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LASTING IMPACT AND RECOVERY FROM THE DEEPWATER HORIZON OIL SPILL
OF A DEEPWATER CORAL COMMUNITY IN THE GULF OF MEXICO

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ABSTRACT

The Deepwater Horizon rig blowout released an estimated 4.1 million barrels of oil, as much as half of which remained in the water column or was deposited onto the seafloor, posing a high risk to deepwater ecosystems. A coral community in BOEM lease block MC294, located 11km from the Macondo well at a depth of 1370m, was discovered in 2010 with many corals showing signs of impact from the blowout. A paper published by Hsing and colleagues (2013) found the median total visible impact of the corals at this site decreased between November 2010 and March 2012, correlating the degree of initial impact with lasting damage. Here, we present a follow-up study, expecting similar decreases in median total visible impact and the continued presence of hydroid colonization. Through a series of eight research expeditions between November 2010 and June 2014, 49 *Paramuricea biscaya* corals were imaged and digitized. Individual branches were categorized into four different categories depending on visible condition. Images were then compared between visits for transitions from one category to another, producing detailed temporal data of condition. The overall median visible impact of the corals decreased significantly between late 2010 and October 2011, but showed no significant changes after. We found significant rates of branch loss between March 2011 and June 2013, up to a peak of 0.72 break points per coral per month between November 2012 and June 2013. On 24 out of 39 corals, portions of hydroid-colonized branches recovered to a non-visibly impacted state, though the degree of recovery was small compared to the amount of hydroids that remained on the coral. Continual changes in hydroid composition and branch loss indicate the corals are still in a state of flux, and despite permanent damage from by branch loss, overall the data suggests that the level of impact has leveled off.

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Chapter 1

Introduction

The Deepwater Horizon rig blowout was fundamentally different from the shallow water spills before it. Before the Macondo well was capped on 15 July 2010, an estimated 4.1 million barrels of oil were released at a depth of 1500m (Reddy et al. 2012). Buoyant oil and gas impacted a variety of shallow coastal and marine ecosystems (Fodrie and Heck 2011, McCrea-Strub et al. 2011, Garcia et al. 2012, Mendelssohn et al. 2012, Whitehead et al. 2012). Large amounts of hydrocarbons remained in the water column (Camilli et al. 2010, Socolofsky et al. 2011) and were deposited onto the seafloor following a patchwork mosaic model of distribution (Valentine et al. 2014), posing a high risk to deepwater ecosystems.

The Gulf of Mexico is composed mostly of soft sediment, with numerous exposed hard bottoms resulting from historical and natural hydrocarbon seepage (Fisher et al. 2007). These hard bottoms are often colonized by megafauna, including cold-water corals, which can alter local flow patterns, provide shelter for other organisms, and increase available organic matter (Raes and Vanreusel 2005); thus, any impact on these corals could affect the entire ecosystem. Furthermore, most cold-water corals are slow-growing and unlikely to recover quickly from damage (Roark et al. 2009, Prouty et al. 2014). In late 2010, a coral community in BOEM lease block MC294 was discovered in the vicinity of the spill (White et al. 2012a). Over half the corals in this community, composed mostly of *Pramuricea biscaya* gorgonians, exhibited signs of adverse impact, including coverage by flocculent material, tissue loss, and excess mucous production (White et al. 2012a), with a distinct patchiness of damage both within and between

coral colonies (Hsing et al. 2013). Analysis of hydrocarbons and dioctyl sodium sulfosuccinate in the flocculent material implicated the Macondo spill and dispersant as the likely causative agent for the damage (White et al. 2012a; White et al. 2012b, White et al. 2014).

Hsing and colleagues (2013) tracked temporal changes in the conditions of the MC294 coral community through a 16-month period from November 2010 to March 2012 (Hsing et al. 2013). They reported a decrease in the median total visible level of impact, correlating the degree of initial impact with lasting damage and secondary colonization by hydroids. Hydroid colonization seemed to be permanent on the coral. They also noted the rare occurrence of branch loss between visits, expecting branch loss to become more significant over time. Here, we present further temporal progression of impact up to July 2014, focusing on recovery from hydroid colonization previously unreported, no further significant changes in median visible impact, and high rates of branch loss as a sign of permanent damage.

Chapter 2

Materials and Methods

Image Gathering

Study Site MC294 (28.6722°N, 88.4765°W) in the Gulf of Mexico is located 11km southwest of the Macondo Well at a depth of 1370m (White et al., 2012a). Corals from this site were imaged during eight research expeditions (the first five of which were covered by Hsing and colleagues in 2013) using digital cameras and remote operated vehicles (ROV) (Table 1).

Date	Research vessel	Submergence vehicle	Camera	Image Availability
November 2010	Ronald H. Brown	ROV Jason II	Adimec 2000 high-def video camera mounted on pan and tilt	Dryad Digital Repository (http://doi.org/10.5061/dryad.73tj5)
December 2010	Atlantis	Alvin	Insite 3 CCD line video camera mounted or held in manipulator arm	Dryad Digital Repository (http://doi.org/10.5061/dryad.73tj5)
March 2011	Sweetwater	ROV Triton XLS	Imenco SDS 1210 digital camera held in manipulator arm	Dryad Digital Repository (http://doi.org/10.5061/dryad.73tj5)
October 2011	Holiday Chouest	Schilling ultra-heavy-duty ROV	AquaPix AquaSLR digital still camera held in manipulator arm	Dryad Digital Repository (http://doi.org/10.5061/dryad.73tj5)
*March 2012	Okeanos Explorer	ROV Little Hercules	Custom high-def video camera mounted on tilt mechanism	Dryad Digital Repository (http://doi.org/10.5061/dryad.73tj5)
November 2012	Falkor	ROV Global Explorer MK3	Digital still camera with 18-55mm lens and high-power LEDs held in manipulator arm	Not currently publicly available
June 2013	Nautilus	ROVs Hercules and Argus	AquaPix AquaSLR digital still camera held in manipulator arm	Not currently publicly available
June 2014	Nautilus	ROVs Hercules and Argus	BFC-6000 camera held in manipulator arm	PSU ScholarSphere (https://scholarsphere.psu.edu/files/5712mj29d#.VSsRA5NUVBA)

Table 1. List of eight research expeditions to collect images of corals at MC294. ROVs outfitted with a camera attachment were used to image corals. Asterisk denotes a visit whose images were of insufficient resolution for this study.

The various vehicles and cameras used during the visits resulted in differences among the datasets obtained. Quality of the images varied, different numbers of coral colonies were imaged each visit, and not every coral was imaged every visit, though efforts were made to re-image previously imaged corals from the same perspectives (vehicle heading) when possible. In several cases, multiple images of the same coral were taken and stitched into a mosaic using a mosaicking algorithm (Pizarro and Singh 2003) in the program MATLAB 2010b (MathWorks 2010).

For this study, the data set was limited to 49 *Paramuricea biscaya* corals (Grasshoff 1977), the most abundant species in the site. One *Acanthogorgia aspera* (Pourtalès 1867), one *Paragorgia regalis* (Nutting 1912), one *Clavularia rudis* (Verrill 1922), and two *Swiftia pallida* (Madsen 1970) were excluded due to difficulties in digitizing these corals that did not have an upright, fan-like structure. Three completely dead coral stubs were also excluded because their condition was not consistent with those of other corals damaged by the blowout. Furthermore, due to the patchiness of image collection during the first and second visits, these visits (only one month apart with no significant differences in total visible impact as reported by Hsing and colleagues) were combined into a single “Late 2010” data set.

AT357 is located 183km away from the Macondo well at a depth of 1050m (Hsing et al. 2013). The site was used as a control site to compare branch loss because corals here had almost zero visible impact, and no previously known coral site located 20km or more from the Macondo well exhibited impact attributable to the spill (White et al. 2012a). The site was first discovered in the October 2011 visit and revisited in November 2012, June 2013, and June 2014, though its data from June 2014 is not included here. 53 coral colonies were imaged at this site in October 2011.

Digitizing

A total of 49 digitizable corals were imaged through all the visits to MC294, though not every coral was imaged in every visit. Using the software Fiji (Schindelin et al. 2012) or Inkscape 0.48.2 (The Inkscape Team 2011), all visible portions of the coral were digitized into one of three categories identical to the categories used by Hsing and colleagues (2013): “1) branches with obvious and significant visible impact in the form of coverage by floc (White et al. 2012a), excess mucous production, obvious tissue damage, or bare skeleton; 2) branches clearly colonized by hydroids; and 3) branches without these forms of obvious visible impact” (Fig. 1c) (Hsing et al. 2013). Two additional categories were added: branches obscured by anemone or were otherwise incapable of being digitized; and lost branches. The total visible impact was defined as the sum of the visibly impacted, hydroid-colonized, and lost branches categories, a difference from Hsing and colleagues (2013) who did not include branch loss.

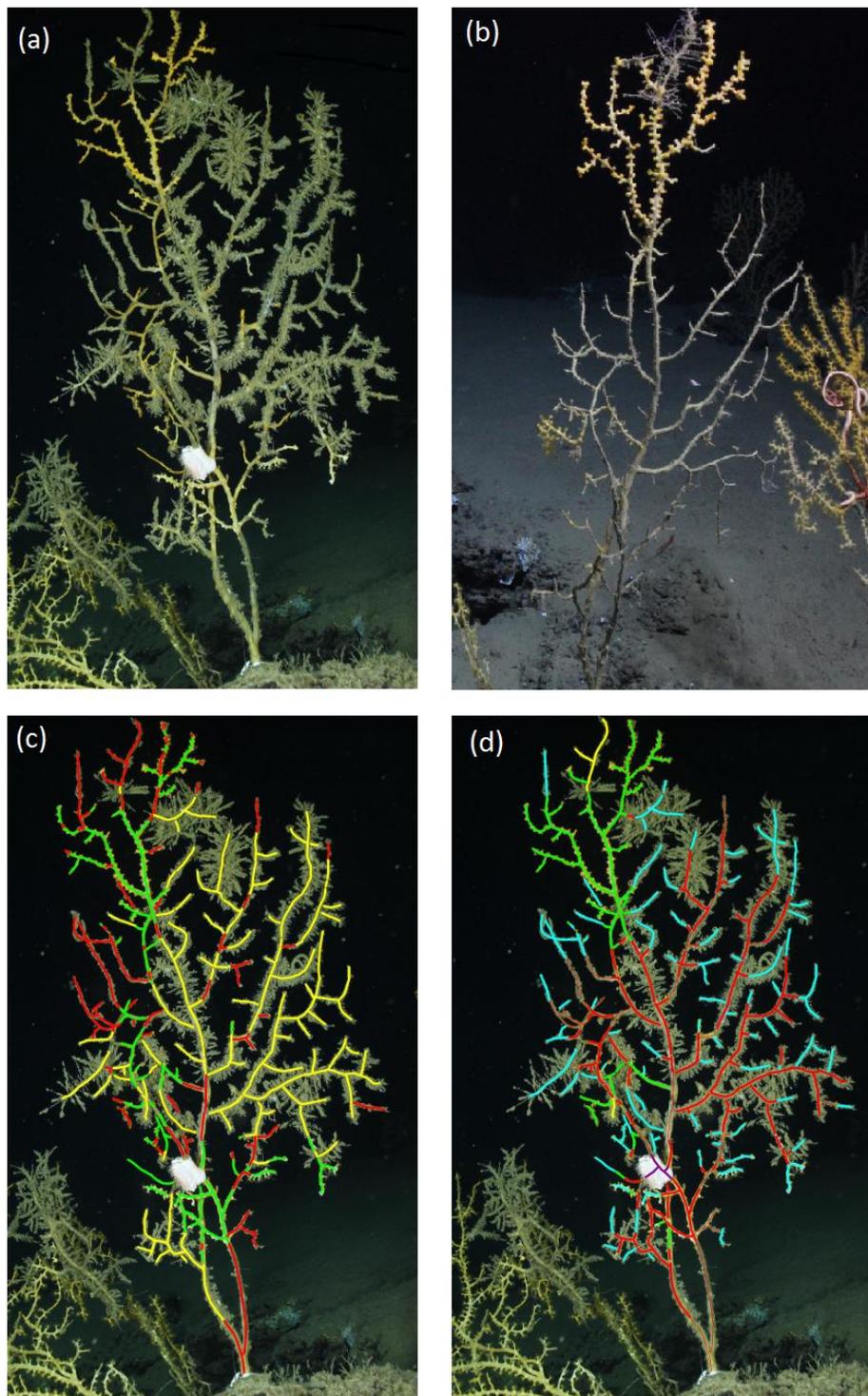


Figure 1. Comparison method of digitization, coral D3. (a) Undigitized image from October 2011; (b) Undigitized image from June 2013; (c) Digitization of image from October 2011; (d) Digitization of October 2011 image using data from the June 2013 image. Green represents a non-visibly impacted branch, red represents a visibly impacted branch,

yellow represents a hydroid-colonized branch, cyan represents a branch that is lost by the later visit, and purple represents a branch that is obscured.

When possible, images of the same coral from two different visits were then compared for transitions from one category to another on individual branches. This was done by using Fiji or Inkscape to re-code the digitization of the image from the earlier visit with the condition digitized at the later visit (Fig. 1d). Branch loss was accounted for in this comparison. This approach required two high-resolution images of the same coral from the same ROV heading during different visits, so only a subset of the total corals imaged could be analyzed this way. In particular, none of the images taken during the March 2012 visit were of sufficient resolution for this analysis and are not considered in this study for this reason. All images obtained after the October 2011 visit were digitized with this method using images from the October 2011 visit – the most complete set of high-quality images – as its base for comparison. Images before the October 2011 visit used images from the Late 2010 set as its base.

Images from each visit were digitized by two independent digitizers (a total of three people digitized the images used in this study). There were no significant differences between the digitizations as measured by ANOVA, and their data was averaged to create the final dataset.

Branch loss was quantified by two methods: the proportion of coral that was lost and the number of break points. Break points were chosen as a secondary measure of branch loss because a single break point could lead to a large proportion of the coral being lost (the number of break points can be a decimal because results were averaged between two digitizers). To account for the differing time lengths between visits (between 4 to 13 months), the average proportion or average number of break points per coral was divided by the time between visits, giving the average per coral per month.

Significant changes in median total visible impact over time was tested using the Wilcoxon rank sum test (Mann–Whitney–Wilcoxon test) for independent samples. Although the data was not independent because the same corals were imaged between visits, using the Wilcoxon signed rank test for dependent samples would severely limit the sample size to corals imaged in multiple visits. The rank sum test was also used to test for significant differences in the number of break points between MC294 and the control site.

A t-test was used to test the null hypothesis of no correlation (Pearson correlation coefficient = 0) between various category transitions and total visible impact. A goodness-of-fit chi-squared test (used to test whether categorical data came from a claimed discrete distribution) was used to test the null hypothesis that the location of a break point is random (does not depend on the condition of the branch).

Chapter 3

Results

Median Total Visible Impact

Median total visible impact in Late 2010 was 40.4% and decreased to 3.6% in March 2011, before increasing to 14.2% in October 2011 (Fig. 2), where it remained relatively constant. The Wilcoxon rank sum test detected significant changes between Late 2010 and March 2011 ($p=0.0024$); and between March 2011 and October 2011 ($p=0.0385$). No significant changes were detected after October 2011: $p=0.46$ between October 2011 and November 2012, $p=0.59$ between November 2012 and June 2013, and $p=0.66$ between June 2013 and June 2014.

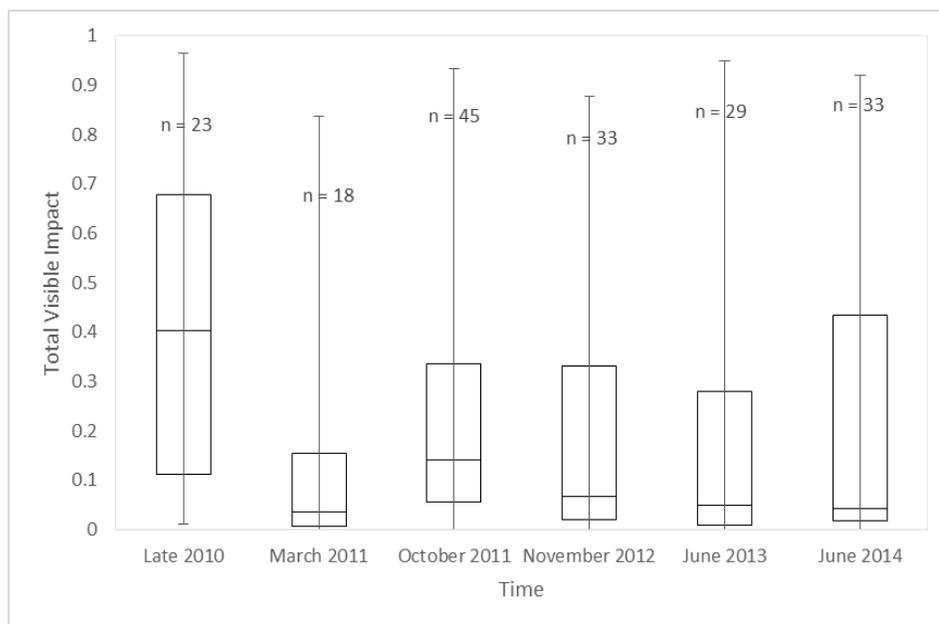


Figure 2: Median total visible impact over time between Late 2010 and June 2014. Box plots indicate the first quartile, median, and third quartile. Whiskers extend to the

outermost data points. Changes were detected between Late 2010, March 2011, and October 2011, showing an overall decrease in median impact. No significant changes in median total visible impact were detected after October 2011.

Branch Loss

Break points occurred in small numbers through October 2011 (Fig. 3). Between October 2011 and November 2012, the rate increased to 0.47 break points per coral per month. The rate increased further between November 2012 and June 2013, reaching a peak at 0.72, before dropping to 0.14 between June 2013 and June 2014.

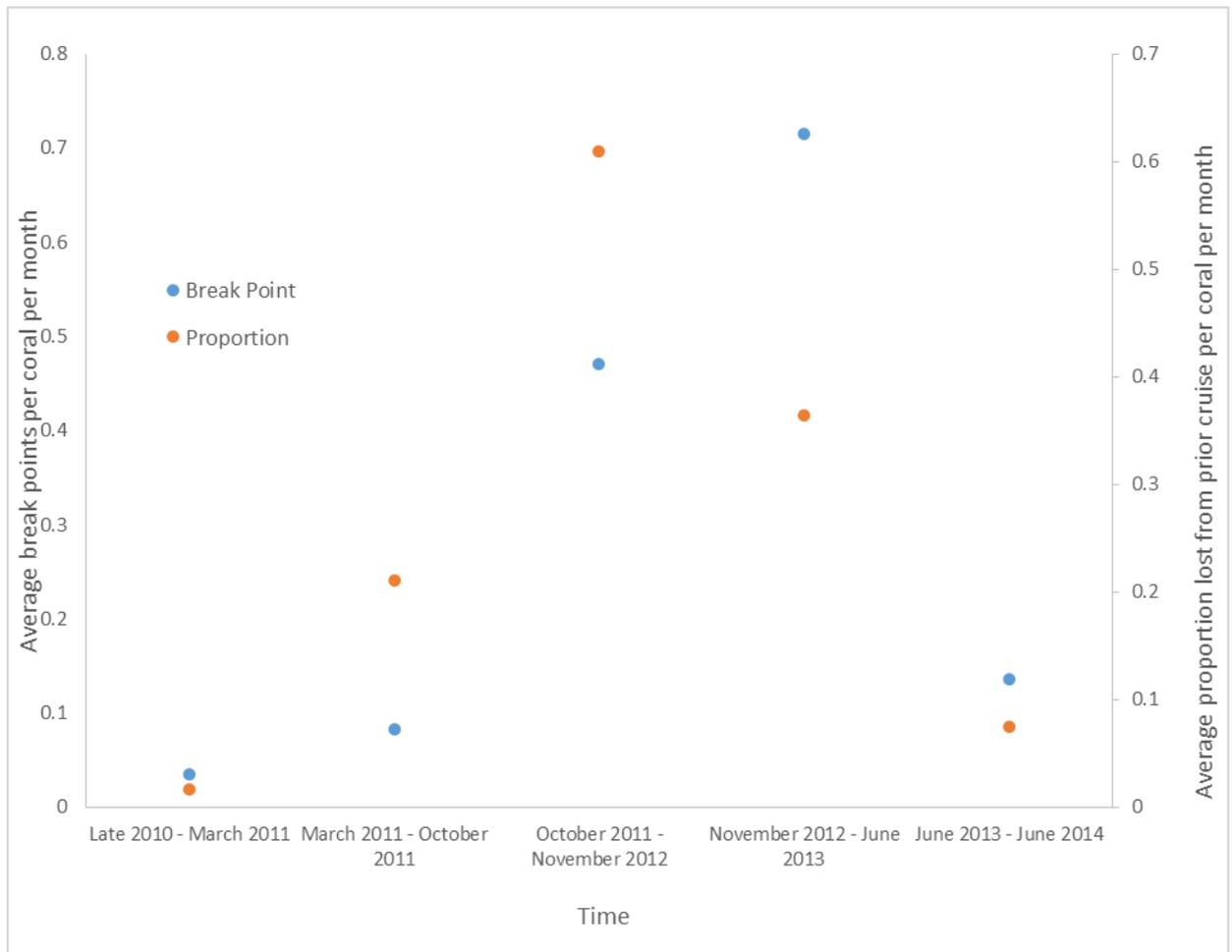


Figure 3. Rate of branch loss as measured by two methods: the number of break points (left) and the proportion lost from the original coral (right). All numbers given as averages per coral per month.

Measuring the proportion of coral lost displayed a similar trend. Small portions of corals were lost between Late 2010 and March 2011. The loss rate increased between March 2011 and October 2011 to 0.21% per coral per month. The rate reached a peak of 0.61% between October 2011 and November 2012, before decreasing to 0.36% between November 2012 and June 2013, and decreasing further to 0.075% between June 2013 and June 2014.

For each set of visits between October 2011 and June 2014, the number of break points per coral was directly correlated to the coral's total visible impact in October 2011 (Fig. 4). The proportion of the coral lost between October 2011 and June 2014 was also directly correlated to the total visible impact of the coral in October 2011 (Fig. 5, $p < 0.001$).

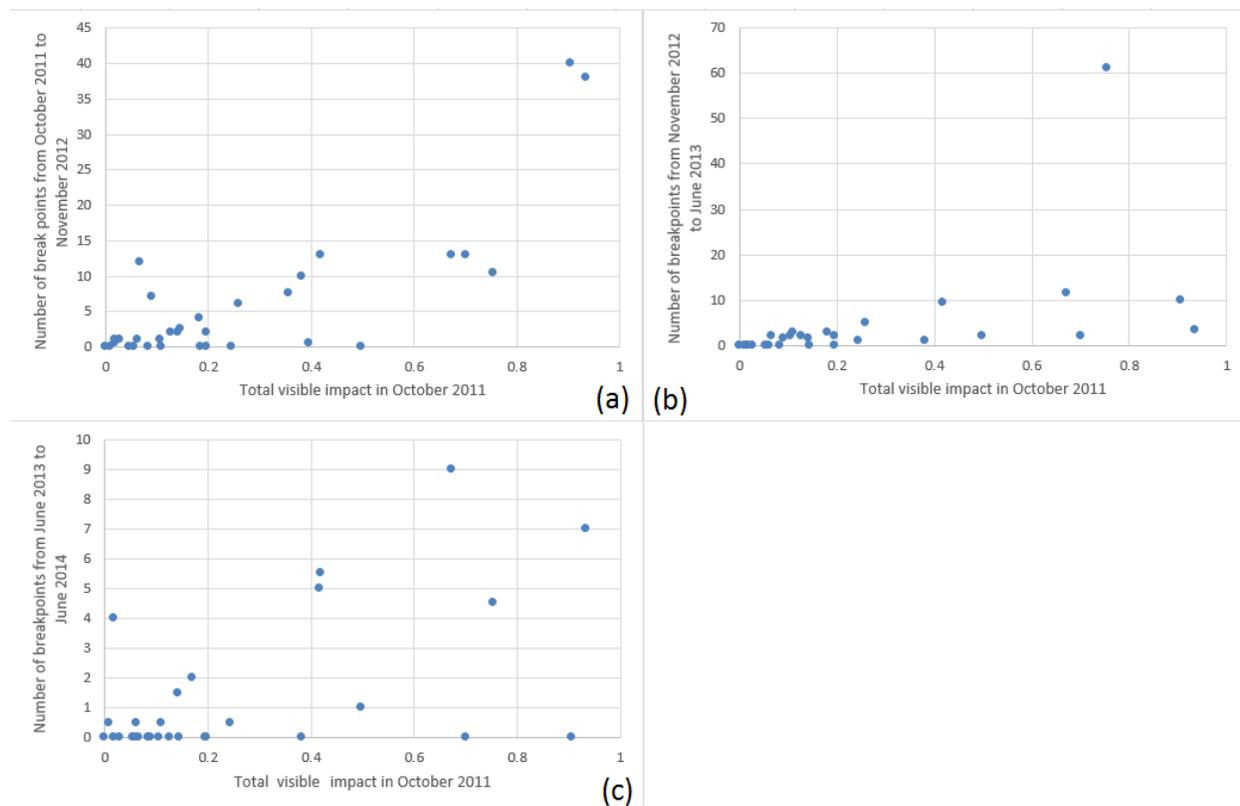


Figure 4. Number of break points related to total visible impact in October 2011. A significant correlation was found between total visible impact and the number of break points during the periods: a) October 2011 to November 2012, $n=32$, $p<0.001$; b) November 2012 to June 2013, $n=28$, $p=0.007$; and c) June 2013 to June 2014, $n=29$, $p=0.002$.

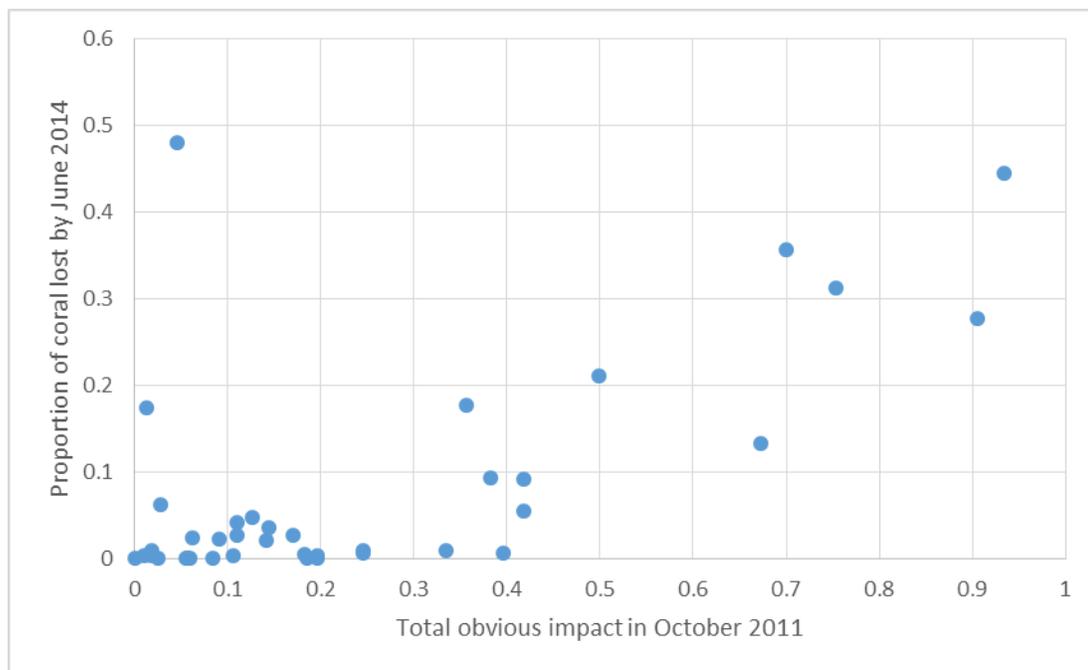


Figure 5. Proportion of coral lost between October 2011 and June 2014 related to total visible impact in October 2011 ($n=39$). A significant correlation was found ($p<0.001$).

Of the 352.5 total break points seen throughout each set of visits between October 2011 and June 2014, 54.5 of them occurred on non-visibly impacted branches, 109.5 occurred on visibly impacted branches, 185 occurred on hydroid-colonized branches, and 3.5 occurred on obscured branches (Fig. 6). Break points occurred significantly more on visibly impacted or hydroid-colonized branches than on non-visibly impacted or obscured branches as measured by a chi-squared test based on the null hypothesis of break points occurring randomly ($p<0.001$). Hydroid-colonized branches also contained a significantly greater number of break points than any other category ($p<0.001$).

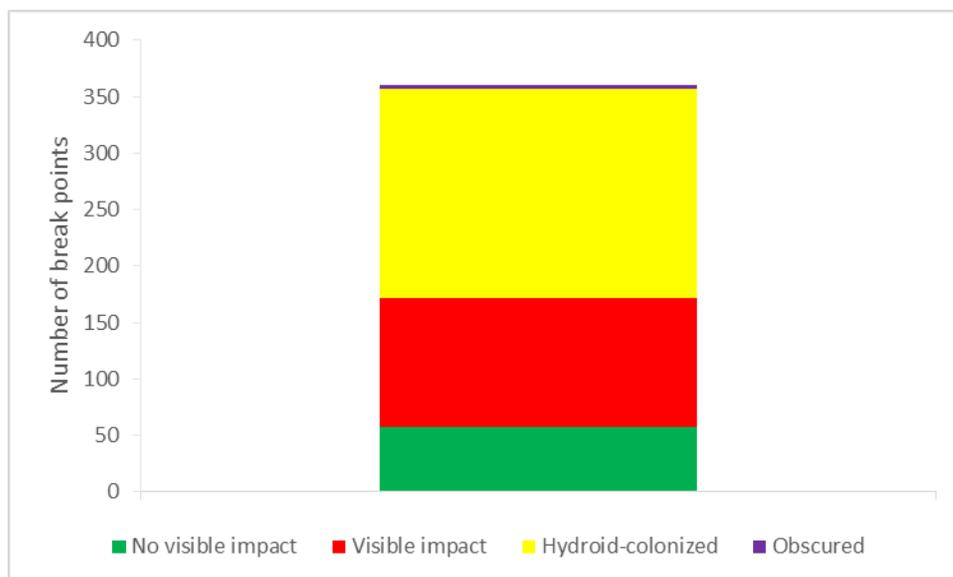


Figure 6. Distribution of break points among four categories throughout all visits between Late 2010 and June 2014. Through all visits, 352.5 total break points were observed: 54.5 on non-visibly impacted branches, 109.5 on visibly impacted branches, 185 on hydroid-colonized branches, and 3.5 on obscured branches. Breaks occurred more on visibly impacted and hydroid-colonized branches than on non-visibly impacted and obscured branches ($p < 0.001$). Breaks also occurred more on hydroid-colonized branches than in other category ($p < 0.001$).

Between October 2011 and June 2013, there was an average of 11.0 break points per coral at MC294, significantly higher than the 0.61 break points observed in the control site during the same period ($p < 0.001$). The average number of break points on non-visibly impacted branches for MC294 was 1.3 per coral, significantly higher than the 0.36 per coral observed at the control site ($p = 0.0011$).

Hydroids

A small amount of hydroid colonization on corals was documented in Late 2010, averaging less than 0.01% per coral (Fig. 7). Hydroid colonization increased dramatically by

March 2011, with hydroids covering an average of 1.4% per coral, and as much as 10.3% on some individually. Hydroid cover peaked in October 2011 at an average of 11.5% per coral, then decreased in the next two visits, reaching 4.6% in June 2013, before increasing slightly to 7.4% in June 2014.

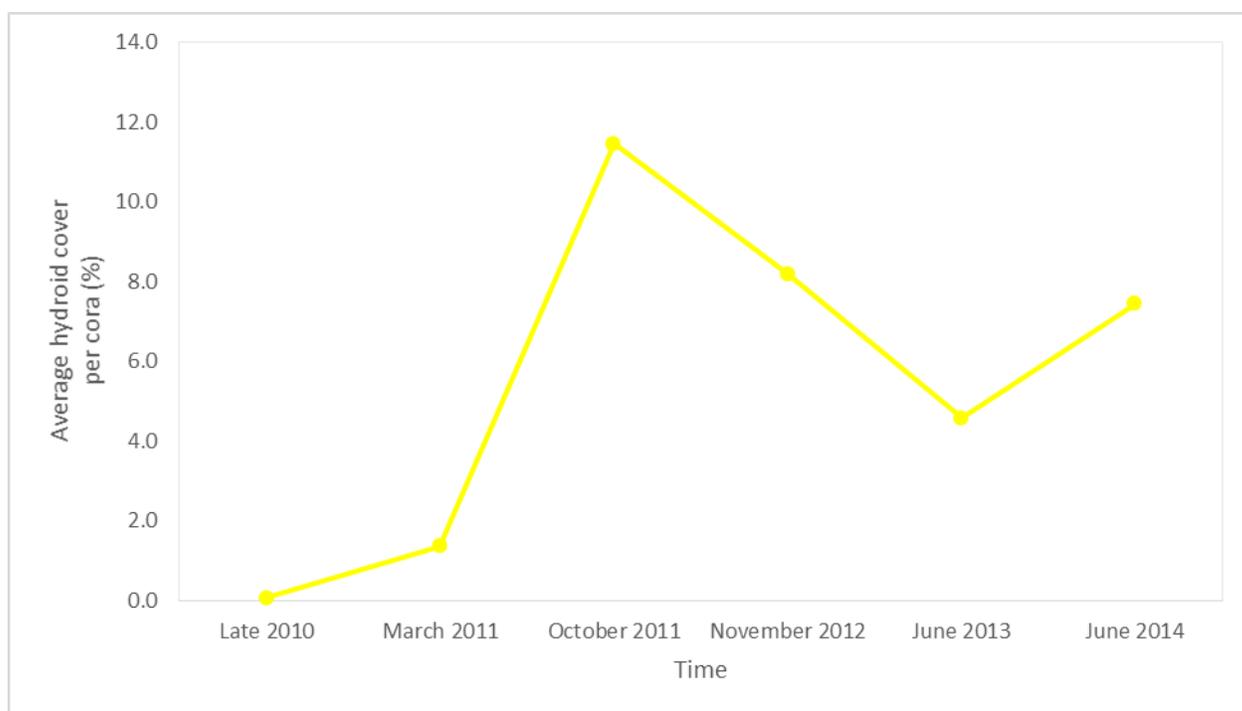


Figure 7: Average hydroid cover between Late 2010 and June 2014. Hydroid colonization was documented in small numbers in Late 2010 and increased dramatically through March 2011 and October 2011.

The decrease in hydroid-colonized branches was a result of these branches becoming lost or transitioning into other categories (Fig. 8). A small proportion of hydroid-colonized branches were obscured during some visits. The transitions varied between visits, though in general hydroids tended to remain on the branch (no transition). Between October 2011 and November 2012, 8.2% of the hydroid-colonized branches in October 2011 were lost; hydroids disappeared from another 18.4% of branches, with 10.2% apparently recovering to a non-visibly impacted state and 8.2% leaving behind branches in a visibly impacted state. Over this time, new hydroid

colonization on visibly impacted branches was minimal, with an average of 12.5% of visibly impacted branches becoming colonized.

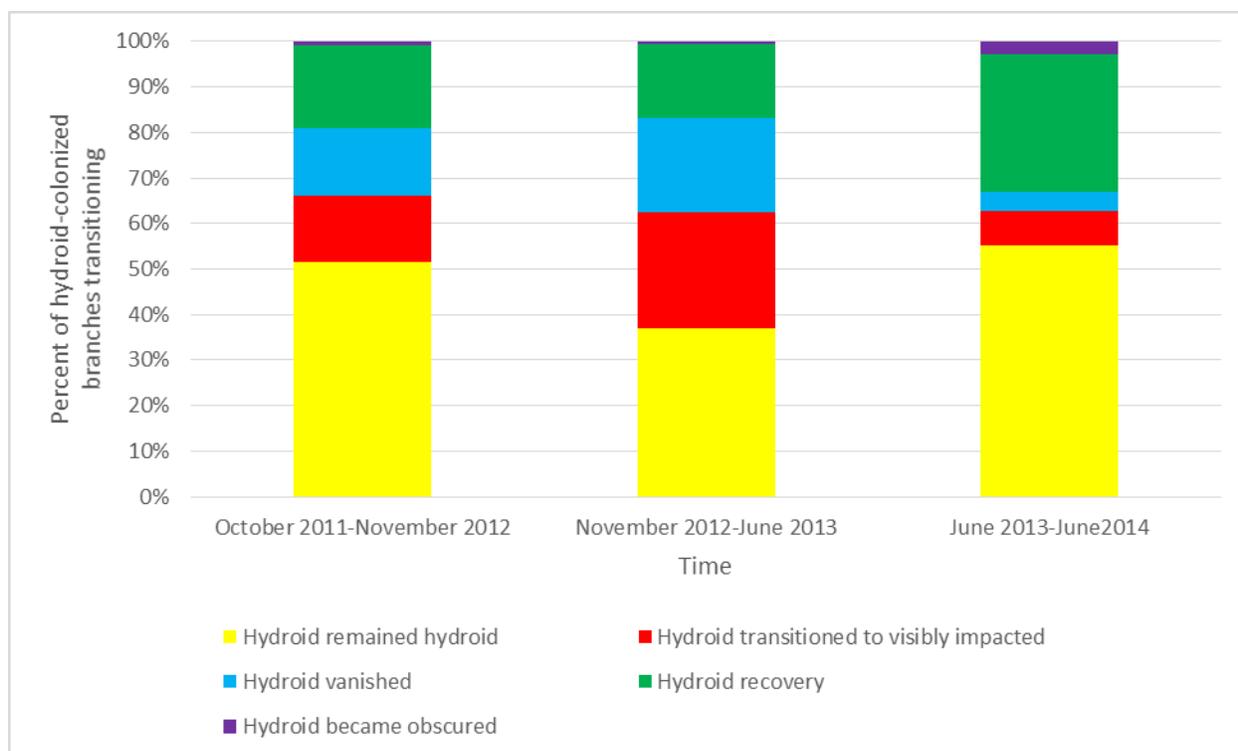


Figure 8: Hydroid transition to other categories between each set of visits from October 2011 to June 2014. In general, hydroids remaining on the colonized branch was dominant. The remaining transitions were responsible for the decrease in hydroid cover between October 2011 and June 2014.

The transitions between November 2012 and June 2013 followed the same general pattern. Thirteen percent of the hydroid-colonized branches were lost while hydroids disappeared from another 25.9% of branches, with 10.1% apparently recovering and 14.8% leaving behind branches in a visibly impacted state. New hydroid colonization on visibly impacted branches was much lower at 5.0%.

The rate of branch loss on hydroid-colonized branches was lower between June 2013 and June 2014, mirroring the decrease in total branch loss over this period (Fig. 3). Although hydroids disappeared from 15.1% of hydroid-colonized branches in 2013, with 12.1% recovering

Chapter 4

Discussion

Median Total Visible Impact

Hsing and colleagues (2013) observed a decrease in median total visible impact between November 2010 and March 2012, attributing the decrease to reduction in flocculent material covering coral branches. A similar decrease in median total visible impact is observed here (Fig. 2), though our new comparison method of digitizing that required higher-resolution images eliminated images taken during the March 2012 visit. After October 2011, the median total visible impact did not change significantly, suggesting that with most flocculent material gone, the corals have reached a state of quasi-equilibrium compared to the period between Late 2010 and October 2011. However, this equilibrium is deceptive. During the period between October 2011 and June 2013, the corals experienced their greatest rates of branch loss, the ultimate level of impact (Fig. 3). Median impact thus cannot be taken as the sole indicator of coral health.

Due to differences in statistical methods, the results here have some differences from those of Hsing and colleagues (2013), who used two statistical methods to track median total visible impact over time. Their first test involved Bayesian multiple imputation to estimate impact for corals that were not imaged throughout every visit, followed by a Friedman test with

post hoc Wilcoxon signed rank test. They found a significant decrease in median total visible impact over time except between March 2011 and October 2011, where no significant change was found; we found a significant increase in median impact between March 2011 and October 2011 (Fig. 2). Their second method used the Wilcoxon signed rank test with just corals imaged during two adjacent visits, severely limiting their sample size. They even noted the problem of small sample size, finding only significant change between October 2011 and March 2012 when the number of corals imaged during both periods was high. Here, instead of limiting our data to corals imaged during two adjacent visits, we decided to use the Wilcoxon rank sum test for independent samples. Despite differences in significance tests between our studies, Hsing and colleagues' data set for their second test (without the imputed values) is qualitatively similar to ours.

Branch Loss

Unlike visibly impacted or hydroid-colonized branches, lost branches obviously do not recover. They represent permanent damage, the highest level of impact. Like most deepwater corals, *Paramuricea* exhibit low growth rates, averaging between 0.34 μ m and 14.20 μ m increase in basal diameter per year (Prouty et al. 2014), making them highly susceptible to anthropogenic activity. Highly-impacted individuals with high rates of branch loss will require decades or centuries to replace the branches they've lost; one particular coral (B10) lost 44.4%% of its branches from October 2011 to July 2014. Break points occurred significantly more on visibly impacted or hydroid-colonized branches than on non-visibly impacted branches (Fig. 6). The rate of branch loss shows a positive correlation with the total visible impact of the coral (Fig. 4 and

Fig. 5), and the rate of branch loss at MC294 is significantly higher than at the control site.

Together, these facts implicate the spill as the causative factor in branch loss.

Break points did not begin to occur in significant numbers until October 2011 (Fig. 3), fifteen months after the spill, and the average number of break points reached a peak between November 2012 and June 2013, over two years after the spill. Measuring the rate of branch loss using proportions revealed a similar trend. Clearly, the corals suffered long-term damage. The initial study published by Hsing and colleagues in 2013, which noted almost no branch loss and did not quantify it, was therefore an underestimate of impact to these corals. The fifteen-month gap between the spill and when branch loss first appeared in noticeable numbers also suggests that it takes a long time for branches to die to the point that they fall off. By June 2014, however, the rate of branch loss had decreased dramatically from its peak in June 2013 and November 2012, suggesting the rate has begun to taper off.

Analyzing branch loss by both the number of break points and the proportion of coral lost was done because the consequences of a break point depend on where the break point occurs; a high number of break points may not necessarily lead to a large loss for the coral if the break points occurred on far tertiary branches, whereas a single break point, if it occurred early in the branch tree, can lead to significant losses. On the other hand, proportion lost does not indicate where the break occurred and can be misleading. For example, corals have been observed to lose small proportions of their non-visibly impacted branches, but this loss occurred because the break point occurred on more basal portions of a visibly-impacted or hydroid-colonized branch; when the impacted branch broke off, the non-visibly impacted portion attached to it was also lost. In the early visits, break points were confined to tertiary branches, while in later visits they began to appear on primary and secondary branches, resulting in greater proportions lost (Fig. 3).

Primary branches likely took more time to break because their larger diameters provide more support and structural integrity. Branch diameter is correlated with the force required to break the branch (Boller et al. 2002).

The number of break points on non-visibly impacted branches at MC294 was significantly higher than at the control site, suggesting that non-visibly impacted branches may, in fact, have been impacted beneath the coral surface, an “invisible” impact unaccounted for in digitizing. Stressful conditions and resource limitation have physiological impacts that may not be immediately visible, causing the coral to divert energy from tissue and skeletal growth (Anthony et al. 2002). Oil and dispersant also causes long-term reproductive problems such as coral larvae death (Epstein et al. 2000, Goodbody-Gringley et al. 2013). Analyzing coral health solely by branch loss and visible impact, as was done in this study and the study of Hsing and colleagues, further underestimates total impact to the population.

Hydroids

Hydroid colonization of dead coral skeleton in deep-sea environments has been documented many times (Henry et al. 2008, Moura et al. 2007, Ross and Nizinski 2007). Hydroid association with a variety of other living marine organisms can be mutualistic (Osman and Haugsness 1981) or parasitic (Piraino et al. 1992, Piraino et al. 1994). In a mutualistic case of hydroid encrustation on bryozoans, the hydroid stings small predators and nearby competitors, helping its host to better survive and compete (Osman and Haugsness 1981). Endosymbiotic association of hydroids with the reef-building coral *Acropora muricata* may also be mutualistic,

with the hydroid providing similar protection for the coral (Pantos and Bythell 2010, Pantos & Hoegh-Guldberg 2011).

In this case, hydroid settlement on *Paramuricea biscaya* is likely to be opportunistic and harmful to the coral. Hydroids are opportunistic feeders, exhibiting high colonization rates on available substrata to take advantage of available food sources (Calder 1991, Migotto et al. 2001, Orejas et al. 2001). Corals, many of which are more productive in high-flow environments that allow higher rates of feeding and gas exchange (Anthony and Fabricius 2000, Patterson et al. 2003), provide prime environments for hydroids. However, toxins discharged by nematocysts during prey capture (Gili and Hughes 1995, Purcell and Mills 1988) and production of noxious secondary metabolites for defense against predators (Stachowicz and Lindquist 2000) may damage surrounding coral tissue. In support of this hypothesis, we found that break points occurred more often on hydroid-colonized branches than on any other categories; the true number of break points on hydroid-colonized branches is also underestimated, as in several cases many visibly impacted branches where break points occurred were previously colonized by hydroids that have since disappeared. Little to no hydroid colonization was observed on control sites, and new hydroid colonization only appeared on visibly impacted branches (many of which appear dead). Visibly impacted branches covered by floc may experience similar effects as sedimentation, which can overwhelm a coral's natural cleaning mechanism and smother the coral, leaving it vulnerable to encrustation (Larsson and Purserb 2011).

By June 2013, the amount of hydroid colonization had decreased greatly since October 2011 (Fig. 7). However, not all of the observed transitions from hydroid colonization were due to recovery; many were accounted for by hydroid-colonized branches either becoming lost or transitioning to a visibly impacted state (Fig. 8), which are not signs of recovery. Branch loss

represents a non-recoverable state for that branch. In cases of hydroid-colonized branches transitioning to a visibly impacted state, the visibly impacted branch either remained visibly impacted or was re-colonized by hydroids by a later visit. In contrast to hydroid disappearance, new hydroid colonization on visibly impacted branches was observed through all visits and was greater than hydroid disappearance in June 2014, resulting in an increase in hydroid cover for the first time since between March 2011 and October 2011. Evidently, hydroid colonization and persistence is still in a state of flux.

Surprisingly, we found numerous examples of recovery of hydroid-colonized branches. Previously, Hsing and colleagues (2013) only noted hydroid-colonized branches being lost or transitioning to a visibly impacted state (in addition to hydroids remaining on the branch), leading them to believe recovery from hydroid colonization was unlikely, as reported for *Paramuricea clavata* (Linares et al., 2005). However, recovery of portions of branches colonized by hydroids in October 2011 to a non-visibly impacted state in June 2014 were documented on 24 out of the 39 corals in October 2011. These recovered branches remained non-visibly impacted through subsequent visits, so the recovery is likely permanent.

The degree the coral recovered from hydroid colonization was not significantly correlated with the coral's level of total visible impact (Fig. 9). Corals with >70% total visible impact were still able to partially recover from hydroid colonization, while several corals with <20% impact exhibited zero recovery. In each case of hydroid recovery, the recovered branch was always adjacent to a non-visibly impacted branch. The recovered portion also seems to extend over time from nearby healthy branches, suggesting that when hydroids disappear, the bare coral skeleton underneath can be recolonized by surrounding healthy tissue (Wesseling et al. 1999). Although hydroid recovery indicates that the particular branch is recovering, it may not necessarily mean

the coral is recovering as a whole. On multiple corals, hydroid recovery occurred in tandem with branches loss as well as new hydroid colonization on previously impacted branches.

Chapter 5

Conclusion

The Macondo spill significantly impacted deepwater corals at MC294. Floc covering branches lead to hydroid colonization on those branches, and large amounts of damaged branches were lost between visits. Continual changes in hydroid composition and branch loss indicate the corals are still in a state of flux. Nonetheless, many corals display the ability to partially recover from hydroids, and data suggests that the rate of branch loss, the worst visible sign of impact, is in decline.

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Schreyer's Honors Scholar at University Park in The Pennsylvania State University. Major in Premedicine and minor in English.

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THE PENNSYLVANIA STATE UNIVERSITY, State College, PA 2011 – Present
Undergraduate Research Assistant at Fisher Lab, PSU Department of Biology

- Member of the team sponsored by NRDA (government organization) to compile a damage analysis of the 2010 BP oil spill on deepwater corals
- Utilized imaging software to track coral health over time and pioneered a new technique to track temporal, individual-level changes in coral colonies
- Co-authored an article in the 2013 edition of *Elementa: Science of the Anthropocene*
- Current writing a thesis project detailing the effects of the oil spill over the last four years

Einstein Healthcare Network, Philadelphia, PA Summer 2013
Premed Volunteer Program, Volunteer Resources

- Competitive program designed to expose undergraduates to the health care profession
- Shadowed doctors in internal medicine, the emergency department, radiology, and anesthesia/surgery
- Attended grand rounds and pre-med only presentations detailing topics such as infection control and organ donation

CHESTNUT HILL HOSPITAL, Philadelphia, PA Summer 2013
Volunteer at The Comprehensive Center for Wound Healing

- Assisted patients with chronic pain treatment programs, particularly in transporting patients who had difficulty walking due to foot wounds
- Worked closely with doctors and nurses in clinical settings, hyperbaric oxygen therapy, and ultrasound scans

DREXEL UNIVERSITY, PHILADELPHIA, PA Summer 2012
Summer Internship at Sang Lab, Drexel Department of Biology

- Research focused on the effects of oxygen deficiency on cell culture
- Primarily educational, duties included working with lab instruments and learning lab techniques such as centrifugation, agarose gel electrophoresis, reporter gene assays, and fumehood procedures

Awards and Distinctions

- Schreyer's Honors Scholar – top 5% of Penn State selected on competitive criteria, includes an academic excellence scholarship
- John K. Tsui Honors Scholarship – award for manifesting promise regarding academic success
- Phi Kappa Phi – highly selective honor society for all academic disciplines
- National Society of Leadership and Success – honor society with a rigorous induction process
- National Society of Collegiate Scholars – honors organization that recognizes and elevates high achievers