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Evaluation of staghorn coral (*Acropora cervicornis*, Lamarck 1816) production techniques in an ocean-based nursery with consideration of coral genotype

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ABSTRACT

Staghorn coral *Acropora cervicornis* is an important framework-building species that has declined severely throughout the Caribbean since the early 1980s. This species is now widely cultured in ocean-based nurseries to restore degraded populations. A variety of techniques have been adopted to grow *A. cervicornis* for restoration purposes, however the effect of each of these methods on nursery-reared corals is not well-understood. In particular, systematic evaluation of nursery-reared *A. cervicornis* between water column-suspended and benthic-attached culture methods is lacking. To better understand the effect of these techniques, a one-year *A. cervicornis* propagation experiment in the Florida Keys was conducted to compare growth, condition, and survivorship between common suspended (i.e. tree) and benthic-attached (i.e. block) grow-out methods. The effect of coral genotype on growth was also considered. Colonies were measured and monitored monthly from December 2014 until November 2015, when only three colonies had survived an extreme bleaching event. Colonies on trees grew up to three times faster than those on blocks and the location of colonies on trees did not affect growth. Genotype had a significant effect on colony growth, which was consistent across grow-out methods. Interestingly, colonies grown on blocks bleached sooner but survived longer than those on trees. These findings contribute to a growing understanding of *A. cervicornis* nursery culture, and could aid in the selection of culture methods and genotypes for coral nurseries throughout the wider Caribbean.

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1. Introduction

Coral reefs are valuable but fragile ecosystems that are in decline globally (Côté et al., 2005; De'ath et al., 2012; Gardner et al., 2003; Pandolfi et al., 2003). In the Florida Keys, staghorn coral *Acropora cervicornis* historically formed dense thickets that were critically important for reef-building and habitat provision (Pandolfi and Jackson, 2006; Precht et al., 2002). More recently, populations of *A. cervicornis* have declined by an estimated 95% throughout its range (Precht et al., 2002) in response to stressors such as disease (Aronson and Precht, 2001), climate change (Quinn and Kojis, 2006), poor water quality (Precht et al., 2002) and overgrowth by macroalgae following the die-off of the keystone herbivore *Diadema antillarum* (Hughes, 1994; Lirman et al., 2010a). Following this widespread decline, *A. cervicornis* was listed as threatened under the U.S. Endangered Species Act (National Marine Fisheries Service, 2006) and critically endangered by the IUCN (Aronson et al., 2008). To mitigate the decline of *A. cervicornis*, coral propagation for active population enhancement was initiated in the 1990s (Bowden-Kerby, 2001), and has expanded rapidly in recent years (Mercado-Molina et al., 2015; Young et al., 2012).

Propagation of *A. cervicornis* for restoration typically relies on fragmenting nursery-grown corals originating from wild donors to rapidly produce new colonies (Johnson et al., 2011). Fast growth, branching morphology, and reliance on asexual fragmentation for reproduction make *A. cervicornis* an ideal candidate for this type of restoration (Herlan and Lirman, 2008; Johnson et al., 2011). Several benthic-attached methods were initially developed to culture *A. cervicornis*, including cement blocks (Herlan and Lirman, 2008) and metal or plastic A-frames (Bowden-Kerby, 2001; Quinn and Kojis, 2006; Johnson et al., 2011; Lirman et al., 2014). Reports of *A. cervicornis* survivorship and growth using benthic-attached methods have been variable and in many cases dependent on factors such as fragment size (Lirman et al., 2010b), time following fragmentation (Herlan and Lirman, 2008), and nursery location (Quinn and Kojis, 2006). Benthic-attached nursery methods can also require extra care during regular monitoring and

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cleaning activities to avoid unintentional breakage by divers (Johnson et al., 2011). Water column-suspended methods, including polypropylene lines (Johnson et al., 2011) and PVC trees (Nedimyer et al., 2011), have also been developed for *A. cervicornis* culture. These methods, particularly the PVC tree method, have been extensively adopted throughout the wider Caribbean, and in some locations have completely replaced benthic-attached methods. Some nursery practitioners have reported higher growth and reduced maintenance needs using water-column suspended methods compared to benthic-attached methods (Johnson et al., 2011; Nedimyer et al., 2011; Hernández-Delgado et al., 2014). Conversely, water-column suspended methods can pose a higher risk of entanglement for marine life and recreational boaters and fishers, while anecdotal reports suggest that corals grown using these methods have lower skeletal density (Johnson et al., 2011).

Along with development and refinement of new nursery grow-out methods, practitioners are increasingly considering genetic factors in the design of *A. cervicornis* restoration programs (Baums, 2008; Baums et al., 2010). Genetic diversity is an important consideration for *A. cervicornis* population enhancement activities, as high genetic diversity promotes sexual reproduction (Johnson et al., 2011) and is typically associated with higher resilience (van Oppen and Gates, 2006). Some *A. cervicornis* genotypes have also been found to resist common stressors including temperature-induced bleaching (Barshis et al., 2013) and disease (Vollmer and Kline, 2008). In a nursery setting, differences in extension, branching, and calcification have also been found among varying *A. cervicornis* genotypes, which could have implications for nursery management and genotype selection for population enhancement (Lirman et al., 2014: Lohr and Patterson, 2017). Despite this variation, systematic monitoring of performance among genotypes is not typically conducted in *A. cervicornis* nurseries.

As restoration programs are increasingly adopted and scaled up throughout the wider Caribbean, there is a need for direct evaluation of available culture methods to optimize *A. cervicornis* production. While both blocks and trees are commonly used to culture *A. cervicornis,* the authors are unaware of a prior study quantitatively comparing growth and survival between these methods. With this primary consideration, and understanding the importance of genetic diversity in nursery culture and population enhancement, a study was executed with the objective of comparing growth and survival dynamics of *A. cervicornis* between blocks and trees in a factorial design with four known genotypes. The results of this study are intended to provide valuable information that could aid in the design of *A. cervicornis* restoration programs.

2. Materials and methods

2.1. Study site and experimental corals

This study was conducted at Mote Marine Laboratory's *A. cervicornis* nursery, located five miles south of Summerland Key, Florida at a depth of 8 m. In December 2014, 60 coral fragments from each of four known lower keys *A. cervicornis* genotypes (previously identified using microsatellites) were collected for study ($n = 240$ total fragments). All fragments collected were non-branching, apical tips approximately 5 cm in length. Genotypes were selected based on practical culture needs of nursery managers following a mass bleaching event that occurred from August to November 2014. Experimental fragments were collected after bleaching had subsided and water temperature had dropped below 24 °C to minimize thermal stress and optimize survivorship.

2.2. Experimental design

For the block culture method, 120 cement disks were epoxied to removable PVC caps, which were then fitted onto sets of 10 PVC pipes anchored in a concrete base. Thirty coral fragments of each genotype were then epoxied to the cement disks in monogenetic groups of 10 (e.g. Fig. 1a) using a two-part marine epoxy (All-Fix, USA). Experimental blocks were located within a larger grouping of the same genotype within the nursery. Each experimental block was marked with "Research" to ensure that corals were not disturbed.

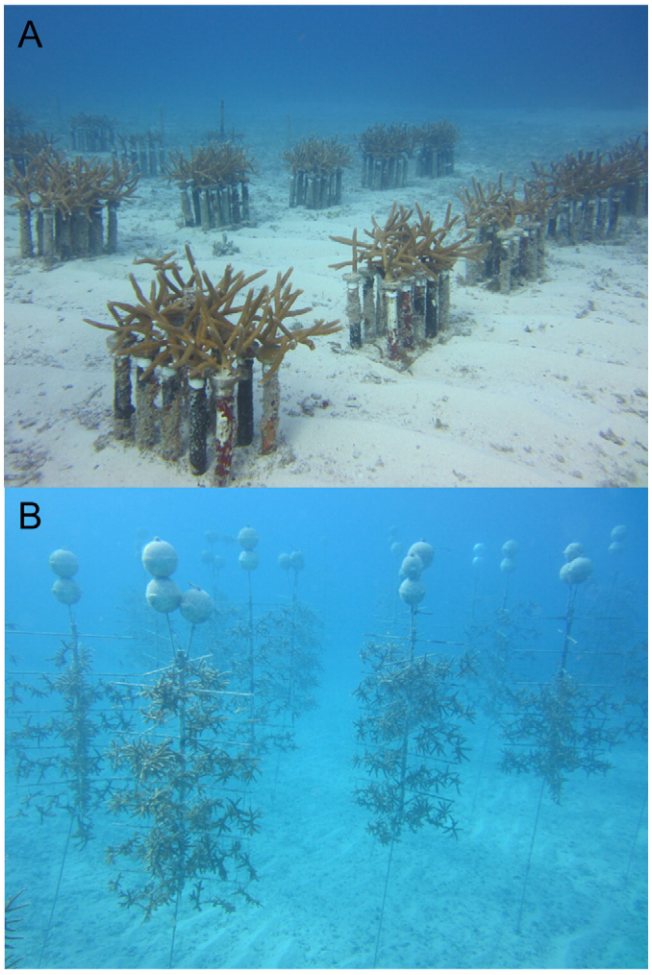

Fig. 1. Representative photos of production-scale *A. cervicornis* culture methods within the Mote Marine Laboratory nursery. A) Benthic-attached (block) method, B) Water column-suspended (tree) method.

An additional 30 fragments from each genotype were distributed among three experimental trees ($n = 10$ per genotype per tree). Fragments were suspended from the tree structure using monofilament and aluminum crimps (e.g. Fig. 1b). Each fragment was assigned an inner or outer position on the tree at each branch level ($n = 5$ branch levels, deepest at 6 m and shallowest at 4 m) such that replicate colonies of all four genotypes were equally represented across branch level and position for each of the three experimental trees.

2.3. Data collection

For each experimental colony, total linear extension (TLE; Johnson et al., 2011; Lirman et al., 2014) was measured to the nearest mm at the beginning of the experiment and monthly thereafter. Colony condition was also noted, including the presence of disease, bleaching, or mortality. Algae and other fouling organisms were cleaned from experimental blocks and trees during each sampling event. Periodic photographs of each tree and block were taken. Temperature loggers (HOBO, Onset Corporation, USA) recorded in situ temperature hourly at the depth of experimental trees (i.e. 4 m) and blocks (i.e. 8 m).

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