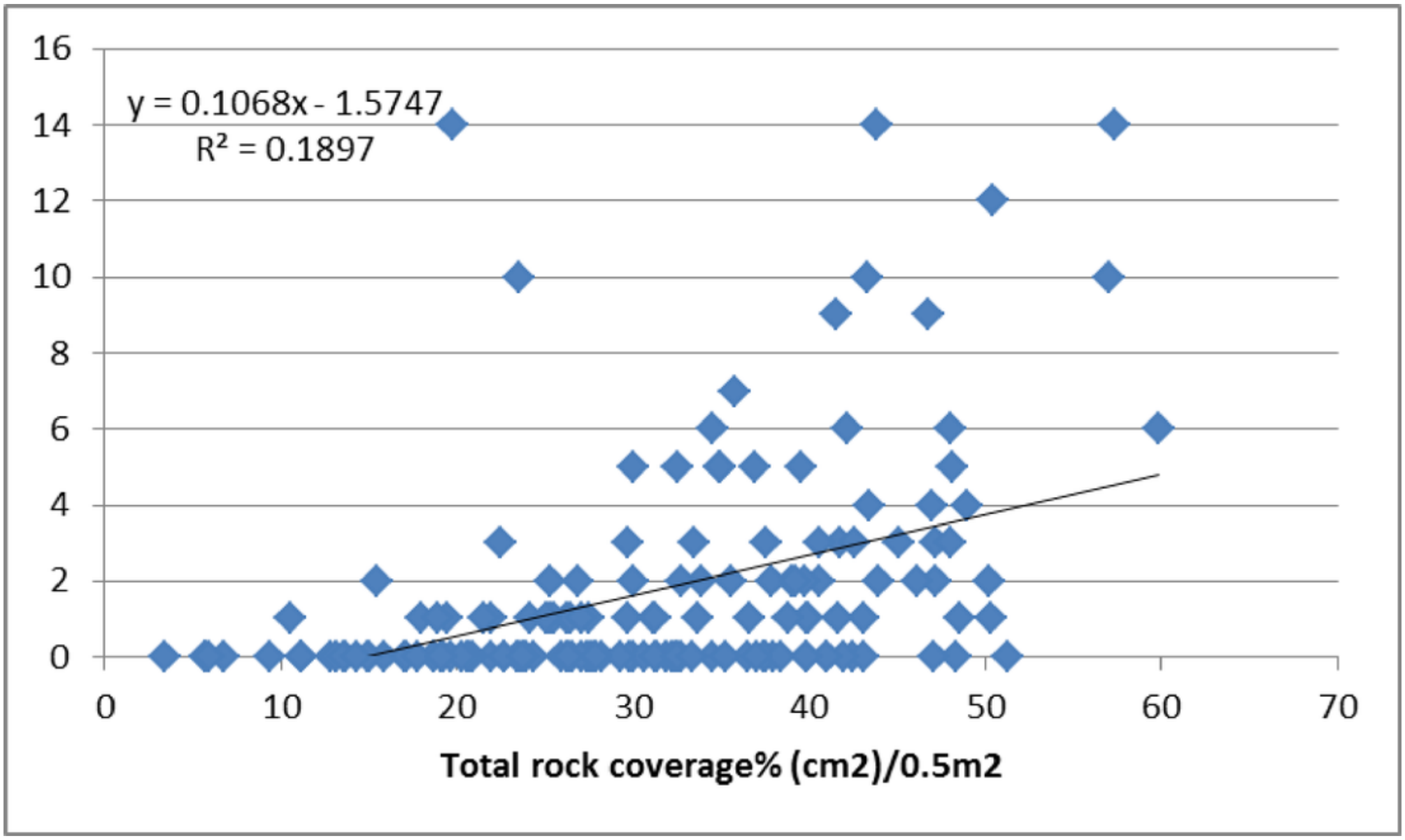


Figure 4

Crabs versus total coverage

Number of crabs as a function of the total rock coverage.



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