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Stabilization of Fragments to Enhance Asexual Recruitment in *Acropora Palmata*, a Threatened Caribbean Coral

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RESEARCH ARTICLE

Stabilization of Fragments to Enhance Asexual Recruitment in *Acropora Palmata*, a Threatened Caribbean Coral

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Abstract

Historically, fragmentation has been a successful life history strategy in *Acropora palmata*. However, in areas where the population is sparse and degraded, the survivorship of fragments is now compromised. This study aimed to determine whether stabilization of *A. palmata* fragments could increase their overall performance. Naturally occurring fragments were found and assigned to one of three treatments: stabilized to the natural substrate (1) using cable ties, (2) using epoxy or (3) tethered to the substrate as an unstabilized control. After 44 weeks, the general "performance" of the fragments was ranked based on their change in live tissue cover and formation of tissue connections with the substrate. Stabilized fragments lost less tissue cover and ranked higher in performance than the unstabilized control fragments. Stabilization using cable ties and epoxy were similarly effective. The results indicate that stabilizing fragments will preserve live tissue and enhance growth of fragments and can thus improve the survivorship of fragments.

Key words: acroporid, Biscayne National Park, Florida, restoration, reef.

Introduction

Acropora palmata (elkhorn coral), with its fast growth rate, branching morphology, and tendency to form dense monospecific stands (Goreau 1959; Bak et al. 1982; Miller et al. 2002a), performs keystone functions within Caribbean reef ecosystems by providing shelter to a variety of fish and other ecologically and economically important reef organisms (Lirman 1999), and accreting reef structure (Shinn et al. 1980). Since the 1970s, acroporid coral species in the Caribbean have experienced extreme and accelerating declines estimated at 90–98% throughout their range (Bruckner 2002; Miller et al. 2002b). The severe and protracted population decline led the United States government to pursue the listing of *A. palmata* (along with its congener, *Acropora cervicornis*) as "threatened" under the U.S. Endangered Species Act in May 2005. This designation carries a legal mandate to plan and implement species recovery.

The life history of acroporid corals relies strongly on fragmentation and the successful recruitment (attachment to the substrate) of the fragments (Bothwell 1982; Highsmith 1982; Fong & Lirman 1995; Lirman 2000). This reproductive strategy can foster rapid proliferation and spatial dominance; however, it can also result in losses because the loose fragments are more vulnerable to export or mortality (Lirman & Fong 1996, 1997; Smith & Hughes 1999). Once broken off of standing colonies, branch fragments may nestle into surrounding reef structures and reattach, or may be transported to sandy areas where they become abraded or smothered and eventually die (Bowden-Kerby 1997; Lirman & Fong 1997; Smith & Hughes 1999).

Successful recruitment of *A. palmata* fragments is severely hindered in the sparse *A. palmata* populations typically found in many locations. Recent evidence from degraded populations in the Florida Keys demonstrates that natural recruitment of *A. palmata* fragments in remnant stands is extremely low (Williams et al. 2008). Stands with low colony density do not retain fragments generated in storms as well as stands with more complex colony structure (Lirman & Fong 1997; Miller et al. 2002a). Weakened skeletons resulting from increased bioerosion associated with degraded water quality (Ward-Paige et al. 2005) may result in more, smaller fragments that are more susceptible to export by waves (Highsmith et al. 1980; Lirman 2000). Although the benefits of fragmentation have historically outweighed the costs (Lirman 2000), the present depauperate state of Caribbean populations may have shifted the balance.

Current consensus recommendations to resource managers to promote conservation and recovery of this species include

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intervention by way of fragment attachment (Bruckner 2002; Acropora Biological Review Team 2005). As the population declines, proactive intervention (Edwards & Clark 1998) through salvage of naturally-produced *Acropora* spp. fragments may be increasingly warranted.

Many fragment transplantation or reattachment projects have been undertaken, including many focusing on *Acropora* spp. However, the vast majority of these studies (Clark & Edwards 1995; Smith & Hughes 1999; Epstein et al. 2001; Lindahl 2003; Soong & Chen 2003) have been with Indo-Pacific species (Nagelkerken et al. 2000). Those studies focused on Caribbean species have utilized *A. cervicornis* (Laydoo 1996; Bowden-Kerby 2001; Chilcoat 2004) rather than *A. palmata*. Because of the unique morphology of *A. palmata* (flat, relatively heavy branches), appropriate interventions would likely differ from those commonly used with staghorn-type *Acropora* spp. The few projects addressing *A. palmata* have been reported in fora relatively inaccessible to either scientists or managers (Garcia et al. 1995; Kaly 1995; Gilliam et al. 2000; Bezy & Vasquez 2006) or lacked unrestored controls (Bruckner and Bruckner 2001; also Laydoo 1996) which are necessary for cost-benefit evaluation. Clearly, cost-benefit evaluation, both in absolute (i.e., benefit relative to no action) and relative terms (i.e., between different methods or practices) is required to appropriately allocate limited resources for species recovery.

This study evaluated whether stabilization of small, storm-generated fragments of *A. palmata* resulted in increased growth and survivorship relative to unstabilized control fragments. We also compared the costs and performance of two simple methods of fragment attachment, that is, a marine epoxy and cable tying to reef substrate.

Methods

Acropora palmata fragments for this experiment were selected from those found naturally occurring at 3 m depth on Amanda's Reef (N25°21.173′, W80°10.682′) in Biscayne National Park, Florida (USA). A total of 54 small (<40 cm) fragments were placed in wire baskets, brought to the surface, and transported to a small nearby (~350 m north) but isolated patch reef (N25°21.359′, W80°10.656′) for the experiment. Fragments were exposed to air for less than 10 minutes during the transfer.

Experimental fragments were photographed, the length was measured and the percentage of live tissue cover (on both sides) was visually estimated. Fragments were then grouped into 18 replicate experimental blocks of three with similar size and tissue coverage (Appendix 1). The three fragments in each block were then haphazardly allocated to one of three treatments: cable tied to the substrate (Fig. 1a–c), epoxied to the substrate (Fig. 1d–f), and an unstabilized control (Fig. 1g–i).

For both cable-tied and epoxied fragments, the substrate was prepared by scrubbing with a brush to remove sediment and macro algae. Positioning for the cable tied fragments was based on the availability of tunnels in the substrate to accommodate the cable tie. Fragments were then situated to maximize contact between the fragment and the substrate and secured with plastic cable ties (Fig. 1a). For epoxied fragments, All-fix epoxy (Cir-Cut Corporation, Philadelphia, PA, U.S.A.) was placed on already dead portions of the fragments when possible, but in cases where fragments were mostly or completely covered with live tissue, the epoxy was placed to maximize fragment stability regardless of the presence of live tissue (Fig. 1d).

Unstabilized fragments were included in each experimental block to provide an "unrestored" control. In a pilot attempt to follow loose *A. palmata* fragments at the experimental site, most migrated out of the area and could not be relocated. Thus, for this study, control fragments were tethered by attaching 1-m length of monofilament to each fragment using a cable tie and attaching the other end of the monofilament to the substrate using a nail and numbered tag (Fig 1g–i). The unstabilized fragment was placed on the substrate in a stable position relatively free from macroalgae or sediment deposits; however, the substrate was not scrubbed as this treatment was intended to simulate unmanipulated fragments. Tethering the control fragments provided a conservative comparison of the performance (relative to completely unmanipulated fragments) as they were still subject to abrasion and flipping over, but their overall distance of movement, and thus their potential for export to unsuitable habitat, was constrained.

Follow-up surveys were conducted to assess the condition and stability of the fragments at 7, 24, and 44 weeks following the initial setup in August 2006 (Appendix 2). During the first follow-up survey (week 7), epoxied or cable tied fragments that had become unstable were restabilized, but in later surveys no further manipulations were made. Only one epoxied fragment needed to be restabilized, but several of the cable ties needed to be tightened owing to settling of the fragments.

The treatments were evaluated based on change in live tissue, and tissue connection to the substrate (hereafter referred to as "connection"). Fragments were scored based on their condition at the final survey, 44 weeks after the setup. Both sides of the fragment were considered when assessing change in live tissue in order to account for tissue loss on the underside of the fragment that resulted from stabilization. Tissue on the undersides was assumed to be lost for all attached, stable fragments in all treatments. Control fragments that were still loose at the final survey were flipped to examine the bottom surface. Tissue connection to the substrate was scored as present once the tissue began to overgrow the adjacent natural reef substrate.

Within each blocked replicate, the "performance" of each treatment fragment was ranked from 1 (lowest) to 3 (highest). Fragments that displayed the greatest tissue growth and connection were ranked higher than those that lost live tissue and lacked tissue connection to the substrate. The fragments that were lost or died in place received the lowest rank within their representative blocks. Performance rank was compared
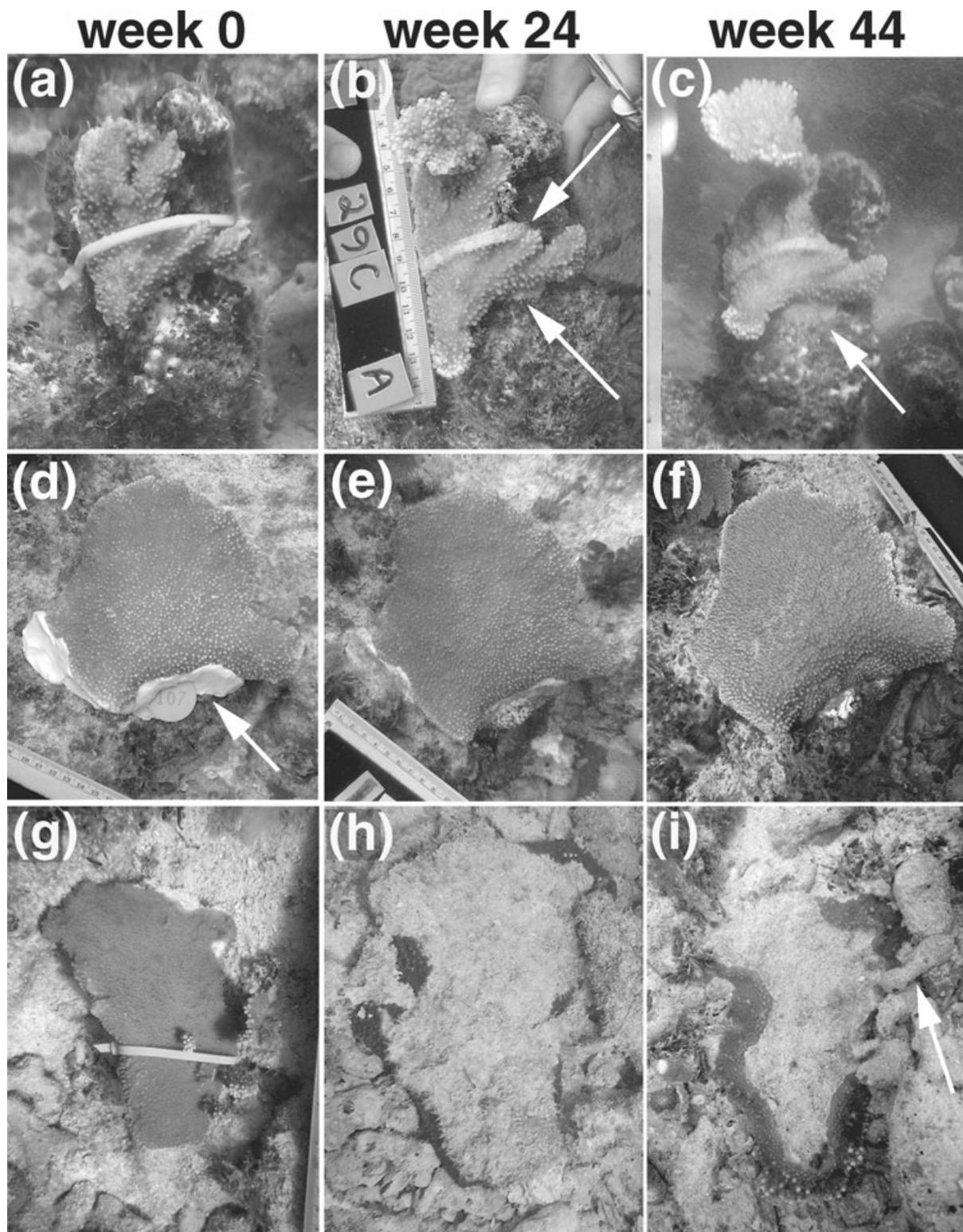
Figure 1. Time series for a typical cable tied (a–c) and epoxy (d–f) stabilized fragment and a tethered control (g–i). By week 24 (b) the cable tie on this fragment is completely overgrown, live tissue has formed an attachment with the substrate (see arrows) and a second protobranch has formed. By week 44 (c) substantial growth of the upper branch was observed. Note that tissue growth has occurred mostly at the branches compared with relatively minor resheeting of the dead skeleton (arrow). Epoxy was used directly on live tissue (d) in cases where no dead areas were present (arrow). No adverse tissue reaction was observed and tissue readily overgrew the epoxy (e–f). By week 24, this tethered fragment (g) had flipped over, burying most of the live tissue and exposing the dead underside (h) and formed small tissue connections to the substrate (not visible in figure). By week 44, the attachments were more robust and some growth of new tissue had begun (i). Note, however, that the attachments were formed with rubble (arrow), which could shift and loosen the fragment.
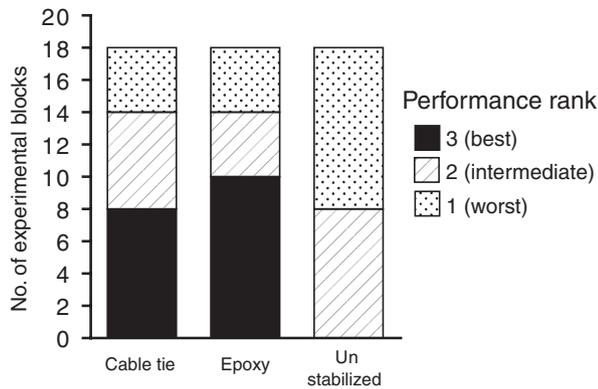
Figure 2. Counts of performance rank among the three treatments after 44 weeks. Performance was evaluated qualitatively based on tissue growth and connection with the substrate and ranked from 1 (lowest, including dead or lost) to 3 (highest) within each blocked replicate.

using a Friedman test, followed by a post-hoc comparison of the rank sums of all pairs (Conover 1980).

To test the hypothesis that initial live tissue cover (rather than experimental treatment) determined eventual success in making tissue connections, the control fragments were grouped into those that ultimately succeeded or failed to make a connection. The initial live tissue cover was compared between these two groups using a Mann–Whitney U test.

Results

At the start of the study, the *A. palmata* fragments ranged in length from 7 to 36 cm and in percent tissue cover between 15 and 95%. Out of 54 total fragments, only one (in the cable tied treatment) suffered complete mortality *in situ*. Nine were physically lost from the experiment, of which five were tethered, two were epoxied and two were cable tied. These fragments were ranked as not attached and lowest in the performance scores.

Performance was significantly different among treatments ($T = 5.02$, $p < 0.025$; Friedman test; Fig. 2). Epoxied and cable-tied fragments performed significantly better (one-tailed $\alpha/2 = 0.025$) than unstabilized fragments but not significantly different from each other. There was no significant difference in the percent live tissue of the unstabilized fragments that made a connection compared to those that did not ($U(7, 6) = 15.5$, $Z = -0.79$, $p = 0.43$).

Discussion

Tissue Loss and Growth

Results indicate that stabilizing small, loose *A. palmata* fragments decreases the tissue that is lost during the natural attachment process (Garcia et al. 1995; Kaly 1995; Smith & Hughes 1999). When fragments were stabilized using epoxy or cable ties, any live tissue on the underside of the fragment was lost due to shading or epoxy coverage. However, loose fragments

lost tissue on both sides as a result of being flipped by wave action in the weeks or months that they were loose on the reef. This observation is different from those made in studies involving *Acropora* spp. with staghorn morphologies (Yap & Gomez 1985; Bowden-Kerby 1997) but similar to those seen in other *Acropora* spp. with plate morphologies (Smith & Hughes 1999) and is clearly a result of the flattened, two dimensional morphology of *A. palmata* (Highsmith 1982). Thus partial tissue loss is an inevitable consequence of the fragment recruitment process for platy acroporid species, but stabilizing the fragment stands to reduce the amount of tissue lost.

The stabilized fragments showed substantially greater growth as indicated by the ranked performance scores. In turn, this is expected to result in decreased time spent as smaller colonies, which are more vulnerable (Williams & Miller 2006). Unstabilized fragments that failed to form connections but remained in place did not grow over the course of the experiment, suggesting that subsequent abrasion and/or the fragment's attempt to attach consumes physiological resources that would otherwise be available for growth (Bak 1983; Oren et al. 1997; Lindahl 2003).

Connections and Stability

Our qualitative observations indicate that the connections formed by the unstabilized fragments were less robust as they tended to settle in depressions alongside other loose material and subsequently attached to that loose material (Fig. 1). Thus, although they were considered "connected" to the substrate, the tissue connections appeared to be more tenuous than those formed in the stabilized treatments.

The initial percent live tissue cover (including both sides of the fragment) was not correlated to tissue connection for the unstabilized fragments. However, qualitative observations indicate that tissue connections to the substrate only occurred where the live tissue on the fragment margin contacted the substrate, regardless of the tissue presence on the remaining parts of the fragment. Thus, positioning the fragment to maximize the contact between a fragment's live edges and the substrate is crucial to the rapidity and success of its autonomous attachment.

Recommendations

While stabilization greatly improved performance, the method used for stabilization did not notably affect performance. Given the lack of an obvious "best" method we were able to conclude that both methods were appropriate for stabilizing fragments. However, we were able to identify some criteria to determine the method that might be most effective depending on various conditions.

When stabilizing the fragments for this study we found that cable ties were generally less applicable in that they require a position on substrate with a tunnel or branch around which to loop the cable tie. Additionally, if the substrate is heavily bioeroded, the added stress of tightening a cable tie may cause the substrate to break off along with the "stabilized" fragment. However, cable ties are more readily available and cost far less

than epoxy, making them more practical in many situations. It should be noted that prior studies have used a nail as an attachment point for cable ties with marginal success (Kaly 1995; Bruckner & Bruckner 2001).

Epoxy was suitable for a wider variety of substrate configurations and fragment shapes than cable ties. We were initially concerned that the epoxy might fail to adhere when applied directly to live tissue and that the contact would be harmful to adjacent live tissue. However, we observed that the epoxy performed very well and had no apparent harmful effect on the tissue (Fig. 1). In fact, the epoxy was rapidly colonized by turf and crustose coralline algae, and was readily overgrown by *A. palmata* tissue.

The epoxy used in this study (All-fix) is mixed in equal parts by hand and must be used within 15–20 minutes of mixing for the bond to be successful. As a result it is more labor-intensive and somewhat impractical for large (>50 cm) fragments. Epoxy is also difficult to use in high surge habitats because it may not set quickly enough (Appendix I in Bruckner 2002). Our study was setup in mild surge and the epoxy was able to cure; and once cured, our site experienced rough seas on many occasions. Only two epoxied fragments were dislodged and these failures were more likely owing to poor mixing/curing of the epoxy as their removal was observed early in the experiment and not coinciding with a rough weather period. All-fix epoxy used in similar applications has been observed to maintain its integrity for more than 5 years (K. Nedimyer 2009, Coral Restoration Foundation, Key Largo, FL, personal communication) which is ample time for fragments to form direct attachment to the substrate and overgrow the epoxy.

The success of fragments (stabilized or otherwise) likely depends on the potential exposure to subsequent disturbances, and the qualities of the surrounding habitat (Lirman & Fong 1997; Nagelkerken et al. 2000; Miller et al. 2002a). These factors should be taken into consideration in determining an appropriate course of action after a fragmentation event. Fragments formed in structurally complex habitats are more likely to be retained (Lirman & Fong 1997; Miller et al. 2002a) and recruit naturally in spite of disturbances, so intervention may not be warranted (Edwards & Clark 1998). Larger fragments (Highsmith et al. 1980; Lirman 2000) and those surrounded by hard reef structure (Miller et al. 2002b) are less vulnerable to export to unsuitable areas; thus, stabilization may not substantially improve their performance. On the other hand, stabilization of smaller fragments and those with sparse coverage of live tissue may result in dramatic increases in their survivorship and growth.

Acropora palmata's life history, with proliferation highly dependent on successful fragmentation, is well suited to a highly abundant species, but because it is no longer highly abundant, this strategy has become a liability. With apparently low success in fragment recruitment (Williams et al. 2008), the tendency to fragment from natural or anthropogenic disturbances may now present more of a threat than a benefit for the remaining *A. palmata* population. Although other substantial threats exist, mitigating this one threat through

simple and effective stabilization methods may improve the prognosis for this threatened species.

Implications for Practice

- Fragment stabilization/rescue is particularly beneficial when the loose fragments are at greater risk of removal from suitable reef structure. This risk is a function of both reef topography and the likelihood of subsequent physical disturbance.
- Stabilization of *A. palmata* fragments increases tissue survival and growth.
- Both epoxy and cable ties proved to be suitable for the stabilization of small *A. palmata* fragments. The choice between these two methods is determined by the configuration of the reef substrate, and access to materials.
- Marine epoxy can be safely used in contact with or adjacent to live *A. palmata* tissue.
- Positioning of the fragment is crucial to success: regardless of stabilization, direct contact between live tissue around the margins of the fragment and the reef substrate enhances tissue connection rate and stability of the fragment.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix 1. Fragments were grouped into experimental blocks of three fragments with similar size and live tissue cover (condition) as illustrated by the two blocks shown.

Appendix 2. Time series of a complete experimental block showing the performance of all three treatments over time. The loose fragment flipped over and lost most of its live tissue before week 7; by week 44 it had not attached but showed some tissue growth and protobranch formation. The cable-tied treatment had formed tissue attachments to the substrate by week 24. It also began to resheet the older dead portions and developed numerous branches by week 44. The epoxy treatment began overgrowing the epoxy by week 7 and new tissue extended down to the natural substrate by week 44. Most new tissue growth occurred in 1 main branch. The fragments in this block were ranked for performance (from low to high) as loose, epoxy then cable tie. The performance of the epoxy and cable tie treatment could be considered approximately equal but in the end the cable tie treatment was ranked higher due to the numerous robust attachment points that were formed. While the loose treatment in this case did not attach to the substrate it should be noted that the growth and branching displayed were not typical of other loose replicates.

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