GROWTH RATES, DENSITIES, AND DISTRIBUTION OF LOPHELIA PERTUSA ON ARTIFICIAL STRUCTURES IN THE GULF OF MEXICO

A Thesis in
Biology
by
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Using industry inspection video and ROV imaging, we examined *Lophelia pertusa* (Linnaeus 1758) on 10 artificial structures of known ages (9 to 103 years) in the northern Gulf of Mexico (GoM). Five different types deep-water hydrocarbon installations with depths ranging from 320 to 995 m, and three shipwrecks with depths ranging from approximately 530 to 615 m were examined. Density, depth ranges, and growth rates of *L. pertusa* colonies were calculated from video and image analysis. *L. pertusa* colonies were present on all structures examined. Minimum calculated growth rates for the largest colonies ranged from 0.32 to 3.23 cm/year on the different structures. Colony density varied with structure type, age, and depth, with the highest density between 503-518 m on the single structure that spanned the entire depth range of occurrence of *L. pertusa*. *L. pertusa* on thinner and deeper, hydrocarbon structure types (spar and tension leg platforms) appear to have higher colonization rates as the support higher densities in less time. However, on average, colonies have slower growth rates on these structures than colonies on more massive, shallower hydrocarbon structure types (compliant and solid platforms). In general, the calculated minimum growth rates were higher on the hydrocarbon installations than on the shipwrecks, which were substantially older. A continuum of colony sizes was documented on all installations, suggesting multiple settlement events. *L. pertusa* thickets were observed on the oldest structures with most structural components covered by colonies of *L. pertusa*. The shallowest depth of *L. pertusa* observed was at 201 m and the deepest at 801 m, considerably expanding the known depth range of the species in the northern GoM. Brown, orange, and mottled morphotypes were documented for the first time in the GoM. All energy platforms examined for this study were colonized by *L. pertusa* and it is likely that most artificial surfaces in appropriate depths in the GoM will be as well.
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Chapter 1

Introduction

*Lophelia pertusa* is an azooanthellic, cold-water, Scleractinian coral that has the potential to form reefs. *L. pertusa* is a cosmopolitan species, though known distribution is reflective of anthropogenic activities (natural gas and oil drilling, fishing) and areas of previous scientific study (Freiwald, 2002). These areas include the North Sea, the Gulf of Mexico (GoM), off the eastern coast of North America, and the western coasts of Europe and Northern Africa. The distribution of *L. pertusa* is primarily limited by the availability of hard substrate, permanent or episodically strong currents, depth of the storm wave base, location of the thermocline, and depth (Freiwald, 2002). Due to metabolic oxygen requirements, *L. pertusa* is particularly sensitive to increased temperatures, especially those above 11°C (Dodds, et al., 2007) and has an upper temperature limit of 12°C (Rogers, 1999). In addition, *L. pertusa* growth and abundance is correlated with the oxygen minimum zone (Freiwald, 2002) where low oxygen levels potentially limit the distribution of *L. pertusa*. In the GoM, *L. pertusa* was previously documented from 204 – 640 m (Schroeder, et al., 2005). *L. pertusa* can tolerate a wide range of salinities, from 33 to 37%, with preference towards the highest salinity in a given location (Freiwald, 2002).

Schroeder, et al., 2005, describe cold-water reef forming coral sites in the GoM at depths 200-1000 meters; 10 contained *L. pertusa*, 9 contained *Madrepora oculata*, and 3 had co-occurrence of *L. pertusa* and *M. oculata*. *L. pertusa* colonies were observed at 204-292 m depth in a total water depth of 393 m the Pompano Oil Production Platform.
A later report commissioned by the Mineral Management Services describes *L. pertusa* reefs, on the Viosca Knoll Lease Block in the northern GoM (Sulak et al., 2008). A conservative age for the *L. pertusa* at this reef is 350 years. Though well-developed natural *L. pertusa* reefs are only found in the northern GoM at the Viosca Knoll Lease Block, *L. pertusa* does occur in other areas of the northern GoM in the Green Canyon and Mississippi Canyon Lease Blocks (Sulak et al., 2008). The reefs found in the Viosca Knoll Lease Block do not form large biogenic mounds, like those off the east coast of the US, but are thinner layers of living coral in the open growth form; there are also no extensive rubble fields as with *L. pertusa* reefs off the U.S. East Coast (Sulak et al., 2008). Subfossil *L. pertusa* branches and a mussel from Big Blue Reef (VK 826) were radiocarbon dated to 22.5-25.0±0.5 ky (BP), which fits within previous estimates of the date of occurrence of *L. pertusa* in the GoM (Sulak et al., 2008).

Out of the 622 azooxanthellate Scleractinian species found in waters deeper than 50 m, there are only 17 cold water, reef forming corals, and only 6 with a wide distribution: *L. pertusa*, *M. Oculata*, *Goniocorella dumosa*, *Oculina varicosa*, *Enallopsammia profunda*, and *Solenosmila variabilis* (Roberts et al., 2009, pp. 26-27). *M. oculata*, has overlapping distributions with *L. pertusa* and can form a secondary framework within *L. pertusa* structures. Two other major reef forming corals, *Enallopsammia profunda*, and *Solenosmila variabilis*, are also sometimes associated with *L. pertusa*. (Roberts et al., 2009 pp.26-32).

*L. pertusa* has the ability to shape the geology of the sea-floor and over thousands of years, can form large carbonate mounds as large as 5 km long, 1 km wide, and 100 m thick; it is estimated that some *L. pertusa* reefs are over 8 thousand years old (Freiwald, 2002). Along with carbonate mounds, *L. pertusa* can form reef-structures with predictable growth and death patterns. Wilson (1979), was the first to describe the “patch development” of a *L.*
pertusa reef. This development begins with a single colony, which grows outward and creates additional external colony rings as pieces break off. Eventually, the center of the patch begins to die, but external colony rings keep forming, called the “thicket” stage. After a while, additional L. pertusa colonies re-colonize the center of the reef, forming what is called the “coppice stage” (Wilson, 1979).

Most importantly, L. pertusa reefs provide habitat for numerous other species. L. pertusa provides habitat though the surface of live coral branches; dead, sediment and detritus covered branches, bioeroded coral skeletons; and spaces in-between branches (Mortensen, et al., 1995). In addition to microfauna and meiofauna, L. pertusa reefs form habitat for megafauna such as fish. In a study done by Ross & Quattrini (2007), 99 fish species were observed on and around L. pertusa reefs in waters off the South Eastern United States. It is hypothesized that concentrated food resources is one reason for increased biodiversity in and around L. pertusa reefs. Dead L. pertusa and mixed patches of live and dead L. pertusa, contribute significantly to the total amount of biodiversity seen on and around L. pertusa reefs (Lessard-Pilon et al., 2010). Scleractinian cold-water corals also serve as a record of aragonite saturation state, temperature, pollution, and nutrients (Roberts et al., 2009 pp.211-230).

Currently there are four major threats to cold-water reef forming corals; trawling, oil and gas exploration and production; climate change; and collection for the jewelry trade (Roberts et al., 2009 pp.237-251),with the first three factors affecting L. pertusa. Trawling is a method of fishing using nets dragged across the sea floor to gather bottom dwelling fish. Damage from trawling can be devastating to L. pertusa reefs resulting in partial to complete destruction of the reef structure and thereby disrupting associated fauna (Roberts et all 2009,
On the Norwegian continental shelf, it is estimated 30-50% of the cold water reefs have been damaged or impacted by trawling (Fosså et al., 2002).

Oil and gas exploration and production can negatively effect *L. pertusa* in two ways: though direct habitat destruction and displacement; and through the discharge of drill cuttings, drilling mud, and other effluents. Complete burial of *L. pertusa* polyps in drill cuttings leads to colony mortality (Larsson and Purser, 2011). Though Bell and Smith (1999), cite apparently healthy colonies growing near oily water and drilling effluent, in a correspondence to Nature, Rogers (2000), warns that there is not enough information to know the effects of oil and gas exploration and production on *L. pertusa*. Lastly, two ways that climate change can impact *L. pertusa* are though increased temperatures and an increased aragonite saturation horizon; both have the potential to severely limit the distribution of many-cold water corals (Roberts et al., 2009 pp.247).

Due to the physical constraints of working and conducting scientific studies at depth, growth rates of deep-sea corals *in situ* are often difficult to obtain. Anthropogenic substrates of known age can be used to calculate minimum growth rates for *L. pertusa* colonies by dividing the length of a coral branch or the height of a colony by the age of a structure. This method assumes the coral larvae settled and started growing immediately after the structure was installed or sank, and can therefore, only provide a minimum rate of growth with considerable variation. Coral colonies are collected or images of the coral and structure are used; the later method minimizes damage or disturbance to the colonies. Minimum growth rates from previous studies using this method range from 5mm/year to 36 mm/year (Bell and Smith, 1999; Duncan, 1877; Gass and Roberts, 2006; Roberts, 2002; Wilson, 1979) (Table 1-1).
### Table 1-1: Top minimum growth rates as measured by previous samples

<table>
<thead>
<tr>
<th>Structure</th>
<th>Location</th>
<th>Water Depth of Occurrence</th>
<th>Installation Year</th>
<th>Minimum Growth Rate (mm/year)</th>
<th>Number of Corals Measured</th>
<th>Sampling Technique</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telegraph Cable</td>
<td>North West of Spain</td>
<td>955-1,006 m</td>
<td>1870</td>
<td>7 mm</td>
<td>One</td>
<td>Direct Sample</td>
<td>(Duncan, 1877)</td>
</tr>
<tr>
<td>ITAL cable</td>
<td>Bay of Biscay</td>
<td>800 m</td>
<td>1930</td>
<td>6 mm</td>
<td>One</td>
<td>Direct Sample</td>
<td>(Wilson, 1979)</td>
</tr>
<tr>
<td>Brent Spar</td>
<td>North Sea</td>
<td>60-109 m</td>
<td>1976</td>
<td>26 mm</td>
<td>Multiple</td>
<td>Direct Sample, Images</td>
<td>(Bell and Smith, 1999)</td>
</tr>
<tr>
<td>Beryl Alpha Platform Moorings</td>
<td>North Sea</td>
<td>75-114 m</td>
<td>1975</td>
<td>5 mm</td>
<td>One</td>
<td>Direct Sample</td>
<td>(Roberts, 2002)</td>
</tr>
<tr>
<td>Tern Alpha Platform</td>
<td>North Sea</td>
<td>167 m¹</td>
<td>1988</td>
<td>25 ±5</td>
<td>15</td>
<td>Images/Video</td>
<td>(Gass and Roberts, 2006)</td>
</tr>
<tr>
<td>North Alwin Alpha Platform</td>
<td>North Sea</td>
<td>62-118 m</td>
<td>1985</td>
<td>6-26mm</td>
<td>16</td>
<td>Images/Video</td>
<td>Gass and Roberts, 2006</td>
</tr>
</tbody>
</table>

¹Depth of Structure. Depth of *L. pertusa* not reported.
References


Duncan, P.M., 1877. On the rapidity of growth and variability of some Madreporaria on an Atlantic Cable, with remarks upon the rate of accumulation of foraminiferal deposits. Proceedings of the Royal Society of London. 26 (179-184), 133-137.


Chapter 2

Growth rates, densities, and distribution of *Lophelia pertusa* on artificial structures in the Gulf of Mexico

Elizabeth A. Larcom, Danielle McKeen, Charles Fisher

Abstract

Using industry inspection video and ROV imaging, we examined *Lophelia pertusa* (*Linnaeus* 1758) on 10 artificial structures of known ages (9 to 103 years) in the northern Gulf of Mexico (GoM). Five different types deep-water hydrocarbon installations with depths ranging from 320 to 995 m, and three shipwrecks with depths ranging from approximately 530 to 615 m were examined. Density, depth ranges, and growth rates of *L. pertusa* colonies were calculated from video and image analysis. *L. pertusa* colonies were present on all structures examined. Minimum calculated growth rates for the largest colonies ranged from 0.32 to 3.23 cm/year on the different structures. Colony density varied with structure type, age, and depth, with the highest density between 503-518 m on the single structure that spanned the entire depth range of occurrence of *L. pertusa*. *L. pertusa* on thinner and deeper, hydrocarbon structure types (spar and tension leg platforms) appear to have higher colonization rates as the support higher densities in less time. However, on average, colonies have slower growth rates on these structures than colonies on more massive, shallower hydrocarbon structure types (compliant and solid platforms). In general, the calculated minimum growth rates were higher on the hydrocarbon installations than on the shipwrecks, which were substantially older. A continuum of colony sizes was documented on all installations, suggesting multiple settlement events. *L. pertusa* thickets
were observed on the oldest structures with most structural components covered by colonies of *L. pertusa*. The shallowest depth of *L. pertusa* observed was at 201 m and the deepest at 801 m, considerably expanding the known depth range of the species in the northern GoM. Brown, orange, and mottled morphotypes were documented for the first time in the GoM. All energy platforms examined for this study were colonized by *L. pertusa* and it is likely that most artificial surfaces in appropriate depths in the GoM will be as well.

**Introduction**

*Lophelia pertusa* (Linnaeus 1758) is a cosmopolitan, azooxanthellie, cold-water, Scleractinian coral. First order limits on the distribution of *L. pertusa* include the availability of hard substrate, presence of permanent or episodically strong currents, the depth of the storm wave base, and the location of the thermocline (Freiwald, 2002). The bottom end of *L. pertusa* distribution is limited by the oxygen minimum zone in the North Sea (Freiwald, 2002). Perhaps reflecting metabolic oxygen requirements, *L. pertusa* is particularly sensitive to increased temperatures (Dodds et al., 2007) and has an upper temperature limit of 12°C in the North Sea (Rogers, 1999).

*L. pertusa* can form substantial colonies up to or greater than 2 m in height and 1.5 m across in the Northern Gulf of Mexico (GoM) (Schroeder, 2002). These single colonies often grow together to form extensive reefs. Though most recent literature has focused on natural *L. pertusa* reefs (Brooke & Schroeder, 2007; Freiwald, 2002; Freiwald & Henrich, 1997; Roberts, et al., 2010; Rogers, 1999; Schroeder, 2002; Sulak, 2008; Willson, 1979), *L. pertusa* growth on anthropogenic substrates such as sub-sea cables (Duncan, 1877; Wilson, 1979), oil and gas
platforms (Bell and Smith, 1999; Gass and Roberts, 2006; Schroeder et al., 2005) and ship wrecks (Church et al., 2007; Roberts et al., 2003), is well documented.

A recent search of the Bureau of Ocean Energy Management’s (BOEM) Platform Structures Query (Bureau of Ocean Energy Management, 2012) found 65 structures in the GoM in water depths greater than 200 m, (deep enough to encompass the minimum depth range of *L. pertusa* in the GoM). In 1997, “deep” (depths greater or equal to 305 m (1,000 ft)), or “ultra-deep” (depths greater or equal to 1524 m (5,000 ft)), wells accounted for 70% of the oil and 36% of the natural gas production in the GoM (Nixon et al., 2009). There are numerous types of hydrocarbon drilling, production, and storage structures in the GoM that either have a surface component supported by long rigid members, buoyancy, or a combination of the two. Other types of installations are entirely sub-sea. All of these structures, and shipwrecks can provide a substrate favorable for the settlement of a variety of invertebrate taxa and have the potential to provide habitat for *L. pertusa* settlement and growth.

Growth rates previously reported for *L. pertusa* vary widely. Growth rates determined for North Sea *L. pertusa* from depths < 300 m range from measurements of 2.6 mm/yr under laboratory conditions to *in situ* estimates of 20 – 25 mm/yr using stable and radio isotopic techniques (Freiwald & Henrich, 1997; Mikkelsen, et al., 1982; Mortensen & Rapp, 1998). Direct measurements of *L. pertusa* from the Mediterranean kept in aquaria had linear extension rates ranging from 15-17 mm/year (Orejas et al., 2007). *In situ* measurements using pieces of *L. pertusa* stained on the surface with Alizarian Red and then deployed in their natural habitat in the GoM found average linear growth rates of 2.4 to 3.8 mm/year (Brooke and Young, 2009). The highest growth rates measured for *L. pertusa* are in the range of slower growing massive shallow-
water scleractinian corals (Orejas et al., 2011) yet are considerably greater than most deep water antipatharian or gorgonian coral growth rates (Prouty et al., 2011; Roark et al., 2009).

Growth rates for colonial corals on anthropogenic substrates can be constrained by dividing colony size by the amount of time the substrate has been available for colonization. Growth rates determined using this method for *L. pertusa* in the North Sea, where it’s maximum depth of occurrence is 132m, range from 5 mm/year to 36 mm/year (Bell and Smith, 1999; Gass and Roberts, 2006; Roberts, 2002; Wilson, 1979). This method assumes the coral larvae settled and started growing immediately after the substrate was first available and therefore provides a minimum growth rate, as settlement is unlikely to occur instantly and will continue to occur as long as suitable substrate is available to competent larvae. Here we determine occurrence, growth rates, densities and distributions of *L. pertusa* colonies on oil and gas platforms, and on several ship wrecks, and examine how these parameters vary with depth and structure type in the GoM.

**Methods**

We examined *Lophelia pertusa* distribution and growth on 6 energy platforms of four different types, one sub-sea installation, and three shipwrecks in the Northern GoM (Table 2-1, Fig. 2-1).
Table 2-1: Structure characteristics, *L. pertusa* occurrence, and *L. pertusa* growth rates

Structures are arranged by the maximum age of corals ranging from least to greatest. The largest and smallest values in each column are bolded. “Thickets” are where corals were too large and or dense to distinguish individual colonies (Fig.1). Due to uneven sea floor elevations and slight discrepancies in ROV depth counters, water depths of structures are approximate. The depth of the base of structure was shallower than the known depth distribution of *L. pertusa* for all structures except Structure C.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Location (Lat., Long.)</th>
<th>Structure Type/ Structure Member(s) Surveyed</th>
<th>Age of Structure at Time of Imaging (years)</th>
<th>Approximate Water Depth of Structure (m)</th>
<th>Depth of Range of Occurrence (m)</th>
<th>Depth Interval of Highest Averaged Density (m)</th>
<th>Highest Averaged Density (colonies/m²)</th>
<th>Number of Colonies Measured for Growth Rate</th>
<th>Min. Growth Rate of top 10% of Corals (cm/year) Ave. ± 1 SD</th>
<th>Minimum Growth Rate (cm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-87.8, 29.2</td>
<td>Compliant Tower/Risers Compliant Tower/Legs</td>
<td>9</td>
<td>532</td>
<td>248 - 530</td>
<td>442-457</td>
<td>0.93</td>
<td>36</td>
<td>3.23 ± 0.18 (n=4)</td>
<td>3.47</td>
</tr>
<tr>
<td>A</td>
<td>-87.8, 29.2</td>
<td>Compliant Tower/Legs</td>
<td>10</td>
<td>532</td>
<td>248 - 530</td>
<td>411-427</td>
<td>1.31</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>B 2008¹</td>
<td>-88.6, 29.0</td>
<td>Solid/Risers</td>
<td>14</td>
<td>400</td>
<td>218 - 378</td>
<td>351-387</td>
<td>1.03</td>
<td>71</td>
<td>2.12 ± 0.14 (n=7)</td>
<td>2.32</td>
</tr>
<tr>
<td>C</td>
<td>-88.1, 29.0</td>
<td>Tension Leg/Log, Leg</td>
<td>15</td>
<td>995</td>
<td>286-801</td>
<td>503-518</td>
<td>10.69</td>
<td>317</td>
<td>1.46 ± 0.16 (n=32)</td>
<td>1.66</td>
</tr>
<tr>
<td>D</td>
<td>-88.0, 20.2</td>
<td>Span/Riser</td>
<td>15</td>
<td>614</td>
<td>262-614</td>
<td>503-518</td>
<td>6.64</td>
<td>632</td>
<td>1.23 ± 0.19 (n=83)</td>
<td>1.78</td>
</tr>
<tr>
<td>B 2011¹</td>
<td>-88.6, 29.0</td>
<td>Solid/Leg and Support Members</td>
<td>17</td>
<td>400</td>
<td>201-364</td>
<td>351-387</td>
<td>2.73</td>
<td>503</td>
<td>2.20 ± 0.20 (n=50)</td>
<td>2.03</td>
</tr>
<tr>
<td>E²</td>
<td>-91.5, 27.8</td>
<td>Tension Leg/Log, Leg Subsea Installation/Conductor Support</td>
<td>23</td>
<td>524</td>
<td>254-unknown</td>
<td>411-427</td>
<td>N/A</td>
<td>230</td>
<td>1.22 ± 0.09 (n=24)</td>
<td>1.53</td>
</tr>
<tr>
<td>F</td>
<td>-89.9, 28.6</td>
<td>Subsea Installation/Conductor Support</td>
<td>21</td>
<td>447</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>38</td>
<td>2.48 ± 0.35 (n=4)</td>
<td>3.00</td>
</tr>
<tr>
<td>G</td>
<td>-98.1, 28.6</td>
<td>Solid/Leg and Support Members</td>
<td>34</td>
<td>320</td>
<td>218 – 320 (seafloor)</td>
<td>325-280</td>
<td>Thickets</td>
<td>50</td>
<td>2.06 ± 0.15 (n=5)</td>
<td>2.30</td>
</tr>
<tr>
<td>GulfPenn</td>
<td>-98.6, 28.5</td>
<td>Ship Wreck</td>
<td>66</td>
<td>-550</td>
<td>N/A</td>
<td>N/A</td>
<td>Thickets</td>
<td>42</td>
<td>1.25 ± 0.08 (n=4)</td>
<td>1.36</td>
</tr>
<tr>
<td>GulfOil</td>
<td>-98.6, 28.1</td>
<td>Ship Wreck</td>
<td>67</td>
<td>-555</td>
<td>N/A</td>
<td>N/A</td>
<td>Thickets</td>
<td>9</td>
<td>1.12 ± 0.32 (p&lt;0.05)</td>
<td>1.60</td>
</tr>
<tr>
<td>Green Lantern</td>
<td>-90.1, 28.0</td>
<td>Ship Wreck</td>
<td>103-86¹</td>
<td>-615</td>
<td>N/A</td>
<td>N/A</td>
<td>Thickets</td>
<td>7</td>
<td>0.36 ± 1.1 (n=7)</td>
<td>0.53</td>
</tr>
</tbody>
</table>

¹Observations on this structure were taken during two separate years at different locations each year. ²Measurements only obtained to 437m, whereas the structure base is located at -524m. ³*L. pertusa* colonies were found growing on the sea floor near the base of the structure. ⁴Exact date of sinking is unknown but is estimated between 1906 and 1920. The structure was imaged in 2009. ⁵Due to small sample size, all measured colonies are used.
Inspection video was provided for three different platforms: Structure A, Structure B, and Structure D, including video from two different years for Structure B and two different member types installed in different years for Structure A. In July 2012 we conducted a cruise specifically to acquire data on *L. pertusa* distribution on energy platforms using the Research Vessel Brooks McCall and the ROV Kraken 2. Imagery was collected using a Kongsberg HD Video Camera and Canon PowerShot G11 10M pixel Digital Still camera. The shipwrecks were imaged in 2009 and 2010 from the ROV Jason II, using an HD video camera. Both frame grabs from video and digital still images were used in our analyses.
The video analysis software Studiocode 4.5.1 was used to log and classify the data acquired from the video survey. Studiocode allows the user to create unique, customizable “codes” (such as “L. pertusa present,” “horizontal structure,” “depth interval”, etc.) that are synced via a timeline to the video and frame grabs from the video, and can be accessed through an interactive database. Although only subsets of the entire video record were suitable for most measurements, the shallowest and deepest unambiguous depth of occurrence of L. pertusa was recorded for each structure.

Two different methods were used to estimate scale in the images. For the quantitative analyses from the industry supplied inspection video, only images with both sides of the structure member in the frame were used for analysis because the structure diameter was used for scale in these images. Scale for the images acquired during the July 2012 cruise and from the ship wrecks was acquired from a pair of forward facing parallel lasers spaced 10 cm apart mounted in the plane of the video and aimed at the center of the structure member. Only colonies clearly attached to a vertical or horizontal structure member where colony attachment point could be reasonably inferred were used for measurements; colonies growing near pipe junctions, on projecting or irregular structures, or on closely adjoining structures were not used for any quantitative analyses. Colony area and growth rate measurements were taken from video screen shots or digital images using Adobe Photoshop CS3 or PixelStick 2.3 and converted from pixels to cm using scale determined as described above.

In order to avoid over estimating growth rates, all measurements for growth determinations were taken from a clear attachment point on the anthropogenic structure to the furthest apparent extension of that colony from that attachment surface (d_l in Fig. 2-2a).
This method always provided a conservative measure for the maximum extension of the colony from its point of attachment, even if the colony was partially obscured by the structure or had fused with other colonies. Growth rate (cm/year) was calculated by dividing $d_f$ by the time that the anthropogenic substrate had been available for colonization. Coral measurements that yielded
the highest growth rates in each data set were re-measured and checked by an independent observer.

Two sets of data that could be obtained from all corals present in suitable quality video of the energy platforms were used for analysis of *L. pertusa* depth distribution patterns; density of colonies and colony area. For density measurements, only *L. pertusa* with attachment points on the side of a vertical structural member facing the ROV were used; *L. pertusa* where portions of a colony were seen “peeking” out from the far side of the structure were not counted for density. Density was calculated by dividing the number of colonies within a 15.25m (50 ft) depth interval by the surface area of half the face of a cylindrical structure (\(\pi rh\)) where \(r\) is the radius of the structure and \(h\) is the length of the structure member or usable video within a given depth interval. Some portions of video unsuitable for colony size or measurements for calculation of growth rate due to video quality were still used for density calculations when *L. pertusa* colonies could be clearly identified.

For colony area measurements, only colonies that were clearly visible and appeared to be single colonies were used. Colonies with shapes that suggested two or more colonies had grown together were not measured. For colonies on the face of a structural member, area was estimated from measurement of two diameters: one along the colony’s longest axis \((d_1)\) and one perpendicular to this \((d_2)\) using the equation for an ellipse where area \(= (d_1/2) \times (d_2/2) \times \pi\) (Fig. 2-2b). Colony area for *L. pertusa* visible in profile on the edge of the structures was calculated using the equation for a circle, where area \(= (d_1/2)^2 \times \pi\), and \(d_1\) was the colony diameter parallel to the structure (Fig. 2-2a).
To estimate the maximum percent coverage of *L. pertusa* on a given structure, non-overlapping screen shots were taken of each rig at the middle of the ten-meter depth interval of maximum colony density and at 5 meters above and below this depth. Inkscape 0.48.2 was used to outline the structure and *L. pertusa* colonies over the surface of the structure and % cover calculated from the areas of each (Fig. 2-3).

This method will overestimate percent coverage as it assumes the structural member is flat so structure surface is underestimated and colonies towards the edge of the column will obscure a disproportionate area of the actual surface. These data, however, were only used for relative comparisons between platforms and over time.
Results

The growth rates calculated from the largest colonies ranged from 1.5 to 3.5 cm/yr on the various platforms and 0.45 to 1.6 cm/yr on the wrecks. Using the average of the largest 10% of the corals measured for this analysis on each structure, the calculated rates ranged from 1.2 to 3.2 cm/yr on the platforms and from 0.4 to 1.1 cm/yr on the wrecks. There was a significant linear correlation between the age of the structure and the calculated growth rate, with the lower growth rates calculated from the older structures ($R^2_{\text{adj.}} = 54.8\%$, $p = 0.009$, Table 2-2).

Table 2-2: Regression statistics for minimum growth rate vs. maximum age of corals

*Separate regression functions have been run based on the category of structure type (compliant/solid, spar/tension leg, wreck, all structures, or only rigs). Only the significant ($\alpha = 0.5$) regression line is shown and p-value is bolded. See figure 10 for graphical representation of these data.*

<table>
<thead>
<tr>
<th>Structure Type(s)</th>
<th>Regression Equation (Minimum growth Rate =)</th>
<th>$R^2_{\text{adj.}}$ (%)</th>
<th>p-value of constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Rigs and Wrecks</td>
<td>– 0.0225 Structure Age$^{1,2}$ + 2.74</td>
<td>54.8</td>
<td>0.009</td>
</tr>
<tr>
<td>All Rigs</td>
<td>– 0.0308 Structure Age$^1$ + 2.87</td>
<td>0.0</td>
<td>0.42</td>
</tr>
<tr>
<td>Compliant/Solid</td>
<td>– 0.0344 Structure Age$^1$ + 3.39</td>
<td>16.9</td>
<td>0.33</td>
</tr>
<tr>
<td>Spar/Tension Leg</td>
<td>– 0.0362 Structure Age$^1$ + 2.36</td>
<td>89.2</td>
<td>0.15</td>
</tr>
<tr>
<td>Wrecks</td>
<td>– 0.0285 Structure Age$^{1,2}$ + 3.23</td>
<td>89.4</td>
<td>0.15</td>
</tr>
</tbody>
</table>

$^1$Structure age at the time of imaging. $^2$ An average of the earliest and latest possible dates of sinking (96 years) was used for the shipwreck *Green Lantern.*

There was not a significant correlation between age and growth rate with individual structure types, all rigs, or only wrecks. Using a two-sample T-test, solid/compliant platforms had significantly higher growth rates than spar/tension leg platforms ($p=0.04$) and all rigs combined had a significantly higher growth rate than wrecks ($p=0.025$).
The shallowest occurrence of *L. pertusa* on the platforms ranged from 201 m on Structure B to 294 m on Structure E (Table 2-1). Only one platform examined spanned the entire potential depth range of *L. pertusa* and the deepest occurrence noted on that platform was 801 m (Structure C, Table 2-1). On all platforms that we were able to survey from above the first occurrence of *L. pertusa* to the sea floor, the density of *L. pertusa* colonies peaked at some intermediate depth (Fig. 2-4).

Figure 2-4: Colony density vs. depth

*Scatter plot of colony density vs. depth for all structures with a vertical component that had measurable colony densities. The rig Structure G was not included because portions of the structure were covered in “thickets” of *L. pertusa* that cannot be quantified by number of colonies per square meter of structure.*

1Measurements only obtained to 437m. Structure depth is 524 m.
2Solid or compliant type structures. The other rigs are spar or tension leg type structures.
For the shallower water platforms, this peak depth was constrained by the platform water depth. On the deeper water platforms, the peak in colony density occurred at about 500 m (Fig. 2-4, Table 2-1). The maximum densities on the different platforms ranged from about 1 to 10.8 colonies/m² and on the older platforms and some wrecks the colonies had merged into thickets (Table 2-1, Fig. 2-4). In general, the highest densities of colonies were observed on the deeper platforms and the solid and compliant tower type structures had lower peak and average densities then the spar and tension leg type structures (Table 2-1, Figure 2-4).

Another measure of the density of *L. pertusa* on the artificial structures is the percent coverage. Using a one-way ANOVA with post-hoc Tukey’s analysis, there was no significant difference (α= 0.05) in the percent coverage of areas with maximum colony density on any platforms except the oldest platform which had the highest percent coverage (average 65.65%, SD 8.9%). However, the lowest maximum coverage occurred on the youngest platform imaged (average 1.67% SD, 1.13%). All wrecks at appropriate depths had *L. pertusa* growth at the thicket stage (Fig. 2-5).
Figure 2-5: Mosaic of *L. pertusa* thickets growing on the bow of the *Gulfoil* and on the two WW2 wrecks with extensive relief, coverage was 100% on many portions of the ship.

Although only colonies where growth away from the attachment substrate could be measured were used for the age calculations, the sizes of all colonies were estimated from the photographs. The largest colony on a platform with shape consistent with it arising from a single settlement event was 5,660 cm². In general, colony size was least in the depth intervals near the edges of the observed depth range and peaked at the same depth as colony density and maximum growth (Fig. 2-6).
On the one platform that spanned the full depth of occurrence of *L. pertusa*, the calculated growth rate of the largest colonies found per 15.25 m (50 ft) depth interval was significantly positively correlated with the density of *L. pertusa* ($R^2_{adj.} = 52.2\%$, p-value < 0.0001) (Fig. 2-7).

Figure 2-6 Scatter plot of colony area (size) vs. depth. *All measurable colonies are presented by depth of occurrence. All rigs except Structure C are shallower than the known range of* *L. pertusa*. *The distribution of colony size measurements are confounded by the amount of structure observed for all rigs except Structure C. Colony measurements are biased against smaller colonies that may have not shown up on poorer quality video and against very large colonies at high densities where individual colonies were difficult to distinguish from one another.*
No *L. pertusa* growth was observed between the sea floor and 5-10 m above the sea floor on any structure although one had *L. pertusa* growing on the sea floor near the base (Structure G) and a colony was found on a mostly buried flowline near another (Structure D). While *L. pertusa* colonies are absent on the base of these structures, anemones and other fauna are often present and abundant (Fig. 2-8).
Of 4,383 *L. pertusa* colonies measured for this study, fourteen were not white. The non-white *L. pertusa* colonies were observed on four platforms between 276 and 497 m depth. Colors ranged from bright orange, various shades of brownish-orange (Fig. 2-9a).

Figure 2-8: Base images of structures

*Examples of “bottom effect.”* Approximately 2.5 to 3 meters of structure are visible in each image. *Image A*: Structure A Leg; *Image B*: Structure B Leg; *Image C*: Structure D riser connection; *Image D*: Structure F abandoned flow tube connection. *Image D* illustrates the beginning of *L. pertusa* growth approximately 8 m off the sea floor.
to one mottled brown/orange and white colony (Fig. 2-9b). Though non-white colonies on the same rig occurred within 50 m of each other, non-white colonies were never observed adjacent to one another.

**Discussion**

In this study we examined the growth rates of *L. pertusa* along with their density and depth distribution on artificial structures in the GoM. The highest growth rates reported here are similar to the highest published rates for *L. pertusa* measured on artificial structures in shallower water (Gass and Roberts, 2006). These rates are higher than those reported for deep water *L. pertusa* in the GoM using other techniques such as *in situ* staining (Brooke and Young, 2009). Although it has been suggested that coral growth is enhanced in association with magnetic fields...
associated with ferrous substrates, we consider it more likely that this non-invasive method for
determining growth rate perturbs the coral less and reflects natural rates at the depths measured.

Though growth rates are variable between structures (Table 2-1), overall, growth rates are
negatively correlated with the age of a structure (Fig. 2-10, Table 2-2). This may reflect
faster growth or younger colonies, and/or the more linear branch growth inherent in early colony
growth vs. the increased zig-zagging morphology of branches on older colonies.

It is difficult to compare solid/compliant and spar/tension leg structures because no
solid/compliant structure reached optimal *L. pertusa* settlement depth. (Table 2-1, Fig. 2-4).
Possibly because of the increased depth available for settlement, the maximum colony densities
on spar/tension leg structures was approximately four times greater than on solid/compliant
structures (Table 2-1). Conversely Solid/compliant structures have significantly higher growth
rates in comparison to spar/tension leg structures of similar ages even though all solid/compliant
structures are at sub-optimal depth for *L. pertusa* settlement. This may reflect the more massive,
cross braced compliant/solid structures effecting currents and facilitating food or oxygen delivery
to the corals. Despite initial colony densities, percent coverage of *L. pertusa* on solid/compliant
towers and ship wrecks is often quite significant (Fig. 2-3, Fig. 2-5), with large colonies reaching
thicket stage by 34 years (Fig. 2-3, 2-6).

It is difficult to compare colony densities between solid/compliant and spar/tension leg
structures because no solid/compliant structure reached optimal *L. pertusa* settlement depth.
(Table 2-1, Fig. 2-4). Possibly because of increased depth, colonies on spar/tension leg structures
reached maximum densities approximately four times greater than on solid/compliant structures
(Table 2-1). Regardless of initial colony densities, even solid/compliant towers and shipwrecks
can reach significant percent coverage of *L. pertusa* over time (Fig. 2-3, Fig. 2-5). Colonies can become quite large within less than 17 years, (Fig. 2-6) and can conservatively reach thicket stage by 34 years (Fig. 2-3).

There are numerous natural potential source populations, both east and west of the structures studied here (Morrison et al., 2011) to provide larva for which may settle on deep water installations. Because we found *L. pertusa* on every artificial structure examined (including shipwrecks at appropriate depths) (Table 2-1, Fig. 2-5) there are likely numerous other structures harboring substantial *L. pertusa* growth in the northern GoM.

This study expands the known depth limit for *L. pertusa* in the GoM from 640 m (Schroeder et al., 2005) to 801 m (Table 2-1). Structure C provided the first opportunity to look at areas suitable for *L. pertusa* settlement throughout a continuous 995 m depth range at a single location. As expected, *L. pertusa* was not present above the thermocline, and it is likely that temperature defines its upper depth range in the GoM. Temperatures of 6° C were recorded at the maximum depth of occurrence during this study; whether *L. pertusa*’s depth range is limited by physiological considerations, food supply, or lack of propagules cannot be determined from this study. In addition, using Structure C as a model, there appears to be a favorable depth range for *L. pertusa* settlement at 500-520 m (Table 2-1, Fig. 2-4) and there is a strong positive correlation ($R^2_{adj.}= 52.2\%, p< 0.0001$) between the growth rate of *L. pertusa* and colony density on this structure. For all structures, the continuum and variation in *L. pertusa* colony size throughout the majority of its depth range (Fig. 2-6) is indicative of regular, re-occurring and ongoing colony settlement as opposed to rare settlement events.
In addition to expanding the depth range of *L. pertusa*, this study is the first to document the presence of non-white *L. pertusa* morphotypes in the GoM (Fig. 9a,b), though non-white *L. pertusa* are common in the North-Atlantic. The rarity and distance separating these non-white colonies suggests they are not clones, but the result of individual larval settlement. The absence of non-white *L. pertusa* on natural substrates in the GoM might indicate the platforms are serving as “stepping stones” for invasion of these colored morphotypes into the Gulf. Though it is unknown whether *L. pertusa* color morphs are linked to genetic differences (Mortensen, 2001), it has been suggested that each may harbor different bacteria consortia (Neulinger, 2008)

For structures shallower than 800 m, there appears to be some type of “bottom effect” that renders the base of structures unsuitable for *L. pertusa*. (Fig. 2-8, Fig. 2-4, Table 2-1) even when the structure is no longer producing or handling hydrocarbons (i.e. Structure F). Although *L. pertusa* was absent on the bottom 5-10 m of all energy installations examined, other fauna were present on this portion of the installations, most notably, fly-trap anemones, suggesting that this effect is not the result of anti-fouling agents. The reason for this “bottom effect” is unknown and may be due to competition from fauna better equipped to utilize food that falls from upper levels on the platforms or some type of unfavorable sediment and/or current condition.

Despite the potential for new and continued *L. pertusa* habitat on artificial structures in the GoM, these are not natural substrates for *L. pertusa* growth. On natural substrates, *L. pertusa* growth can progress from single colonies, to thickets, then mature coppices (Wilson, 1979), which provide habitat for a variety of species on live, dead, and live/dead mixtures of *L. pertusa* (Cordes et al., 2008; Jensen and Frederiksen, 1992; Lessard-Pilon et al., 2010; Mortensen et al., 1995). Community biodiversity on and around *L. pertusa* reefs can be comparable to that of shallow-water reefs (Jensen and Frederiksen, 1992; Rogers, 1999) and can provide habitat for
commercial deep-sea fish (Ross and Quattrini, 2007). Though artificial structures will provide habitat for numerous other species, this live/dead mixture of *L. pertusa* cannot form on vertical or steep diagonal structures where dead-bioeroded *L. pertusa* will be swept away and fall to the sea floor. As a result, the communities closely associated with *L. pertusa* on platforms are not as species rich as those associated with natural *L. pertusa* reefs.

Energy platforms, subsea installations, and shipwrecks afford a unique and valuable opportunity to study many aspects of *L. pertusa* biology because of: 1) the known date of installation for growth rate and population studies, 2) the large depth range of potential substrate in a single location represented by the deeper water platforms, and 3) wide distribution and large numbers of potential substrates in known locations of the deep GoM. Here we reported on a relatively small number of artificial structures, at very limited points in time. Repeat visits to these and additional structures will allow researchers to better understand *L. pertusa* settlement and growth patterns, physiological requirements, and the connectivity of populations throughout the Gulf of Mexico.
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Chapter 3

Conclusions

Artificial structures have been shown to provide habitat for faunal settlement; *L. pertusa* was present on every structure observed, likely indicating that numerous other artificial structures in the GoM of appropriate depth will also harbor *L. pertusa*. Solitary corals and fauna such as anemones were also present on all structures. We have just begun to study artificial structures in the GoM, especially at depths greater than 200 meters. Currently there are over 4,000 hydrocarbon installations, active and inactive, in the GOM (Bureau of Ocean Energy Management, 2012).

As of 2000 the Rigs to Reefs program established by the Mineral Management Service, has identified 151 rigs donated to be used as artificial reefs whether though towing, toppling, or removal of upper portions (Dauterive, 2000). According to the MMS “The MMS supports and encourages the reuse of obsolete offshore petroleum structures as artificial reefs in the U.S. waters. The structure must not pose an unreasonable impediment to future mineral development…. (Dauterive, 2000).” Also, the Bureau of Safety and Environmental Enforcement (BSEE) website states, “approximately 420 platforms have been converted to reefs, the majority of these off the coast of Louisiana and Texas, with the purpose of serving as “essential fish habitat.” The current impetus for leaving the rigs in place is cost saving and fisheries development, not cold-water coral habitat.

These structures, however, have the potential to harbor and, because of their number and proximity, quickly facilitate the spread of invasive species. Artificial structures are not “natural”
and regardless of whether a species is native or non-native, considered “beneficial” or “detrimental” to an ecosystem, these structures are disruptions to the environment. As previously mentioned, though rigs can be habitat for *L. pertusa*, these “reefs” are fundamentally different than natural *L. pertusa* reefs and could potentially disrupt natural *L. pertusa* communities. In addition, *L. pertusa* carbonate mounds form over thousands of years; unmaintained steel structures may only last a few hundred years. At present, no deep-water invasive species have been identified on hydrocarbon installations, but the spread of shallow water non-native species such invasive ascidians has been facilitated by oil rigs (Lambert, 2002). Semi-submersible rigs also provide a great risk of spreading non-native species, as documented with finfish, as they move from one drilling site to the next (Wanless, et al., 2010).

In addition to impacting fauna living on or around the structure hydrocarbon structures, especially drilling operations through the disposal of drill cuttings and mud, have the potential to negatively affect the abundance and community structures of macro, meio, and micro benthic fauna (Gates and Jones, 2012; Netto et al., 2010; Santos et al., 2009). Though drilling disturbs macro, meio, and micro benthic fauna, known disturbance is generally limited to a few hundred meters surrounding the drill site and species abundance and richness improves as time progresses from the cessation of active drilling (Gates and Jones, 2012; Netto et al., 2010; Santos, et al., 2009). A study done by Netto et al. (2010), describes a more expedited faunal recovery from sites using water-based drilling fluid as opposed to water/synthetic drilling fluid, which can contain a variety of non-aromatic hydrocarbons. With respect to *L. pertusa*, polyps suffered tissue damage and death at sediment levels of 6.5 mm while current model thresholds for drill cutting risk assessment are set at 6.3 mm (Larsson and Purser, 2011).
This study used the video analysis software package Studiocode 4.5.1, which was designed for use in athletic video analysis and has been adapted for use in business and educational research. This novel adaptation of Studiocode may prove especially useful to other deep-sea research to extract and organize data from large video data sets. This software allows the user to organize and code complex sets of discontinuous video then search and return to any specific occurrence as needed as well as export coded data to spreadsheets for analyses. With proper video collection formatting, first tier coding could be conducted in real time.

Some major limitations to this study include image quality, oil company permissions, rig schematics and ROV capabilities. For most inspection videos, image quality was relatively poor and led to uncertainties in measurements, causing measurements to be more conservative than with higher quality images. Permission to obtain structure measurements and visit rigs resulted in significant time delays with research. In addition, in all cases except Structure D, company employees were unable to assist with the identification of rig structures as they related to each video to within 6 inches and, oftentimes, employees misidentified structures. Lastly, there was difficulty navigating the ROV around the complicated structures of the rigs as well as numerous ROV malfunctions. For future studies, pilots who have more experience working around rigs with ROVs tested under similar conditions would be optimal.

As with all studies, there are many avenues for future research. Re-imaging some or all of the rigs in the study and specifically imaging previously identified corals of various sizes would provide a more accurate growth rate over a known time period, as well as changes in growth rate with coral size, depth, and density. In addition, re-scanning entire legs or members could determine how coral density changes with time could also address the question of continuous larval settlement vs. sporadic or rare larval settlement with varying growth rates. If
possible, a partnership between researchers and oil companies could lead to permanent imaging and water monitoring stations on rigs as well as the continued sharing of inspection videos. Required parameters could be available for rig inspectors to quickly run scans usable for such studies.

More research needs to be conducted on deep-water corals and other fauna, as well as shallow water species, (not just fisheries development) on and around artificial structures to better understand the ecological implications for leaving them in place after oil/gas production has ceased. Regardless of whether these structures are removed or left in place after cessation of operation, these structures have already been in place long enough for the establishment of substantial communities of *L. pertusa* and potentially invasive species. Benthic communities are impacted though the drilling phase but would be in some form of recovery phase at the time of platform removal, causing a second disturbance event. A presentation by the Outer Continental Shelf Advisory Board estimates the cost of leaving a rig in place (cutting off the top 85 ft of structure for shipping clearance) to cost between 0.5 and $1 million, a saving as much as $20 million per platform (OCS Advisory Board, 2010). If energy extraction companies do leave substantial parts of structure or pilings of rigs in place; part of the cost savings incurred by these companies should continue to be set aside for marine research and protection.
References


