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Tiling the reef – Exploring the first step of an ecological engineering tool that may promote phase-shift reversals in coral reefs

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ABSTRACT

Phase shifts from coral- to algal-dominated reefs have grave effects on reef biodiversity and key ecosystem functions, further influencing management approaches that have generated fewer returns than desired. Harnessing the ability of corals to 'self-anchor' to substrates and of tissue fusions between isogeneic fragments, we develop here a novel ecological engineering approach based on the 2D Coral Preparative (2D-CP) tool. Using this tool we propose to create flat, two dimensional coral units that are first grown in a mid-water coral nursery and then transplanted to overlay phase-shifted coral reef surfaces as floor tiles. Here, we assess the feasibility of the 2D-CP's first stage- growth in the nursery. Ten coral colonies from each of the species: *Stylophora pistillata*, *Pocillopora damicornis* and *Cyphastrea* spp. were collected from localities at the northern Gulf of Eilat (Red Sea, Israel), fragmented into nubbins and glued onto flat surfaces (CDs) to create 235 2D-CP units (32 nubbins/unit). All 2D-CPs were hung in a mid-water coral nursery, in both horizontal and vertical positions, and were digitally photographed once a month for a year. Images of each 2D-CP were used to determine the percentages of live coral tissue coverage on the substrates and the nubbins' survival percentage. Results revealed high survival rates, with >80% of the 2D-CPs possessing live coral tissues at 12 months post setup (mps). The nubbins of all three species displayed an extensive 2D growth on the substrates, and as of 6–7 months (species and genotype specific) many of the 2D-CPs were completely covered with coral tissue (20% of all the 2D-CPs showed >100% coral coverage at 12 mps). The coral coverage of *S. pistillata* and *P. damicornis* 2D-CPs was significantly higher in the vertical placement position, 1.5 and 3 times, respectively.

Overall, these results imply that the 2D-CP units can be successfully grown in a coral nursery for the purpose of creating 'live tiles' that can be placed directly over a denuded reef covered by turf algae, a novel ecological engineering tool to be used for coral-algae phase shifts reversals. We further anticipate that even in completely/partially dead 2D-CP units, newly exposed calcium carbonates would be expended as preferable substrates for either coral larval recruitment or coralline algae growth, boosting reef rehabilitation.

1. Introduction

Coral reefs, of the most diverse ecosystems on earth, are under continuous threats from anthropogenic and climate change impacts (Bruno and Selig 2007; Crabbe 2008; van Dam et al., 2011). Estimates in *Reefs at risk revisited* (Burke et al., 2011) predict that by 2050 approximately 75% of coral reefs worldwide will be categorized within the high threat to critical threat levels, with lower resiliency to threats. As long as the coral reef is healthy and has a high resilience, the corals may outcompete algae and thus dominate the coral reef's environment (McCook et al., 2001). In disturbed and stressed reef ecosystems, however, the equilibrium may shift to a state where the algae outcompete and overgrow coral colonies (McCook et al., 2001) and bare surfaces, further inhibiting coral recruitment (Hughes 1994; McCook et al., 2001; Hughes et al., 2003; Bruno et al., 2009), leading to reduced biodiversity and biological phase shifts from coral- to algal-dominated reefs (McManus and Polsenberg 2004; Ledlie et al., 2007; Bruno et al., 2009).

Phase shifts occur commonly throughout the Caribbean and the Indo-Pacific reefs, many of which experience the proliferation of turf algae [lawn-like low-lying landscape (mm to cm tall) algal

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consortia (Connell et al., 2014)]. Documented globally, turf algae have become one of the most abundant benthic functional groups in coral reef communities worldwide, rapidly colonizing exposed reef substrates and dead and damaged coral colonies while out-competing corals due to their fast growth rates (Titlyanov and Titlyanova, 2008; Wild et al., 2014). Proliferating turf algae lawns may have pivotal ecological roles. They are the upshots following catastrophic natural disturbances, reinforcing coral–algal phase shift phenomena (Hughes et al., 2003; Bruno et al., 2009; Dudgeon et al., 2010; Wild et al., 2014). In contrast, closely grazed and cropped turfs support key ecosystem functions in healthy, coral-dominated reefs (McManus and Polsenberg, 2004; Korzen et al., 2011).

Phase shift phenomena are further portrayed by the emergence of alternate ecological stable states and highlight the presence of critical thresholds that mark the usually 'one-way' trajectory from more primeval stable states to anthropogenic novel statuses (Mumby et al., 2007). Significant scientific strides have been made by empirical (Scheffer et al., 2001; Pandolfi et al., 2003; Folke et al., 2004; Collie et al., 2004; Ledlie et al., 2007; Dudgeon et al., 2010; Wild et al., 2014) and theoretical (Hughes et al., 2003; Bozec and Mumby 2014; Jouffray et al., 2015) reef ecologists regarding the mechanisms, drivers, constraints and regulators that shape biological phase shifts in coral reefs (Scheffer et al., 2001; Folke et al., 2004; Collie et al., 2004; Graham et al., 2013), and revealing only rare cases of shifts back to coral dominance statuses (e.g., Edmunds and Carpenter, 2001). In contrast, only a few suggestions for effective management tools that can help control phase shifts were discussed (Scheffer et al., 2001; Pandolfi et al., 2003; Hughes et al., 2003; Folke et al., 2004; Collie et al., 2004; Bellwood et al., 2006; Dudgeon et al., 2010), as these ecologists focused on bottom-up control processes (Korzen et al., 2011; McClanahan et al., 2011) or on the physical removal of algae (Conklin and Smith, 2005; Battista et al., 2016). Both aforementioned approaches generated less returns than desired when assessing reef health and success of act.

Following the above, this study aims to test the first step of a new strategy for reversing coral–algal phase shifts by developing a novel ecological engineering approach (termed the "two Dimensional Coral Preparative tool", or 2D-CP) developed as part of the coral gardening concept of active reef restoration (Rinkevich, 1995, 2008, 2014, 2015). Here we harness the corals' ability to 'self-anchor' to the substrates by the formation of thin 2D layers of calcium carbonate covered tissues (Reynaud-Vaganay et al., 1999; Shafir et al., 2001, 2003, 2006c, 2007, 2014; Bongiorni et al., 2003; Soong and Chen 2003; Rinkevich, 2005; Raz-Bahat et al., 2006; Guest et al., 2011), as well as the aptitude of tissue fusions between contacting isogeneic fragments (Rinkevich, 2004). Employed here as a proof-of-concept, we examine and describe the most suitable conditions for growing the 2D-CP units in a coral nursery setting. With the goal of deploying the 2D-CP units as a novel ecological engineering tool that can be set like 'floor tiles' over turf-covered reef areas, we propose reversing coral-algae phase shift trajectories in future full scale tested projects.

2. Materials and methods

For the 2D-CP experiments we used 235 clear CD-ROM plastic discs (Ecma International, 1996), leached from manufacturing residues by soaking them in running sea water for several days. Two small holes were drilled at the top and two at the bottom of each CD, which was then labeled (for: coral species ID, nursery placement and the experimental repeat) on the back by etching it with a Dremel Rotary Tool (100 Series Rotary Tool). The CDs were then tied five cm apart using a thin nylon monofilament fishing line (ø 0.7 mm), in groups of three intended for hanging in both vertical and horizontal positions (Suppl. Fig. 1) on the underwater floating nursery's railing (Fig. 1). Two sets of CDs were made per each position (vertical/horizontal) for each coral genotype, amounting to 12 CDs per genotype.

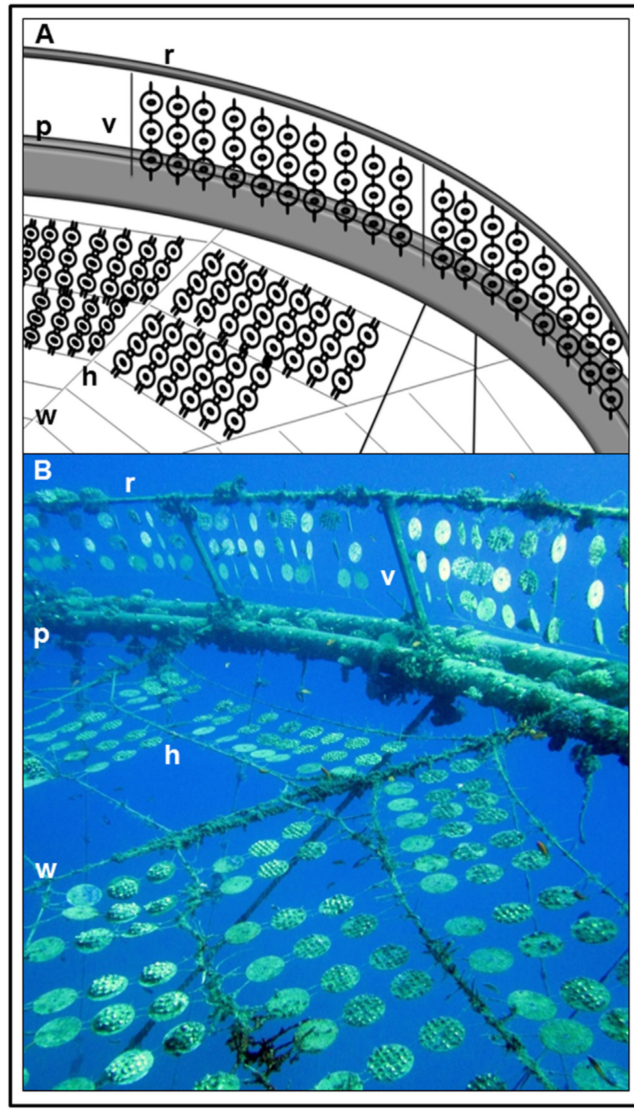

Fig. 1. 2D-CP placement in the coral nursery. (A) A schematic illustration of the coral nursery and the placement of the 2D-CP units. (B) an image of part of the 2D-CP setup in the coral nursery. (v) 2D-CPs in the vertical hanging position, (h) 2D-CPs in the horizontal hanging position, (r) railing, (p) the peripheral ring and (w) the rope web.

2.1. Coral collections and 2D-CP unit creation

Three coral species were selected for the experiment. For the small-polyped, highly plastic and fast-growing branching coral species (Rinkevich, 2002; Shaish et al., 2007) we chose *Stylophora pistillata* Esper, 1797, and *Pocillopora damicornis* (Linnaeus, 1758). The third species was the sub-massive, large-polyped (~1.5 mm) and slow growing coral *Cyphastrea* sp., Edward and Haime, 1848.

Ten genotypes (located at least 3 m from each other) per coral species were collected from the northern Gulf of Eilat, Israel, at 1–15 m depths, using SCUBA. *S. pistillata* and *P. damicornis* genotypes were collected from natural recruits on the coral nursery structure (N 29° 32′ 34.843″ E 34° 58′ 24.88″). The *Cyphastrea* colonies were natural settlements collected from artificial struc-