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# Final report

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# Contents

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# 2 Executive summary

Coral reefs have immense ecological, economic and cultural values and provide many $billions of resources and essential ecosystem services to national economies annually. Increasing chronic stressors from human activities including destructive fishing, unsustainable reef use and coastal development exacerbated by climate change impacts are degrading coral reefs and eroding resilience in many parts of the world including the Philippines, and increasingly threaten food security and ecosystem services. Coral reef degradation and loss is therefore a major global problem that is relevant to all nations with significant coral reef areas including the Philippines and Australia. Natural recovery of degraded reefs takes many decades or may not occur without active intervention, therefore restoration of degraded reefs has great potential to improve local ecosystems and socio-economic development in dependent coastal communities.

This ACIAR project directly addressed this problem through innovative transdisciplinary reef restoration approaches. The project aimed to actively restore damaged reef coral communities in the Bolinao-Anda Reef Complex (BARC) located in Northern Luzon region of the Philippines using mass coral larval restoration and to evaluate the socio-economic impacts of reef restoration strategies. The main project objectives were to:

1) Increase reproductive success of ecologically important branching and massive corals by optimising fertilisation rates and mass embryo and larval rearing
2) Maximise coral larval settlement in reef reseeding trials and quantify settlement preferences on natural and artificial surfaces for reseeded and cultured corals
3) Increase post-settlement survival and growth of juvenile branching and massive corals in reef reseeding trials and cultures for reef restoration
4) Evaluate the social, environmental and financial impacts of alternative reef restoration strategies

Significant outcomes were attained for all four project objectives, and the key achievements are briefly summarised below.

Substantial new data have been obtained on major coral spawning periods on Bolinao-Anda reefs in northern Luzon, enabling predictable access to many millions of spawned gametes and embryos for mass larval rearing on reefs and in the laboratory. Large multispecific coral spawning events were recorded after full moons in March and April 2016-2020, with additional corals recorded spawning from February to July at the Bolinao Marine Laboratory (BML) hatchery. A new technique was developed to collect coral spawn slicks at the sea surface, and many millions of coral larvae have been successfully reared at BML and in reef pools for larger scale larval restoration experiments. Experiments examined fertilization responses for three coral species, and results showed that fertilization rates are optimized using sperm densities of $>10^4$-$10^6$ $mL^{-1}$, and that eggs and sperm should be combined within two hours after spawning to maximize larval production.

Seven successful coral larval restoration reef trials were initiated on degraded reef sites in two municipalities of the Province of Pangasinan. These include a high-density *Acropora tenuis* larval restoration in 2016 and *A. millepora* larval restoration in 2018 in the municipality of Anda, and multispecies larval restoration with *A. tenuis* and *Favites colemani* brain coral larvae at Hundred Islands National Park (HINP), City of Alaminos. In 2019, two innovative controlled larval release methods were successfully trialled using concentrated larvae squirted onto degraded reefs at HINP, and a larger-scale multihectare larval release trial at Caniogan reef, Anda, using an autonomous underwater vehicle developed by a colleague from QUT. Timing of larval release has also been tested to optimise settlement on reefs.

We have now also established multiple new breeding populations from the current and previous ACIAR projects, thereby closing the life cycle and proving that coral larval restoration can be successful even on badly degraded reef areas. These breeding populations include successful reproduction in 2018 by some of the larger 2016 restored *Acropora tenuis* colonies after only two years growth on degraded reef plots, which represents a new world record for coral growth to reproductive size for broadcast spawning corals. We have also successfully established a third generation of *A. tenuis* restored corals using mass culture and settlement of larvae from 2013 and 2016 reproductive colonies. In 2021, all breeding colonies from the 2013, 2016 and 2018 experiments spawned, and gametes were collected for use in another set of larval enhancement experiments. Continued monitoring of restored corals has shown persistent survivorship and growth, with significantly increased coral cover and fish abundance in larval restoration plots compared with control plots without enhanced larval supply. Higher abundance of damselfish that shelter in branching corals and coral-eating butterflyfish coincided with increased coral colonies and cover in larval restoration plots compared with controls.

Evaluations of the social, environmental and financial impacts of alternative reef restoration strategies using comparative benefit-cost analyses and valuation studies on the use and non-use values of coral reef restoration showed that coral reef restoration in the Philippines would generate net social welfare gains. This conclusion holds for both coral gardening and mass larval enhancement techniques at both local and national scales, but evidence suggests that the benefit-cost ratios for the larval enhancement projects are greater than those of the coral gardening projects. In addition, the higher net values of the national projects compared to local projects suggest that the returns to the community from reef restoration investments warrant a nationwide approach. The research also demonstrated the capacity of choice modelling as a tool suitable for estimating non-market values in benefit cost analysis.

Other significant achievements from the project include publication of twelve new research papers, plus additional manuscripts being finalised for submission. The project also supported successful HDR completions of three PhD students, two Masters students (with a third student nearing completion), and one Honours student. Other capacity building outcomes include successful completion of training workshops on reef restoration and choice modelling, and continued community engagement and training with three local government municipalities, NGOs and local community members including High School and college student training internships. The success and scientific impacts of this project are also demonstrated by the uptake and further development of the larval restoration methods in multiple projects on the Great Barrier Reef and new projects in the Philippines, and planning for other international projects using these methods.

Project outcomes have been communicated in many oral and poster presentations at international and national conferences in the Philippines and Australia and elsewhere, including in invited Keynote presentations and online webinars. Key project achievements were also highlighted in a project presentation at the Australian Embassy Manila in April 2019 with the Ambassador, Consul General, DFAT/Embassy staff, and representatives from Philippines Government Departments and Authorities, UNDP and FAO. Outcomes from the project were also presented and discussed in detail at a joint meeting of the ACIAR Commission and the Policy Advisory Council in Townsville during September 2019. The project success has also attracted extensive international media interest, and project outcomes have been featured in many broadcasts, interviews and other media stories including *ABC Landline*, *ABC World Today*, *ABC Science Show*, *BBC Blue Planet Live*, many online and news articles, and in the *ACIAR Partners* magazine in 2020. These media outreach activities have highlighted the ACIAR project successes to many millions of people around the world, and stimulated further interest in using the larval restoration methods on damaged reef systems in other countries.

Based on the successful outcomes of the project it is recommended that the coral restoration process be scaled up across multiple regions in the Philippines by establishing and training coral restoration networks involving local communities, local government units and government agencies, researchers and the private sector using a range of innovative techniques to restore coral and fish assemblages and essential reef ecosystem services on larger areas of degraded reefs.

# 3 Background

Coral reefs are globally important marine ecosystems with diverse ecological, economic and socio-cultural values worth $billions to national economies (Birkeland 1997, Harrison and Booth 2007, Burke et al. 2011, Costanza et al. 2014). These reefs are highly productive centres of marine biodiversity that supply essential fisheries and other resources and ecosystem services to hundreds of millions of people in tropical coastal communities (Burke et al. 2011). A key problem is that coral reef ecosystems are highly sensitive to disturbance and are declining globally (Hoegh-Guldberg et al. 2007, De'ath et al. 2012, Jackson et al. 2014, Hughes et al. 2018). More than 60% of the world's coral reefs are under immediate and direct threats from human activities including global warming and mass coral bleaching, overfishing and destructive fishing, coastal development and pollution (Hoegh-Guldberg 1999, Wilkinson 2008, Burke et al. 2011). Furthermore, nearly 95% of coral reefs in SE Asia are threatened, with the Philippines and Indonesia having the largest areas of threatened reefs globally (Burke et al. 2011).

Reef-building scleractinian corals are the foundation species of reefs (Harrison and Booth 2007, Ellison 2019); they build the primary reef structure and form habitats for many thousands of other species including important fisheries species (Jones et al. 2004, Russ et al. 2021). Successful reproduction by these corals enables recovery of damaged reefs thereby enhancing natural resilience (Harrison and Wallace 1990, Randall et al. 2020). However, corals have limited tolerance to environmental changes and pollution stressors hence the coral reefs they create are particularly vulnerable to chronic human disturbances and climate and ocean change (Hoegh-Guldberg et al. 2007, Burke et al. 2011, Hughes et al. 2018). Periodic mass mortality or chronic declines in coral communities can result in coral-dominated reef systems undergoing phase shifts to algal-dominated systems (Done 1992, Bruno et al. 2009). The collapse of healthy coral reef ecosystems creates significant problems for local human communities through loss of essential food and other resources, and reduced economic and other values (Birkeland 1997, Burke et al. 2011, Costanza et al. 2014). Furthermore, natural recovery of coral and reef communities can take many decades (Connell et al. 1997, Gilmour et al. 2013, Gouezo et al. 2019), or may not occur without active intervention.

The global coral reef crisis requires global action on climate change and development of more effective and larger-scale active management intervention through coral reef restoration, which is increasingly a major priority for reef management (Rinkevich 2005, Edwards 2010, Bostrom-Einarsson et al. 2020). Coral reefs that are damaged and degraded but which are ecologically 'recoverable' because they are not subject to chronic or other disturbances that prevent successful coral recruitment if sufficient larvae are supplied (dela Cruz and Harrison 2017, Harrison et al. 2021), occur in many regions including the Philippines and in some parts of Australia, and represent a significant proportion of degraded reef systems globally.

Coral reef restoration is the core issue being addressed by this transdisciplinary project, which aims to actively restore damaged reef coral communities in the Northern Luzon region of the Philippines using mass coral larval restoration ('reseeding') and to evaluate the socio-economic impacts of reef restoration strategies. This project developed from the previous successful ACIAR SRA FIS/2011/031 project (Harrison et al. 2016), which proved that larval restoration can be very effective in initiating coral recovery on degraded reefs in the Philippines (dela Cruz and Harrison 2017, 2020).

Australia and the Philippines have some of the largest coral reef areas in the world and these reef systems face increasing threats from local human activities and climate and ocean changes (Gomez et al. 1994, Burke et al. 2011, Horigue et al. 2012, Hughes et al. 2018). Therefore, both nations require research and development of methods to more effectively manage their coral reef resources and restore damaged reefs in future. This issue is an important priority for both Australia and the Philippines as recognised by the 'Memorandum of Understanding between the Philippines and Australia on Coral Reefs', which acknowledges that "Australia and the Philippines share a common view on the protection and conservation of coral reefs" and recognises the important roles coral reefs play in the marine ecosystem, their significant economic benefits, and the "benefits arising from cooperating and exchanging information on key issues associated with the protection and conservation of coral reefs". The MoU also specifically recognises that "Australia and the Philippines are collaborating on projects that seek to restore coral reefs in the Philippines using coral larval reseeding", which refers to the outcomes from the previous SRA FIS/2011/031 Project.

The Philippines' coral reefs form part of the Coral Triangle that has the highest diversity of corals, fish and other reef biota in the world (Carpenter et al. 2011). However, the Philippines is characterised by having about 1.4 million ha of degraded reefs from a total of about 2.6 million ha (Burke et al. 2011). This represents the world's second largest area of threatened coral reefs behind Indonesia, with a high proportion of reefs in the high or very high threat categories (Burke et al. 2011), so further declines and loss of reefs in the Philippines are likely to occur in future. When coral reefs are degraded, fisheries production and other goods and services decline or are lost and therefore their economic values diminish in proportion to the loss of resources and ecosystem function (Costanza et al. 2014). Key threats to these coral reefs are destructive blast fishing and overfishing, watershed-based pollution and ongoing coastal development arising from increasing coastal populations, and climate change (Burke et al. 2011, Russ et al. 2021). Reef fish and other fish provide a major part of the diet for many Philippine communities and blast and poison fishing and other forms of unsustainable fishing have resulted in reef degradation in many areas (Gomez et al. 1994, Licuanan et al. 2019).

Despite increasing conservation efforts with about 1200 marine protected areas across the Philippine archipelago that have been in implemented over the past 25 years (Horigue et al. 2012), the condition of many reef areas has not improved significantly and in some cases has worsened (Gomez et al. 1994, Licuanan et al. 2019). Recognising the increasingly urgent need to improve the degraded state of local reefs, the Philippine government has been funding research to develop techniques to restore damaged reefs, based largely on asexual fragmentation and coral gardening methods (Rinkevich 2005, Cabaitan et al. 2008, dela Cruz et al. 2014). This project enables the development of another approach to coral restoration in the Philippines using mass larval production and recruitment.

Australia has the second largest area of coral reefs and most reefs are considered to be managed and protected to varying degrees in MPAs (McCook et al. 2010, Burke et al. 2011, Emslie et al. 2015). However, long-term monitoring of hundreds of reefs in the Great Barrier Reef (GBR) showed a substantial 50.7% decline in coral cover over the period 1985 to 2012 primarily from cyclone and crown of thorns starfish outbreaks with additional impacts from coral bleaching mortality (De'ath et al. 2012). Increasing severity and frequency of mass coral bleaching events associated with increasing sea temperatures and light stress has led to rapid declines in coral cover and reef condition on many GBR reefs, particularly in recent years (Hoegh-Guldberg 1999, Berkelmans et al. 2004, Hughes et al. 2018), and natural recovery has been sporadic. The loss of breeding corals from climate change and bleaching events threatens the natural reef resilience of the GBR (Ainsworth et al. 2016), and UNESCO has been re-evaluating the Outstanding Universal Values of this World Heritage Area, which contributes more than $6 billion to the Australian economy each year (DA Economics 2013). Therefore, increasing attention is being given to active coral restoration interventions on the GBR, including coral larval restoration projects (Harrison 2018, Harrison et al. 2019, 2020) developed as a result of the successful outcomes from ACIAR projects in the Philippines.

# 4 Objectives

The overall **aim** of this project is to actively restore damaged reef coral communities in the Northern Luzon region of the Philippines using mass coral larval reseeding to enhance coral recruitment, and to evaluate the socio-economic impacts of reef restoration strategies.

The main project objectives and activities were:

**Objective 1: Increase reproductive success of ecologically important branching and massive corals by optimising fertilisation rates and mass embryo and larval rearing**

Activities:

1) Complete replicate experiments to determine optimal coral spawning and fertilisation conditions for some ecologically important but as yet unstudied branching and massive corals in the Philippines and Australia
2) Optimise coral embryo and larval rearing techniques to maximise survival for mass larval settlement of some ecologically important but as yet unstudied branching and massive corals
3) Prepare and publish multimedia materials detailing the optimal coral reproduction and larval rearing techniques
4) Conduct training courses with local research, management and community groups to build capacity for future restoration programs

**Objective 2: Maximise coral larval settlement in reef reseeding trials and quantify settlement preferences on natural and artificial surfaces for reseeded and cultured corals**

Activities:

1) Reseed replicate areas of damaged coral reef habitats through mass settlement of larvae from ecologically important branching and massive coral species and compare settlement rates in reseeded versus control (not reseeded) reef areas and using different larval densities
2) Compare and quantify larval settlement preferences of branching and massive corals on natural and artificial settlement surfaces deployed on reseeded reefs and control reefs (not reseeded) and in culture tanks to maximise successful larval settlement and initial recruitment success
3) Monitor post-settlement survival and growth of these early coral recruits on reseeded reefs and in culture tanks to determine the best combinations of species for use in mass larval reseeding restoration programs

**Objective 3: Increase post-settlement survival and growth of juvenile branching and massive corals in reef reseeding trials and cultures for reef restoration**

Activities:

1) Complete experiments to determine the optimal environmental conditions needed to maximise juvenile coral survival and growth for different species of branching and massive corals on reseeded reefs and in culture tanks leading to increased post-settlement survival and ongoing recruitment success for coral restoration and reef community recovery
2) Use feeding trials to determine the effect of food provisioning on juvenile coral growth rates and survival

3) Experimentally manipulate uptake of different types (clades) of *Symbiodinium* dinoflagellate microalgae symbionts that naturally occur in local coral species to determine their effect on juvenile coral growth and survival rates
4) Prepare and publish multimedia materials detailing the optimal coral settlement and recruitment techniques
5) Conduct training courses with local research, management and community groups to build capacity for future restoration programs

**Objective 4: Evaluate the social, environmental and financial impacts of alternative reef restoration strategies**

<u>Activities</u>:

1) Use predictions of social, environmental and financial impacts of alternative reef management strategies to inform benefit cost analyses
2) Use market and non-market valuation techniques to estimate the values of the predicted impacts of alternative reef management strategies
3) Conduct a social benefit cost analysis
4) Conduct a distributional analysis of benefits and costs
5) Conduct short training courses on socio-economic evaluation methods and practice
6) Develop policy and advice for public and private sector decision makers on alternative reef management strategies

# 5 Methodology

The methods used for this project were based on proven research techniques developed by the team members and colleagues for coral reproduction, larval settlement and recruitment studies, and socio-economic analyses using benefit cost analysis (BCA), and are highlighted in the cited publications. Additional innovative approaches and new equipment were developed and tested during this project to enable larger scale collections of coral spawn and mass larval rearing in situ on reefs, and larval delivery and settlement over larger reef scales. Given the wide range of experiments and research completed during this project it is more efficient to communicate the methodology for each component when reporting the key results and discussion, hence the methodology for each component is briefly summarised in Section 7 below.

The coral and reef research for this project was primarily focused on the Bolinao and Anda regions in the Province of Pangasinan in Northern Luzon, Philippines (Figure 5.1), and was expanded to include larval rearing and larval restoration trials on reefs in the Hundred Island National Park (HINP) co-administered by the City of Alaminos and the Protected Management Board of the Department of Environment and Natural Resources. These regions were chosen as they include some remnant healthy coral reef areas that enabled collection of coral spawn, and large nearby areas of degraded reefs suitable for restoration.

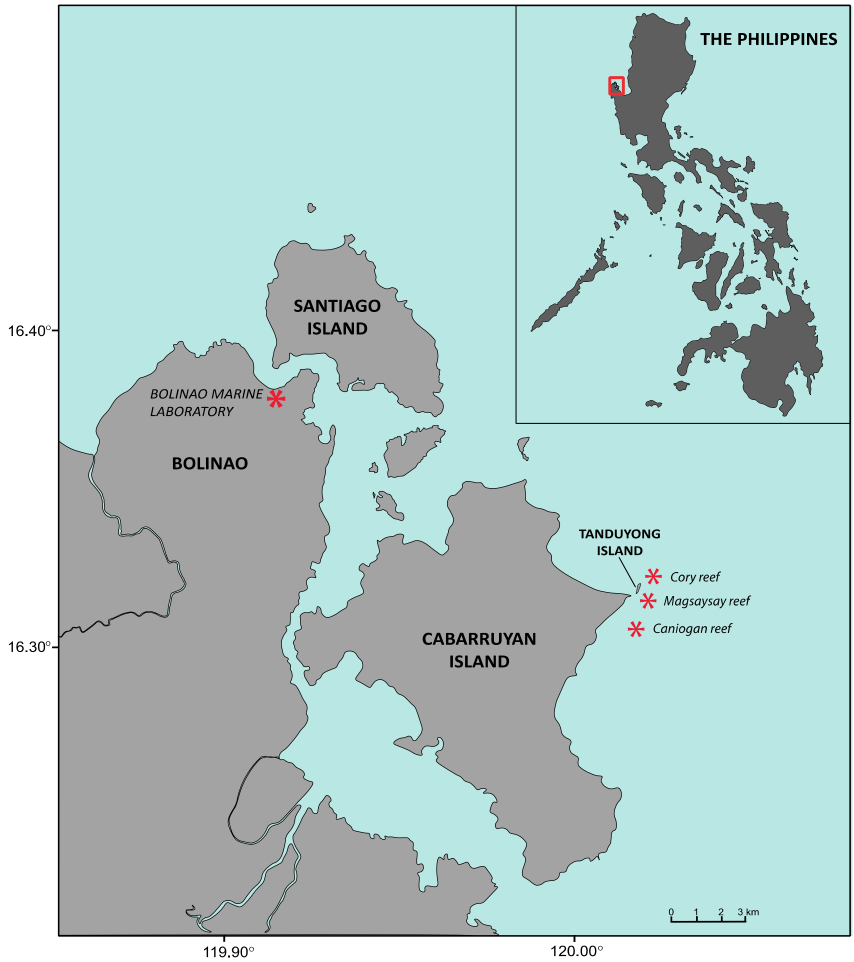


Figure 5.1. Location of the main coral restoration sites at Magsaysay reef and Caniogan reef, and the Bolinao Marine Laboratory in Northern Luzon, Philippines (from Harrison et al. 2021).

Prior to the early 1980s, reefs in the Bolinao-Anda Reef Complex (BARC) and HINP in the Lingayen Gulf had relatively high 30-50% mean live coral cover and a healthy reef status (Gomez et al., 1981). However, extensive blast fishing, aquaculture development and crown-of-thorns starfish outbreaks severely impacted coral and other reef communities in the Lingayen Gulf, and resulted in significant degradation of these reefs during subsequent decades (Cruz-Trinidad et al., 2009). Blast fishing was subsequently banned and has now effectively ceased in local communities from Anda and nearby towns, therefore these reefs are now potentially ‘recoverable’ but are limited by low rates of natural coral recruitment (dela Cruz and Harrison, 2017). Hence, these reefs provide good opportunities for reef experiments and research to test the efficacy of using increased larval supply and settlement to promote increased coral recruitment and recovery of coral populations and communities, and enhancing fish habitats.

In addition, the Bolinao Marine Laboratory (BML) of The Marine Science Institute, University of the Philippines is located near Bolinao (Figure 5.1) and has extensive laboratory and seawater outdoor hatchery and aquaculture facilities that have enabled detailed research and experiments on coral spawning, fertilization, larval culture and settlement for this project.

<u>ACIAR Research facility</u>

The extensive field research and diving operations for this Project required efficient access to Magsaysay reef and nearby reefs, hence in 2016 project team members contacted the Galsim family who own Tanduyong Island at Tondol, which is located near Magsaysay reef. The Galsim family generously agreed to the Project team setting up a temporary field station on Tanduyong Island using their family hut for field operations in 2016. In 2017, the Galsim family requested us to design and build a bigger separate ACIAR Project research facility on the island, which was completed in April 2017 using local builders and BML staff. Ready access to this facility and storage room has greatly increased the efficiency of fieldwork during 2017 to 2019 (Fig. 5.2). This ACIAR facility is also benefitting other marine research projects from UP which use the facility for field-based research in the Lingayen Gulf.


Figure 5.2. ACIAR Coral Larval Restoration Project research facility on Tanduyong Island, Tondol, with some of the Project team members in March 2019, and some team members and volunteers with ACIAR Project team T-shirts in April 2019.

# 6 Achievements against activities and outputs/milestones

### *Objective 1: To Increase reproductive success of ecologically important branching and massive corals by optimising fertilisation rates and mass embryo and larval rearing*

| No. | Activity | Outputs/ milestones | Completion date | Comments |
|---|---|---|---|---|
| 1.1 | Determine optimal coral spawning and fertilisation conditions for ecologically important but as yet unstudied branching and massive corals | Publications of scientific papers in high-ranking journals detailing new methods for optimising coral spawning and fertilisation rates (dela Cruz and Harrison, 2020a *JEMBE*), and timing of multi-species spawning in Bolinao-Anda Reef Complex (Harrison et al., 2021 *Frontiers in Marine Science*) | Outputs completed in 2020 and 2021 | Substantial new information has been gained on spawning periods for a wide range of additional coral species including consistent timing of major spawning events resulting in coral spawn slicks on reefs, which provide access to many millions of gametes for mass larval rearing. |
| 1.2 | Optimise coral embryo and larval rearing techniques for some ecologically important but as yet unstudied branching and massive corals | Publication in high-ranking journal highlighting improved technical knowledge for optimising coral embryo and larval cultures in reef larval pools (Harrison et al., 2021) and report on increasing larval settlement and survivorship through larval feeding and Symbiodiniaceae manipulations (Boulotte PhD thesis 2021) | Initial field and laboratory trials completed in 2017. Output completed in 2021 | Developed new techniques for managing healthy cultures of millions of embryos and larvae, including development and trials of new in situ larger-scale floating spawn-catchers and larval rearers on reef sites using locally available materials and steel frames. Additional lab culture experiments and larval conditioning experiments have been done in conjunction with Harrison's projects on the GBR. |

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| 1.3 | Produce multimedia materials detailing optimal coral spawning and larval rearing techniques | Updated multimedia resources detailing best-practice methods for coral spawning, fertilisation and larval cultures | Materials were completed during 2017, 2018 and 2019 for workshops and conferences. Online multimedia platforms including Facebook project pages have been updated regularly throughout the duration of the project. | Multimedia materials have been developed for teaching, training workshops, public outreach, media releases and inter/national conferences. These have been incorporated into updated multimedia resources for 2018 and 2019 training workshops, and disseminated to other workers to improve practical understanding of coral reproduction and larval culture techniques. Project videos have been broadcast in multiple inter/national programs including *ABC Landline*, *ABC World Today*, *ABC Science Show*, and *BBC Blue Planet Live.* |
| 1.4 | Train stakeholders to build capacity with coral spawning and larval rearing techniques | Stakeholder training workshops conducted in the Philippines | Workshop with DENR completed May 2017, BML workshops completed in in May 2018 and 2019 | Coral reef restoration workshop led by Cabaitan in May 2017 attended by ~50 DENR staff. Further capacity building and training workshops completed in May 2018 and 2019 at BML with project researchers, and two workshops completed in September 2018 at Alaminos, for Alaminos LGU members and Anda municipality, resulting in agreement between the two towns to draft a joint resolution to patrol and catch illegal fishers in their waters.<br>The project also supported eight postgraduate research students, and BML staff who were trained in improving coral reproduction and larval rearing techniques. |

*PC = partner country, A = Australia*

### *Objective 2: To Maximise coral larval settlement in reef reseeding trials and quantify settlement preferences on natural and artificial surfaces for reseeded and cultured corals*

| No. | Activity | Outputs/ milestones | Completion date | Comments |
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| 2.1 | Reseed damaged coral reef areas using mass larval settlement and different densities | Publications of scientific papers in high-ranking journals reporting new field mass larval enhancement experiments (dela Cruz and Harrison, 2020b *PLoS ONE*; Harrison et al., 2021) and optimum larval densities for reseeding (Cameron and Harrison, 2020 *Scientific Reports*). In addition, new larger scale larval restoration trials completed in HINP in April 2018, and March and April 2019, and at Caniogan reef in April 2019. | Additional mass larval experiments in the field completed yearly from 2014 to 2019. | Successful larger-scale larval restoration experiment initiated in 2016 using higher-density larval supply with 4.6 million *A. tenuis* larvae. Initial settlement rates and numbers of surviving coral colonies significantly higher in 2016 trial, using increased larval density cf. 2013 pilot study (dela Cruz and Harrison 2017). Results presented in conferences and workshops, and monitoring of all larval restoration experiments continued throughout the duration of the project. |
| 2.2 | Determine larval settlement preferences on natural and artificial settlement surfaces | Experiments and reports quantifying larval settlement of branching and massive corals using natural coral tiles, 3D printed plastic tiles, and wax coated settlement plugs | Experiments using 3D printed tiles completed in 2014, and on natural tiles each year. New larval settlement experiments using wax coated plugs and different larval densities completed in 2019. | Settlement of *A. tenuis* larvae in field trials showed no significant preferences among tile surfaces. Other experiments demonstrated very strong settlement preferences for cryptic habitats by brain coral larvae on innovative 3D printed plastic tiles with complex surface microtopography. Larval settlement preference experiment results presented in SCU Honours thesis (Horan 2017, First Class Hons), manuscript in preparation. Manuscript on comparison of settlement patterns on three types of tile surfaces being revised for submission. |
| 2.3 | Monitor early post-settlement survival and growth of settled corals on reseeded reefs and in culture tanks | Publications on factors controlling initial post-settlement survival and growth for branching and massive corals (dela Cruz and Harrison 2017, dela Cruz and Harrison 2020b; Harrison et al., 2021). | Annual monitoring and reporting of initial settlement outcomes from all reef experiments | Monitoring of initial post-settlement survival and growth for 2016 *A. tenuis* larval restoration experiment on degraded reef plots, with 250 colonies alive in larval plots in 2017 and 2018. Additional post-settlement monitoring of all ten field trial experiments completed each year. Survival and growth data from initial larval restoration trials were published in three papers (dela Cruz and Harrison 2017, dela Cruz and Harrison 2020; Harrison et al., 2021). Additional experiments showing that coral chimeras improve settlement and survivorship were reported in Ligson's Master's thesis 2021. |

*PC = partner country, A = Australia*

## *Objective 3: Increase post-settlement survival and growth of juvenile branching and massive corals in reef reseeding trials and cultures for reef restoration*

| No. | Activity | Outputs/ milestones | Completion date | Comments |
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| 3.1 | Determine optimal conditions for maximising juvenile coral survival and growth for different species | Publications on post-settlement survival and growth rates of juvenile corals from additional larval enhancement experiments were published in *Scientific Reports* (dela Cruz and Harrison 2017), in *PLoS ONE* (dela Cruz and Harrison 2020) and *Frontiers in Marine Science* (Harrison et al. 2021) | Experiments competed in 2014, and from 2016 to 2019 | Survival and growth of *Acropora* recruits and colonies resulting from the various field trials in 2014, 2016, 2018 and 2019 have consistently demonstrated that survivorship stabilises once juvenile corals grow large enough to be visible recruits. Importantly, larger *A. tenuis* colonies became reproductively mature after two years (Harrison et al. 2021) or three years (dela Cruz and Harrison 2017), re-establishing breeding populations on degraded reef areas. |
| 3.2 | Complete feeding trials to determine effect of food provisioning on juvenile coral growth and survival | Manuscripts detailing improved methods to increase survival and growth of juvenile corals through lipids provision have been prepared | Final outcomes were included in Boulotte's PhD thesis in 2021 | Feeding experiments with coral larvae were completed on the GBR and Australian Institute of Marine Science in conjunction with related projects by Harrison in Australia, and the results indicate that larval provisioning can increase nutrient stores available to coral larvae. These results are being used to plan further trials in the Philippines. |
| 3.3 | Complete experiments on effects of uptake of different types of dinoflagellate symbionts on juvenile coral growth and survival | Manuscript detailing effects of different dinoflagellate symbionts on growth and survival of branching and massive corals has been prepared | Outcomes of algal uptake experiments were included in Boulotte's PhD thesis in 2021 | Pilot studies examining uptake of symbionts by coral larvae and effects of symbiont supply during larval settlement have been done on the GBR as part of related projects, and results indicate that post-settlement survival can be enhanced by supplying dinoflagellate symbionts. Genetic samples for identification of dinoflagellate symbiont clades present in adult, larvae and juvenile corals are being analysed in partnership with molecular biology researchers at UP. Results from those experiments will be used to plan further trials in the Philippines in future. |

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| 3.4 | Produce multimedia materials detailing optimal coral settlement and reseeding techniques | Updated multimedia resources detailing best-practice methods for coral larval settlement and reseeding presented in teaching materials, training workshops and conferences | Materials updated annually after results from reseeding and juvenile culture trials analysed, materials finalised June 2020 | Multimedia materials have been prepared for inclusion in teaching materials, workshops and presentations at international conferences and through international media. These materials were incorporated into updated workshop and multimedia resources for the 2018 and 2019 training courses for stakeholders and can be disseminated to other workers to improve practical understanding of juvenile coral culture and reef restoration techniques. |
| 3.5 | Train stakeholders to build capacity for best-practice reef restoration techniques | Multiple stakeholder training workshops conducted in the Philippines, and postgraduate theses completions | Training workshops have been completed at BML in May 2017, 2018 and 2019 and at Alaminos City in September 2018 (2 workshops) | In addition to stakeholder and other workshops conducted, eight UP and SCU postgraduate PhD, Masters and Honours research students plus many BML staff, and staff from local government, high school students and other members of the public have been trained in improved coral restoration techniques as a result of their involvement in this project. Field training for three UP postgraduate researchers was completed on the Great Barrier Reef in 2018. |

## *Objective 4: Evaluate the social, environmental, and financial impacts of alternative reef restoration strategies*

| No. | Activity | Outputs/ milestones | Due date of output/ milestone | Summary of achievements |
|---|---|---|---|---|
| 4.1 | Use predictions of social, environmental and financial impacts of alternative reef management strategies to inform benefit cost analyses | Publication of paper highlighting predictions of social, environmental and financial impacts of alternative reef restoration options (Abrina and Bennett, 2021, *Science of the Total Environment*) | Initial analyses completed May 2016, analyses completed July 2019 and published in 2021. | A comparative benefit-cost analysis (BCA) of mass larval enhancement and coral gardening was published in *Science of the Total Environment* in 2021. Local and national scales of restoration using the two techniques were compared in the BCA. Based on predictions from reef restoration outcomes, the mass larval enhancement investments are estimated to produce higher net benefits and benefit-cost ratios compared to those of coral gardening. Higher net social outcomes for the local-scale investments support more localized approaches to coral restoration. |
| 4.2 | Use market and non-market | Publications detailing effective | Initial analyses completed October | The results of the study using a modified Travel |

| | | | | |
|---|---|---|---|---|
| | valuation techniques including socio-economic surveys to estimate the values of the predicted impacts of alternative reef management strategies | estimates of the values of market and non-market impacts of reef restoration options (Abrina and Bennett 2018, *Journal of Environmental Science and Management*). Non-market valuation of non-use values using a choice modelling experiment were published in the *Journal of Ocean and Coastal Management* in (Abrina and Bennett 2020) | 2016, analyses completed July 2019, publications in 2018 and 2020 | Cost Method with Contingent Behaviour survey (a use valuation technique) was published in the *Journal of Environmental Science and Management*. Non-market valuation of non-use values was done using a choice modelling experiment and the results were published in the *Journal of Ocean and Coastal Management*.<br><br>Both surveys compared the mass larval enhancement reef management strategy to a do-nothing strategy (i.e. with and without active restoration intervention). |
| 4.3 | Conduct social benefit cost analysis | Publication highlighting socio-economic benefit cost analyses outcomes (Abrina and Bennett, 2021, *Science of the Total Environment*) | Initial analyses completed December 2017, final analyses completed June 2019, published in 2021. | A comparative benefit-cost analysis (BCA) of mass larval enhancement and coral gardening was published in *Science of the Total Environment*. Local and national scales of restoration using the two techniques were compared in the BCA. |
| 4.4 | Conduct a distributional analysis of benefits and costs | Publication detailing improved knowledge of the distribution of benefits and costs of reef restoration strategies among various groups of people affected (Abrina and Bennett, 2021, *Science of the Total Environment*) | Initial analyses completed April 2018, final analyses completed June 2019, publication 2021. | Results from the comparative benefit-cost analysis (BCA) of mass larval enhancement and coral gardening were published in the journal *Science of the Total Environment*. Local and national scales of restoration using the two techniques were compared in a BCA, and groups were limited to non-users near the restoration site, and in Metro Manila. |
| 4.5 | Train relevant stakeholders to build capacity for socio-economic evaluation methods and practice | Short training course on socio-economic evaluation methods and practice conducted in the Philippines in April 2017 | Workshop was conducted in 2017 at the School of Economics in UP | Bennett conducted a short course on Choice Modelling, hosted by the UP School of Economics in April 2017. Among the attendees were researchers and students from the School of Economics and the Marine Science Institute.<br><br>As part of the initial Travel Cost Method with Contingent Behaviour survey, tourism officers and several students from Anda were trained to design and conduct a travel cost |

| | | | | |
|---|---|---|---|---|
| | | | | survey. A presentation and analysis workshop of the Travel Cost survey was done April 2018 for the Anda local government. The team also trained a local market research company to conduct a choice modelling application on non-use values of coral reef restoration. |
| 4.6 | Develop policy and advice on alternative reef management strategies | Publication of updated policies and advice provided to public and private sector decision makers on alternative reef management strategies | Report provided in January 2018, with updated advice and policy information provided in March 2020 | The MPA MEAT analysis was completed during 2016, and provides a baseline assessment for future management plans.<br>A presentation and analysis workshop of the Travel Cost survey was conducted April 2018, and this provides a venue to develop policy recommendations. The results of the Abrina and Bennett 2020 publication in *Journal of Ocean and Coastal Management* on the non-market values of reef restoration were submitted to the Department of Environment and Natural Resources (DENR). The values were also applied in Abrina's master's thesis on reviewing coral damage fines. |

# 7 Key results and discussion

The extensive research including many reef-based field trials and laboratory-based experiments encompassed by this project has provided a wide range results and outputs. Therefore, the key research and outcomes are presented in four sections below. Objective 1 was focused on aspects of coral reproduction, spawn collection and larval culture, and these outcomes are reported in Section 7A below. Objectives 2 and 3 were focused on larval settlement and recruitment, and longer-term monitoring of larval restoration experiments on reefs, and the reef-based trials and research outcomes are reported in Section 7B, with the related primarily laboratory-based experiments presented in Section 7C. Objective 4 was focused on evaluating the social, environmental and financial impacts of alternative reef restoration strategies and the main results are reported in Section 7D.

## Section 7A: Objective 1

### *Coral spawning research*

Research from this project has resulted in substantial new information on the timing of coral spawning including major multispecific coral spawning events during March and April each year resulting in coral spawn slicks on local reef areas in the Anda, Pangasinan Province in the northwestern Philippines. This information is important for enabling collection of many millions of spawned egg-sperm bundles for mass embryo and larval culture, and development of innovative methods for rearing larvae on reefs *in situ* using large mesh enclosure designs.

Data on coral reproduction and spawning periods were obtained from extensive diving and monitoring of reef corals of many species on healthy reefs at Magsaysay reef, Anda, Pangasinan (16°19'36" N, 120°02'01" E), and other reef areas nearby by the ACIAR project team. Reproductive condition was assessed by monitoring the development of eggs and sperm and presence/absence of mature eggs in colonies by carefully breaking a few branches of branching corals or removing small sections of massive corals with a hammer and small chisel, to determine if colonies contained pigmented mature eggs in the weeks prior to spawning, with pigmentation indicating that spawning was imminent (after Harrison et al. 1984, Babcock et al. 1986). In addition, extensive research was completed during coral spawning night dives on healthy reefs at Magsaysay reef to quantify the species and numbers of colonies recorded spawning, and some of these data were synthesised and published in Harrison et al. (2021) (Table 7.1).

Large multispecific coral spawning events were recorded *in situ* on night dives around the 'Coral Garden' remnant coral community near Magsaysay Reef from 3$^{rd}$ to 5$^{th}$ March 2016 corresponding to 10-12 nights after full moon (nAFM). Multiple colonies of different *Acropora* spp. were recorded spawning including *A. cytherea, A. hyacinthus, A. humilis, A. latistella, A. sarmentosa, A. samoensis, A. digitifera, A. millepora, A. gemmifera, A. nana* and *A. florida*. Peak spawning occurred on 5$^{th}$ March (12 nAFM) resulting in large coral spawn slick areas on the sea surface. These coral spawn slicks provide an important source of many millions of gametes for larger scale larval rearing and restoration trials. A second split-spawning (sensu Willis et al. 1985) of some *Acropora* spp. following the subsequent late March full moon period was recorded at Magsaysay reef in 2016. Multispecific spawning of *A. hyacinthus, A. intermedia, A. florida, A. sarmentosa* and one colony of *A. humilis* occurred on 31$^{st}$ March (8 nAFM) and on 1$^{st}$ April 2016 (9 nAFM).

In 2017, spawning was observed *in situ* on night dives around the 'coral garden' from 19-22 March (8-11 nAFM). Peak spawning occurred on 10$^{th}$ nAFM involving many colonies of *A. millepora, A. cytherea, A. hyacinthus, A. latistella, A. samoensis, A. digitifera, A. florida, A. sarmentosa, A. humilis, A. valida, A. muricata* and *A. intermedia* (Figure 7.1), resulting in a coral spawn slick. Some colonies of *A. cytherea* and *A. hyacinthus* were also observed spawning on 30-31 March (18-19 nAFM).

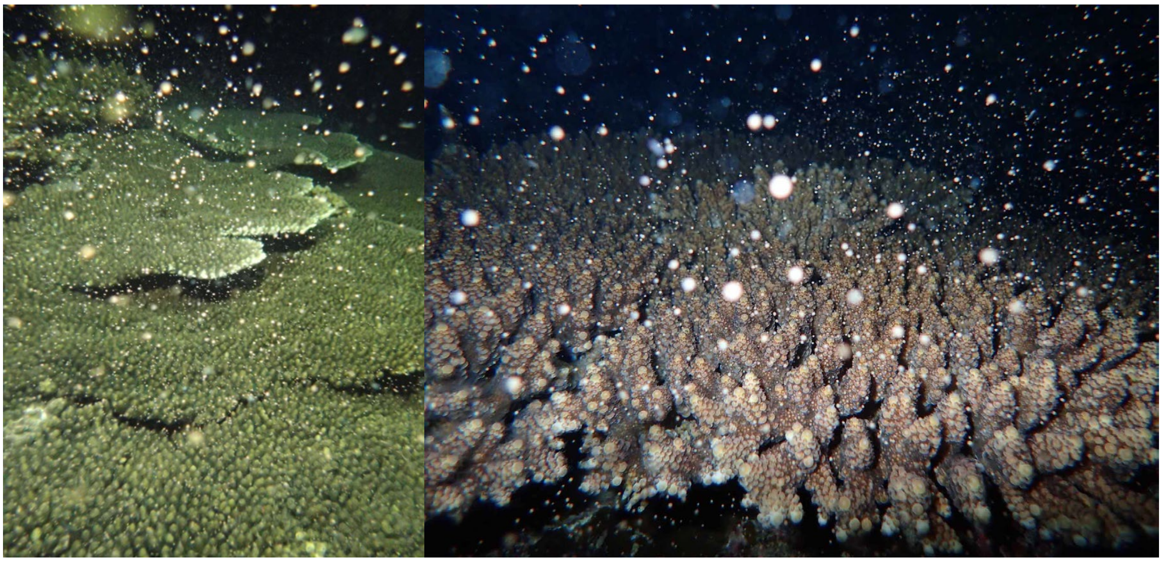


Figure 7.1: *Acropora* corals spawning buoyant egg and sperm bundles at night during peak coral spawning nights at the 'coral garden' site Magsaysay reef in 2017 (Images: Peter Harrison).

In 2018, large multispecific coral spawning events were recorded *in situ* on night dives in the 'Coral Garden' remnant coral community near Magsaysay reef on 12th and 13th March (10-11 nights after full moon (nAFM)), with smaller spawning events recorded on 14th March and 15th March. Many colonies of different *Acropora* spp. were recorded spawning including *A. hyacinthus, A. cytherea, A. sarmentosa, A. samoensis, A. digitifera, A. millepora, A. florida, A. verweyi* and *A. humilis*, with spawn slicks forming after spawning on 10th and 11th nAFM.

Table 7.1. Summary of multispecific coral spawning events at Magsaysay reef, 2016–2018 (from Harrison et al. 2021).

| **Year** | **Multispecific spawning nights** | **Species observed spawning** | **Notes** |
|---|---|---|---|
| 2016 | 3–5 March<br>(10–12 nAFM) | *A. cytherea*<br>*A. digitifera*<br>*A. florida*<br>*A. gemmifera*<br>*A. nana*<br>*A. humilis*<br>*A. hyacinthus*<br>*A. latistella*<br>*A. millepora*<br>*A. sarmentosa*<br>*A. samoensis* | Multiple colonies recorded spawning from 2020 h to after 2130 h.<br><br>Peak spawning occurred on 5th March (12 nAFM), resulting in large coral spawn slicks on the sea surface. |

| | | | |
|---|---|---|---|
| | 31 March–<br>1 April<br>(8–9 nAFM) | *A. florida*<br>*A. humilis*<br>*A. hyacinthus*<br>*A. intermedia*<br>*A. sarmentosa* | A second split-spawning (*sensu* Willis et al., 1985) was recorded after the second full moon in March. |
| 2017 | 19–22 March<br>(8-11 nAFM) | *A. cytherea*<br>*A. digitifera*<br>*A. florida*<br>*A. hyacinthus*<br>*A. intermedia*<br>*A. latistella*<br>*A. millepora*<br>*A. muricata*<br>*A. samoensis*<br>*A. sarmentosa*<br>*A. humilis*<br>*A. valida* | Peak spawning occurred on 21 March (10$^{th}$ nAFM) resulting in a large coral spawn slick at the sea surface.<br><br>Some colonies of *A. cytherea* and *A. hyacinthus* had mature gametes after these spawning periods, and these were subsequently observed spawning on 30-31 March (18-19 nAFM). |
| 2018 | 12–15 March<br>(10–13 nAFM) | *A. cytherea*<br>*A. digitifera*<br>*A. florida*<br>*A. humilis*<br>*A. hyacinthus*<br>*A. millepora*<br>*A. samoensis*<br>*A. sarmentosa*<br>*A. verweyi* | Large coral spawning events recorded on 12$^{th}$ and 13$^{th}$ March (10-11 nAFM), resulting in a large coral spawn slick at the sea surface.<br><br>Smaller spawning events recorded on 14$^{th}$ March and 15$^{th}$ March. |

In 2019, large multispecific coral spawning events were recorded *in situ* on night dives in the ‘Coral Garden’ remnant coral community near Magsaysay reef on 8$^{th}$ and 9$^{th}$ March corresponding to 13-12 nights before full moon (nBFM), with smaller spawning recorded on 11$^{th}$ March. Many colonies of different *Acropora* spp. were recorded spawning including *A. millepora, A. hyacinthus* (Figure 7.2)*, A. sarmentosa, A. digitifera, A. verweyi and A. cytherea*, with spawn slicks forming on the sea surface after spawning on 8$^{th}$ and 9$^{th}$ March (Figure 7.2).

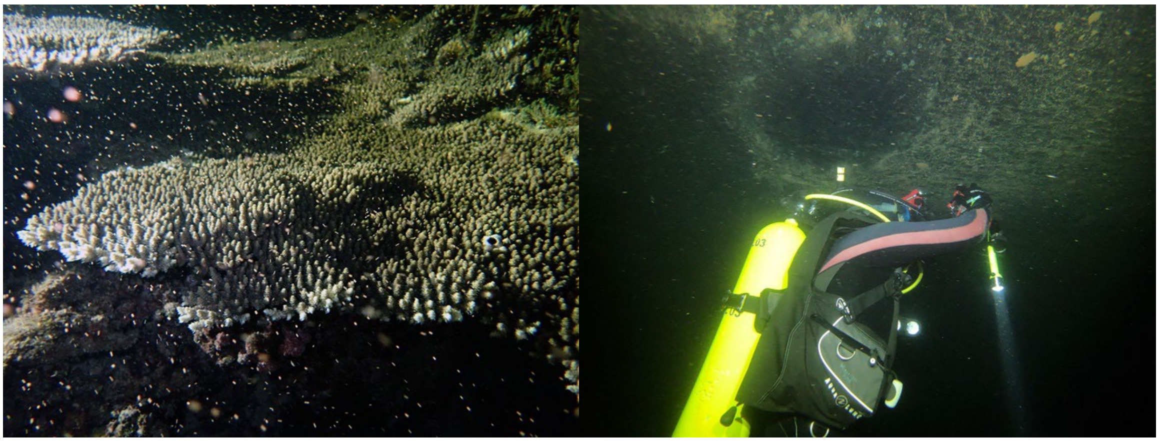


Figure 7.2: March 2019 *Acropora hyacinthus* spawning buoyant egg and sperm bundles during major coral spawning night at the ‘coral garden’ site Magsaysay reef (Left image: Peter Harrison), and diving under large coral spawn slick coating the sea surface (Right image: Ian McLeod).

During April 2019, spawning of *A. tenuis* colonies from previous restoration trials was recorded (see below), with additional coral spawning recorded during these twilight and night dives, including the massive corals *Dipsastraea*, rapid blast spawning by *Lobophyllia*, and colonies of *Galaxea* releasing white sperm and pseudo-egg bundles (*sensu* Harrison 1988) (Figure 7.3).

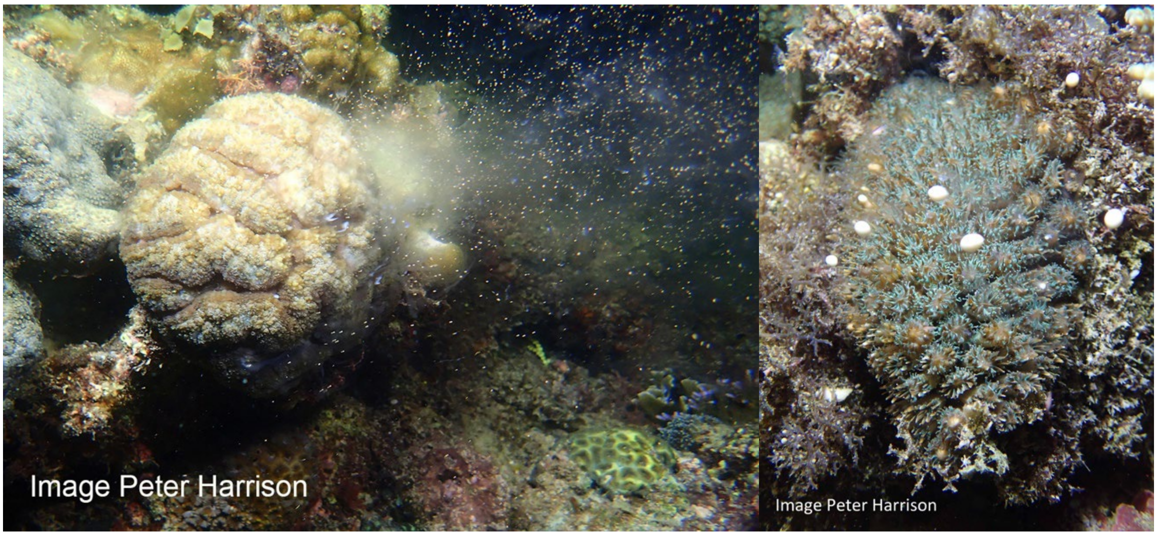



Figure 7.3: Blast spawning *Lobophyllia* (left) and *Galaxea* colony spawning white sperm and pseudo-egg bundles (right) at Magsaysay reef restoration sites in April 2019 (Images: Peter Harrison)

Having established the relatively predictable timing of these major coral spawning events before and after full moon phases in March or early April and the occurrence of coral spawn slicks containing hundreds of millions of gametes from a range of different species, this information enables us to plan for collecting larger samples of biodiverse embryos for further larger scale larval rearing and coral restoration trials in future.

Additional coral spawning records have been obtained each year from corals temporarily collected from reef sites and transported to the BML hatchery for spawning during February to July. Following spawning, the corals are returned alive to the reef collection sites, and larval cultures are reared at BML for larval settlement experiments and field trials. Colonies of *A. millepora* and *A. digitifera* were collected in March 2018 for spawning at the BML hatchery, with minor spawning observed 19 nAFM and substantial spawning of

*A. millepora* and two *A. digitifera* colonies on 25 and 26 nAFM. In 2019, colonies of *A. millepora* spawned at the BML hatchery on 27 March (6 nAFM), with spawning of *A. tenuis* colonies occurring on 23 April (4nAFM).

### *Collection of coral spawn slicks and mass larval rearing on reefs*

Samples from the large coral spawn slicks that form on the sea surface after major spawning events described above, have been collected using a range of fine mesh larval nets, and smaller mesh spawn cones that were temporarily placed over spawning corals on the reef. The design of the nets used to capture and rear the embryos and larvae in situ on reef areas has continually evolved during the project, resulting in innovative approaches to addressing the problem of larger-scale *in situ* larval culture on reefs for larger-scale larval restoration trials. Information on the reef-based spawn catchers and larval pool systems were recently published in Harrison et al. (2021), and further details are provided below.

In 2016, replicate 5 × 5 m and 10 × 10 m low-cost bamboo floating frames were constructed near the field site on Tanduyong Island, Tondol, Anda, with large drum floats attached to provide extra buoyancy (Figure 7.4A). A new larval mesh net design with an upper layer of vinyl and a 4-metre deep curtain of 180 µm plankton mesh was attached to a 5 × 5 m bamboo frame anchored over gravid *Acropora hyacinthus* and *A. cytherea* colonies in the Magsaysay reef 'coral garden' and coral spawn was collected in the net following spawning (Figure 7.4B). Additional gamete bundles were collected using spawn cone nets temporarily placed over spawning corals, and spawn was also collected from surface slicks by swimming spawn cones through the slicks as neuston nets to collect gametes, which were then added to the larval rearing enclosure.

Healthy developing embryos were recorded within the culture pool 12 and 20 hours after spawning indicating that the system provided suitable environmental conditions for larval rearing on the reef. Additional coral spawn was added to the pool after spawning on 1 April 2016 before increasing wind dispersed the spawn at the sea surface preventing further slick collection. Strong winds and heavy wave action began to damage one corner of the larval culture pool's bamboo frame early the next morning, causing many of the developing larvae to wash out of the net system. Consequently, the bamboo frames were cross-braced and strengthened and four bamboo frames were stress-tested in at-sea trials while anchored near Magsaysay reef. These frames remained intact after three weeks including intermittent periods of strong winds and heavy wave action, hence the cross-braced bamboo frames provide a suitable low-cost frame system for *in situ* larval cultures, that can be constructed locally on reef systems where steel and other materials are too expensive or not readily available.

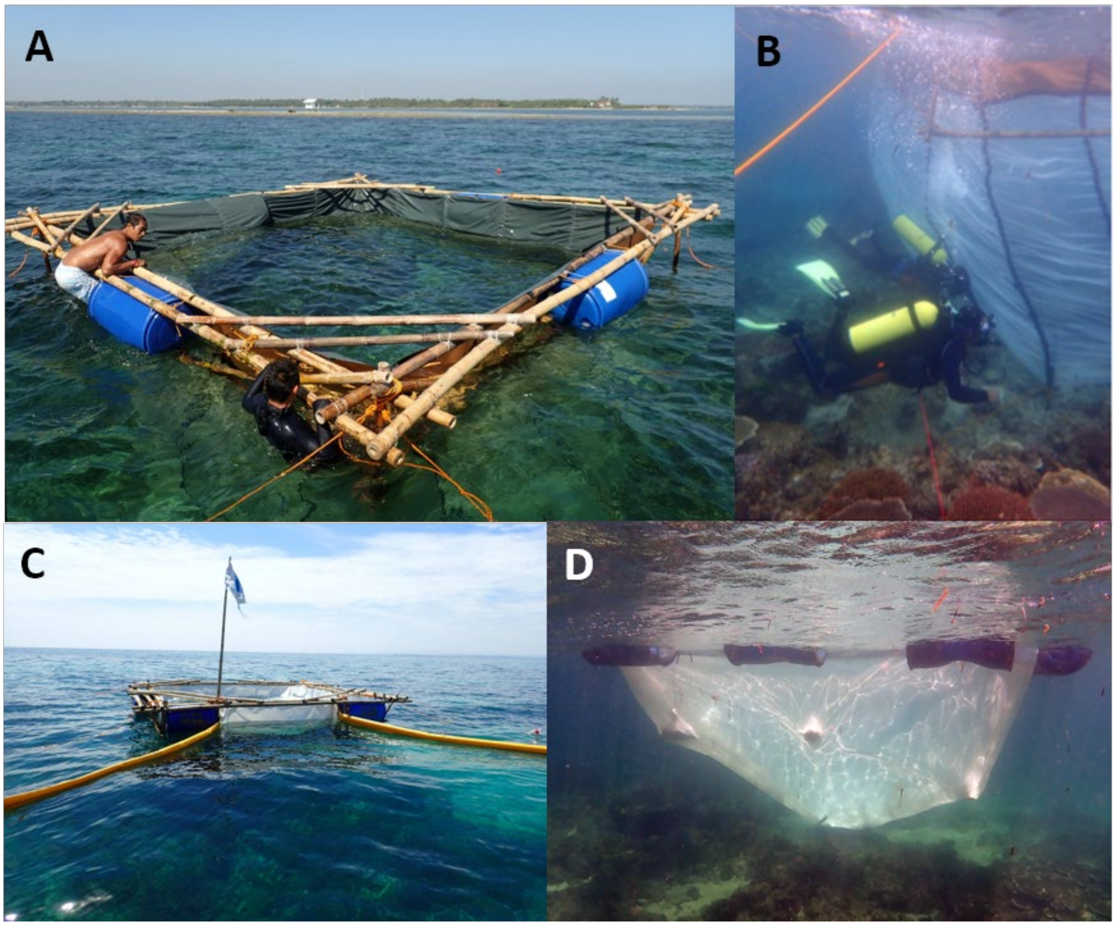



Figure 7.4: A prototype 5 × 5 m floating bamboo frame larval rearing pool deployed on Magsaysay reef in 2016 (A), and the submerged mesh curtain attached to the bamboo frame on reef site (B). Spawn catcher with booms attached to bamboo frame in 2017 on Magsaysay reef (C), and 2018 larval rearing net deployed under a floating steel frame (D) (Source: Harrison et al. 2021).

Subsequently, an innovative surface 'spawn catcher' net with inflatable floating surface booms was designed to efficiently direct the highly buoyant spawned gamete bundles into the larval net attached to the catcher. A prototype 2 × 2 m PVC pipe semi-submersible frame was built in April 2016 and the design was further refined in 2017 during field trials on the reef. In March 2017, a 150 µm plankton mesh net with an upper vinyl panel extending 0.5 m above and below the sea surface (designed to avoid abrasion of the delicate developing embryos on the plankton mesh), and paired 15 m inflatable spawn collector booms were attached to a 5 × 5 m floating bamboo frame which was positioned into the wind and down current from spawning corals on Magsaysay reef (Figure 7.4C). The booms were held apart at ~90° using anchor ropes, and had a 30 cm weighted vinyl curtain submerged below the water surface to facilitate spawn slick collection. Spawn slick samples were collected after the major spawning on 10 nAFM in March 2017, and an estimated 317,000 larvae were reared in the larval culture pool net enclosure supported within a 5 × 5 m steel frame with drum floats, which was temporarily moored adjacent to Magsaysay reef.

Subsequently, the submerged 150 µm larval culture mesh nets were redesigned to be free-floating within a frame, and with tapered sides and a zipper opening at the base to allow for release of larvae directly from the net onto target reef sites. These redesigned nets were attached to stronger 5 × 5 m floating steel frames to increase the success of spawn collection and larval culture on the reef in adverse weather conditions (Figure 7.4D). Many millions of spawned egg-sperm bundles were collected in the spawn catchers following large multispecific *Acropora* spp. spawning events at Magsaysay reef in March 2018 (Table 1), with >90% fertilization rates recorded in samples. In 2018, a solar powered seawater pump and aeration system was attached to the floating steel frames to maintain good water quality and increase the efficiency of larval cultures on the reef.

In 2018 and 2019, newly designed larval rearer nets were deployed within the 5 × 5 m floating steel frames, resulting in larger volumes of coral spawn and larvae being cultured *in situ* on reefs (Figure 7.5). A new larval rearing net design with higher protective sides attached to the steel larval rearer frame and a horizontal section added around the top of the net was successfully trialled in 2019 (Figure 7.5). The new design prevents highly buoyant embryos and early larval stages from being washed out of the net during adverse weather conditions. During April 2019, an estimated 5.2 million *A. tenuis* larvae were reared from spawn collected from the 2013 and 2016 restored populations using these new nets deployed at HINP (further details provided below), and 18 million larvae from wild coral spawn slicks were collected in March 2020.

Figure 7.5: Coral spawn within a spawn catcher-larval rearing pool in March 2019 (left image), and mass culture of *A. tenuis* larvae in newly designed larval pools at HINP (right image) (Images: Peter Harrison).

The spawn catcher and larval culture pool systems developed during this project have been further re-designed and optimised for mass larval culture on GBR larval restoration projects (Harrison et al. 2019, 2020), and will be used in other international coral larval restoration projects in the near future.

### *Sexual reproductive patterns among Acroporidae species*

Research on gametogenic cycles and sexual reproductive patterns among three species of the ecologically important hermatypic coral family Acroporidae formed part of Elizabeth Gomez's Masters research, supported by this project. Replicate colonies of *A. millepora*, *A. tenuis* and *Montipora aequituberculata* have been repeatedly sampled from three different sites (Caniogan, Cangaluyan and Magsaysay reef, respectively) along the Bolinao-Anda Reef Complex (BARC), and dissection and histological analyses have revealed gametogenic cycles, fecundity and spawning patterns. All three species are broadcast spawning simultaneous hermaphrodites as expected from previous research in other regions (e.g. Harrison et al. 1984, Babcock et al. 1986, Baird et al. 2021). Similar to most other broadcast spawning corals (Harrison and Wallace 1990, Randall et al. 2020), these species had longer oogenesis cycles compared with spermatogenesis, with oocytes developing from July and spermary development in January (Figures 7.6, 7.7).

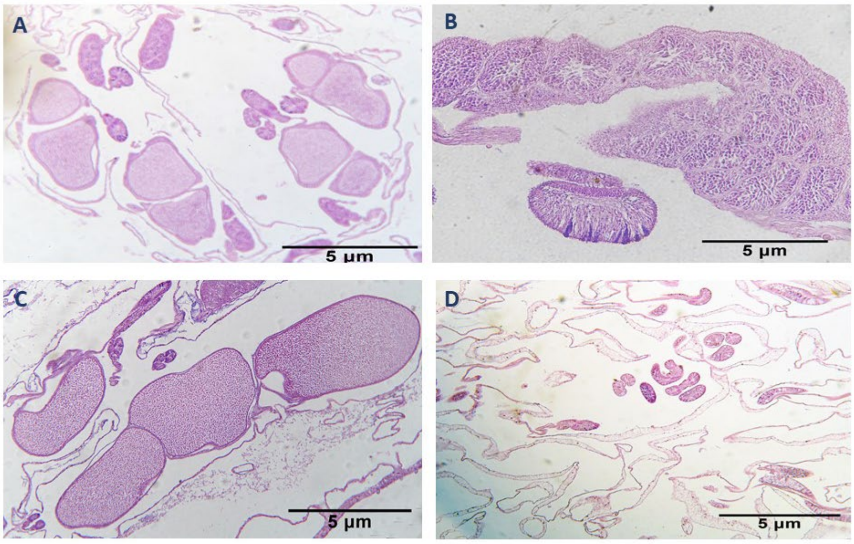



Figure 7.6. Oocyte (A,C) and spermary (B,D) development in histological sections of *A. tenuis* corals (Images: E. Gomez).

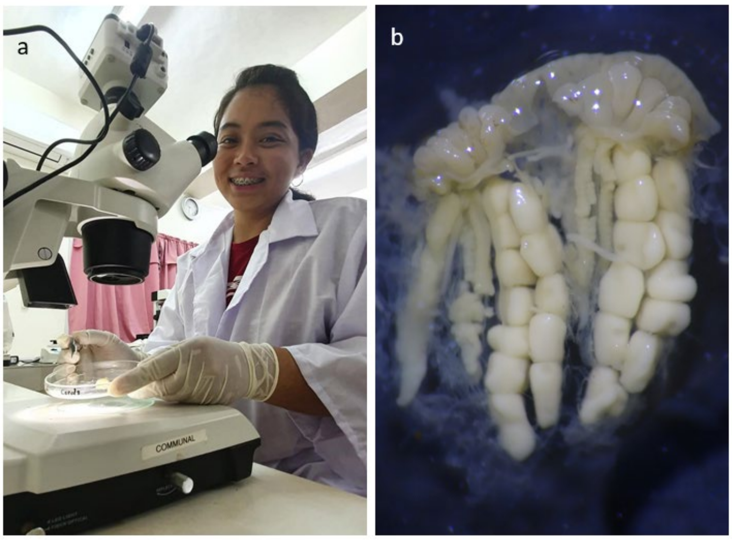



Figure 7.7. Elizabeth Gomez, an ACIAR Masters student researcher, examining corals to determine their reproductive timing and pattern. Elizabeth dissected coral polyps to quantify egg and spermary patterns (A). A dissected *A. tenuis* polyp showing strands of well-developed oocytes on four mesenteries, and spermaries on adjacent pairs of mesenteries (B) (Images: E. Gomez).

Similar to most other broadcast spawning corals (Harrison and Wallace 1990, Randall et al. 2020), these species had longer oogenesis cycles compared with spermatogenesis, with oocytes developing from July and spermary development in January. The annual reproductive cycle of *A. millepora* culminates in spawning as early as February and peaks in March in Caniogan reef. Similarly, analyses of *Montipora aequituberculata* data suggest that gamete release occurs in March each year. *Acropora tenuis* spawning occurs during April at Caniogan reef similar to patterns found at Magsaysay reef, but a more extended split-spawning pattern (*sensu* Willis et al. 1985) from April to June occurs in colonies at Cangaluyan reef (Figure 7.8).

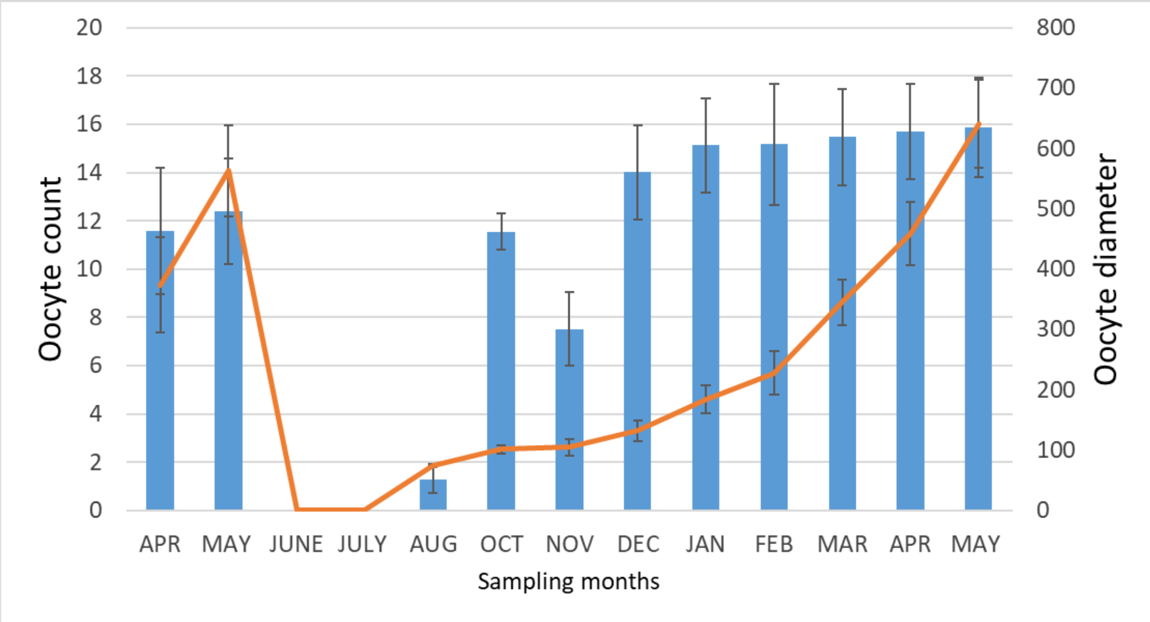



Figure 7.8. Mean oocyte abundance and diameter of *Acropora tenuis* colonies at Cangaluyan reef (Data courtesy: Elizabeth Gomez).

Spawning months for these species coincided with increased sea surface temperatures and high light conditions at the study sites, suggesting that temperature and light are some of the suite of proximate cues driving the onset and timing of reproduction (Babcock et al. 1986, Randall et al. 2020). These findings provide detailed information on sexual reproductive patterns in three Acroporidae species in the northwestern Philippines, which will inform future coral conservation and restoration research, and replenishment of local coral populations.

### *Optimising fertilization rates for mass embryo and larval culture*

Research on fertilization rates of *Acropora tenuis*, *A. millepora* and *Favites colemani* corals was completed as part of Dexter dela Cruz's PhD research (dela Cruz 2019). The research was initiated in 2014 with ongoing analyses and the recent publication of the paper supported by this project.

dela Cruz, D. and Harrison, P.L. (2020). Optimising conditions for in vitro fertilization success of *Acropora tenuis*, *A. millepora* and *Favites colemani* corals in northwestern Philippines. **Journal of Experimental Marine Biology and Ecology 524:** 151286
https://doi.org/10.1016/j.jembe.2019.151286

The key outcomes from this research are summarised below.

Scleractinian corals that spawn their gametes directly into the water column may experience limitations from sperm dilution and delays in initial sperm-egg encounters that can impact successful fertilization. The same issues can be experienced during *ex situ* larval culture. Therefore, experiments were completed using spawned eggs and sperm of the reef corals *Acropora tenuis*, *A. millepora* and *Favites colemani* to determine the optimal ranges of sperm concentrations ($<10^3$ to $10^7$ $mL^{-1}$) and temporal response patterns when crossing of eggs and sperm was delayed (30 min to 10 h). The results showed that sperm concentrations below $10^3$ $mL^{-1}$ yielded low rates of fertilization for all three species (<30%), but that sperm concentrations at $10^4$ $mL^{-1}$ resulted in higher rates of fertilization for the *Acropora* spp. (>65%) and >90% fertilization rates for *F. colemani*. Sperm concentrations of $10^5$-$10^7$ $mL^{-1}$ resulted in the highest observed fertilization rates for all three species (>90%).

High fertilization rates (>80%) occurred when eggs and sperm were combined after 30 minutes and up to 2 hours after spawning for *F. colemani* and up to 4 hours for *A. tenuis* and *A. millepora* gametes. Fertilization rates were significantly reduced (<30%) after a delay of 4 hours for *F. colemani* and after 6 hours for the two *Acropora* species. No fertilization occurred after a 10-hour delay in combining gametes for all the tested coral species.

The results of these experiments show that optimal fertilization success for these coral species is achieved at sperm densities of $\geq 10^4$-$10^6$ $mL^{-1}$. Furthermore, gametes should be combined within a few hours after spawning for optimising embryo and larval culture for mass larval rearing. These outcomes need to be considered in future mass coral culture and reef restoration programs, and sperm limitation problems can be partly overcome by combining millions of eggs and sperm from many colonies during collections of coral spawn slicks on reefs before transfer to larval culture pools, as described above.

## Section 7B: Objectives 2 and 3 Coral larval restoration reef trials

Outcomes from the reef-based larval restoration research are presented chronologically.

### *2016 Acropora tenuis high density larval restoration reef trial*

One of the major achievements of this project was the successful larval enhancement experiment initiated in 2016 using higher densities of *A. tenuis* larvae, led by Peter Harrison with ongoing coral monitoring and analyses coordinated by Dexter dela Cruz. This reef experiment followed on from the 2013 successful larval restoration pilot study on Magsaysay reef by PhD student Dexter dela Cruz (dela Cruz and Harrison 2017). Results from the 2016 experiment and longer-term monitoring outcomes have been presented in previous ACIAR project reports, and were published in 2021:

Harrison PL, dela Cruz DW, Cameron KA and Cabaitan PC (2021). Increased Coral Larval Supply Enhances Recruitment for Coral and Fish Habitat Restoration. Frontiers in Marine Science, 8:750210. https://www.frontiersin.org/articles/10.3389/fmars.2021.750210/full

The key results and conclusions are presented below.

Rationale: Loss of foundation reef-corals is eroding the viability of reef communities and ecosystem function in many regions globally. Coral populations are naturally resilient but when breeding corals decline, larval supply becomes limiting and natural recruitment is insufficient for maintaining or restoring depleted populations. Passive management approaches are important but in some regions they are proving inadequate for protecting reefs, therefore active additional intervention and effective coral restoration techniques are needed. Coral spawning events produce trillions of embryos that can be used for mass larval rearing and settlement on degraded but recoverable reef areas.

The higher-density mass larval enhancement experiment was initiated in late April-early May 2016 on nearby degraded reef sites at Magsaysay reef, Anda, Pangasinan. The 2016 larval restoration reef trial was scaled up using 4.6 million *A. tenuis* larvae, comprising larvae reared from spawned gametes from the three-year old restored colonies from the 2013 larval recruits (dela Cruz and Harrison 2017), plus larvae reared from spawned gametes of other *A. tenuis* colonies from nearby reefs. Photo-quadrats of all plots were taken to quantify the baseline benthic cover and reef community status, which was badly degraded and phase-shifted to dominance by algae rather than corals. Ten biologically conditioned 10x10 cm *Acropora* skeleton recruitment tiles were deployed inside each of the plots just prior to the larval enhancement experiment to quantify initial settlement rates of the *A. tenuis* larvae. Ten additional tiles were placed outside of the control plots to determine if any larvae were naturally recruiting onto these reef areas during the larval enhancement period when experimental plots were covered in fine mesh enclosures. Fish communities within each plot were monitored prior to the experiment in 2016 using standard Fish Visual Census (FVC) techniques.

Spawned egg-sperm bundles were collected *in situ* from 31 three-year old *A. tenuis* colonies that had grown to reproductive size on Magsaysay reef sites from the 2013 larval enhancement experiment (dela Cruz and Harrison 2017), using spawn cones placed over gravid colonies. Spawn was transferred to the BML seawater facility for embryo and larval rearing, and additional cultures of embryos and larvae were reared from spawned gametes from 29 'wild' *A. tenuis* colonies at BML collected from Caniogan and Magsaysay reefs.

After seven days, larvae were filtered with a total of 4.6 million larvae available (3 million larvae from the 'wild' colonies and 1.6 million larvae from the 2013 three-year old colonies). DNA samples were taken from parent 2013 *A. tenuis* colonies and larval cultures to enable identification of parental genotypes that are most successful in producing surviving recruits in future, and are being analysed at UP. Larvae were transported to the larval enhancement plots at Magsaysay Reef, and ~1.54 million larvae were dispersed into each of the three larval plots that were enclosed in 5x5 m by 60 cm high tent enclosures made from 200 µm plankton mesh attached to 5x5 m PVC frames (Figure 7.9). Control plots were also covered with 5x5 m plankton mesh enclosures but no larvae were supplied.

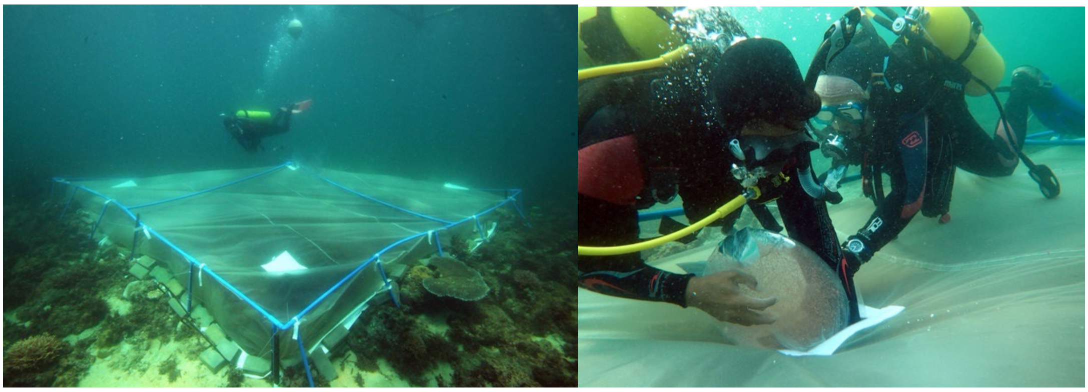


Figure 7.9: Larval mesh enclosure with frame attached onto reef (left image: Peter Harrison); and dela Cruz and Harrison adding *A. tenuis* larvae into resealable portal on a mesh enclosure prior to dispersal through the enclosure (right image: Kerry Cameron).

Very high settlement rates of *A. tenuis* spat were recorded on tiles in larval enhancement plots with a total of 6,307 settled spat present, and a mean of 210.2 (± 86.4) spat per tile (Figure 7.10). Highest and similar mean settlement rates occurred on the sides and bottom surfaces of tiles with lower rates on the top surfaces, but these were not significantly different ($F = 0.53$, $P = 0.61$) (Figure 7.10). Coral spat had well-developed primordial skeletons indicating rapid settlement after release onto the reef plots (Figure 7.10B). No *A. tenuis* recruits settled on tiles in control plots covered in mesh enclosures or on tiles in open control areas without mesh that were used to monitor natural recruitment during the five-day larval settlement experiment. These results confirm that mass larval enhancement can significantly increase the initial settlement of corals even on degraded reefs where natural coral recruitment has been compromised by loss of adult breeding corals and poor water quality.

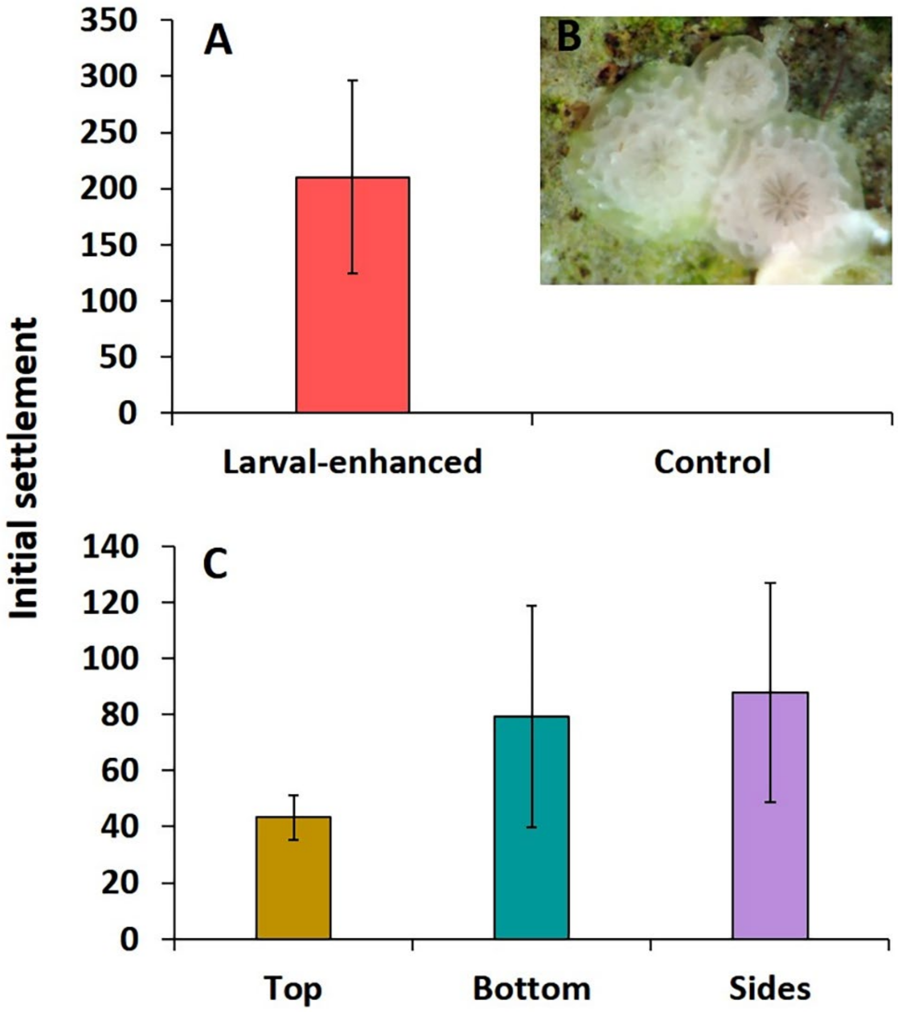



Figure 7.10. Initial mean *A. tenuis* larval settlement on tiles in larval enhanced (N = 3) and control (N = 3) plots after 5 days larval settlement (A), three newly settled spat with well-developed primordial skeletons (B), and mean settlement on different tile surfaces in the larval enhanced plots (C). Error bars are ± SE. (Source: Harrison et al. 2021).

High mortality occurred during early post-settlement life stages as expected for broadcast spawning corals with Type III survivorship life histories, however, juvenile coral survivorship stabilised once colonies had grown into visible-sized recruits (1.9 ± 0.26 cm mean diameter) on the reef by 10 months (Figure 7.11). Most recruits survived and grew rapidly, resulting in significantly increased rates of coral recruitment and density in larval-enhanced plots. Some of the larvae settled close together and after a few months some of these juveniles fused to form chimeras. After 25 and 27 months, a total of 14 fused colonies were recorded with each fused colony comprising of two to seven settled recruits. From 10–34 months after settlement, the number of recruits on tiles declined slowly with 13 recruits alive on top surfaces after 25 months, and eight of those colonies surviving at 34 months (log-rank test, $\chi^2 = -255.24$, $P = 0.00$, top > sides = bottom; Figure 7.11B). The mean number of surviving colonies on tiles in each of the three larval plots after 34 months was 2.7 ± 0.67SE per plot. Higher numbers of juvenile colonies resulting from larval settlement directly on reef substrata were found, with a total of 212 colonies alive in the three larval enhancement plots after 34 months. The mean number of surviving colonies on natural reef substrata in each larval enhancement plot at 34 months was 70.7 ± 16.83, equivalent to ~5.7 colonies surviving per $m^2$ from larval settlement onto available reef areas in each larval enhancement plot.

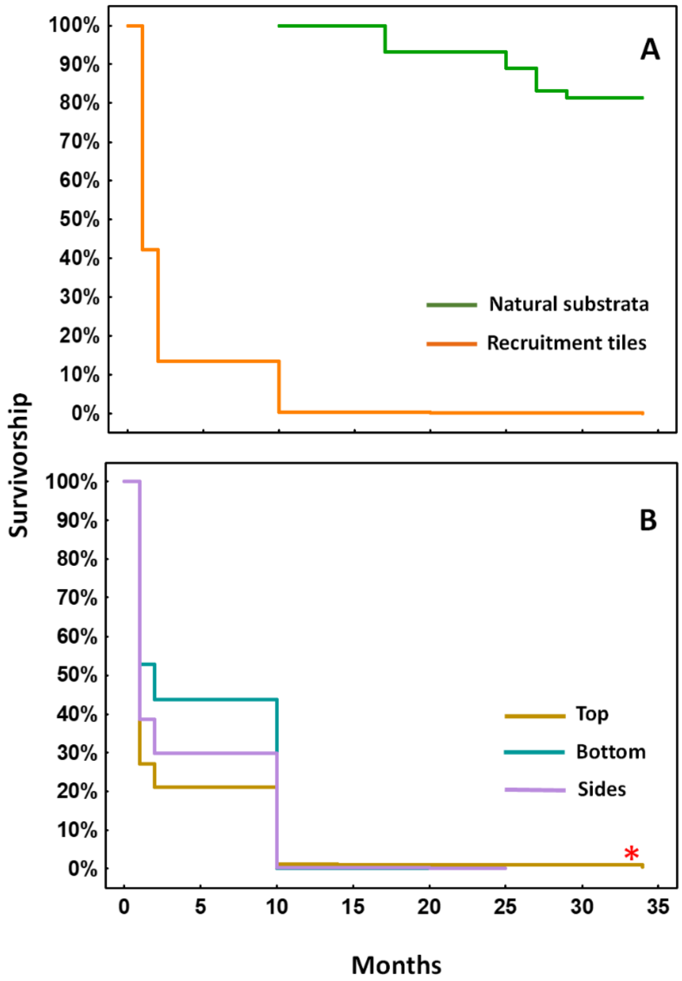



Figure 7.11 Kaplan-Meier survivorship over 34 months for settled *A. tenuis* polyps, juveniles and recruits in (A) larval enhanced plots on tiles (orange) and for visible recruits on natural reef substrata (green) starting at 10 months after larval settlement, and (B) survivorship of recruits on different tile surfaces in the larval enhanced plots. Asterisk denotes significant difference between tile surfaces. (Source: Harrison et al. 2021).

After two years growth, mean colony size reached 11.1 ± 0.61 cm mean diameter (Figure 7.12), and colonies larger than 13 cm mean diameter were gravid and spawned, the fastest growth to reproductive size recorded for broadcast spawning corals (Figure 7.13). These gravid colonies were observed spawning from 1830 to 1900 h on 1 and 2 May 2018 (1–2 nAFM, Table 1) on Magsaysay reef restoration plots. Gametes collected from spawn cones placed over the gravid colonies were combined and transferred to the BML hatchery where high rates of fertilization were confirmed.

After three years, mean colony size reached 17 ± 1.7 cm mean diameter, with colonies ranging from 6 cm to more than 40 cm mean diameter. A total of 77 colonies were sexually reproductive at this size and age, with gravid colonies ranging in size from 13.2 to 42.3 cm mean diameter (Figure 7.13). These gravid colonies included four colonies growing on tiles and 73 colonies growing on natural reef substrata. Gravid colonies were observed spawning (Figure 7.13C) from 1830 to 1900 h on 23 and 24 May 2019 (4–5 nAFM), and gametes were collected from the spawn cones and transferred into floating larval pool nets on the reef for larval culture (Figure 7.5).

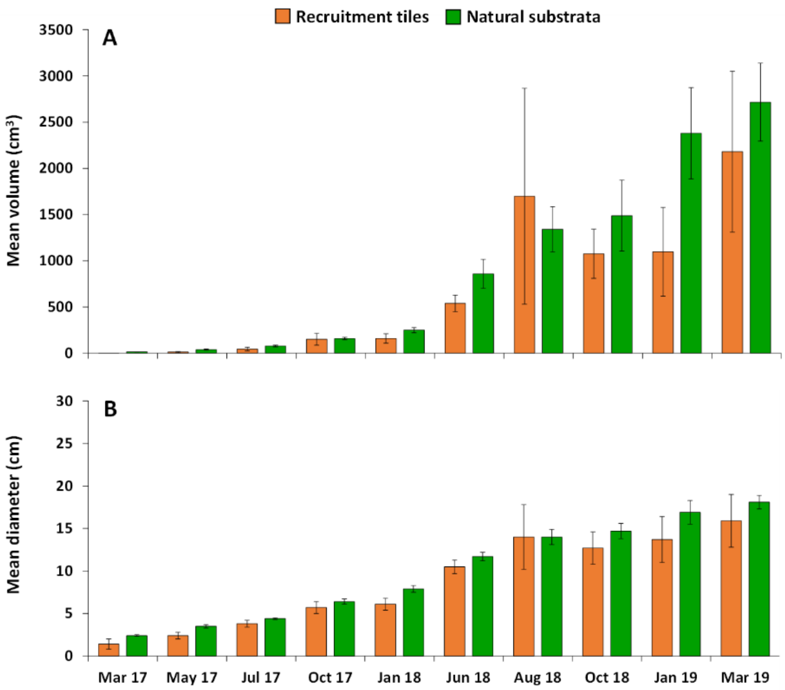



Figure 7.12. Mean growth of *A. tenuis* colonies over 34 months in the three larval enhanced plots, (A) mean volume and (B) mean diameter of colonies on settlement tiles (orange) and natural substrata (green). Error bars are ± SE. (Source: Harrison et al. 2021).

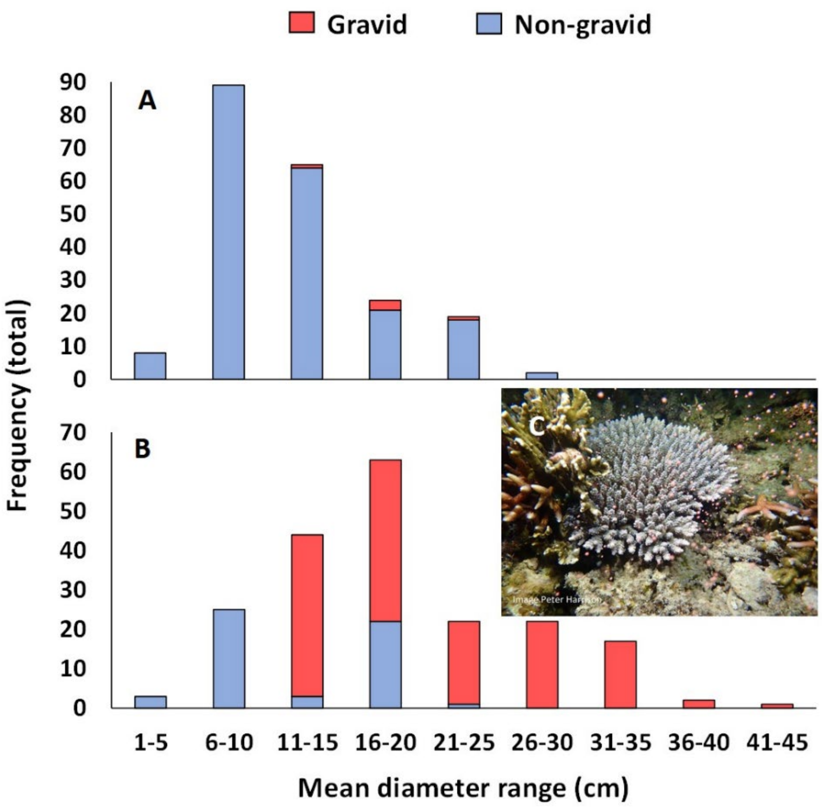



Figure 7.13. Size frequency plots of mean colony size of gravid and non-reproductive *A. tenuis* colonies in the three larval enhanced plots (A) in June 2018 and (B) March 2019, and (C) a three year old colony spawning in a larval restoration plot on 25 April 2019. (Source: Harrison et al. 2021).

Baseline reef community surveys in 2016 showed that the Magsaysay reef experimental plots were initially characterised by low mean live cover of reef corals and high cover of algae (Figure 7.14), consistent with other degraded algal phase-shifted reefs (Bruno et al., 2009; Ceccarelli et al., 2018). Three years after larval restoration, mean coral cover had doubled in the restoration plots to 40% primarily due to the restored *A. tenuis* population and growth of encrusting *Montipora* colonies present in the plots prior to larval enhancement. Coral cover also increased in the control plots due to growth of encrusting *Montipora*, but *Acropora* cover and growth of other colonies was negligible, and no additional *A. tenuis* colonies recruited onto the control plots over the three years of monitoring. These results indicate that these reefs have low natural larval supply and recruitment consistent with earlier studies (dela Cruz and Harrison 2017, 2020b), therefore reef recovery will require active intervention through increased larval supply to catalyse the recovery of the foundation coral communities.

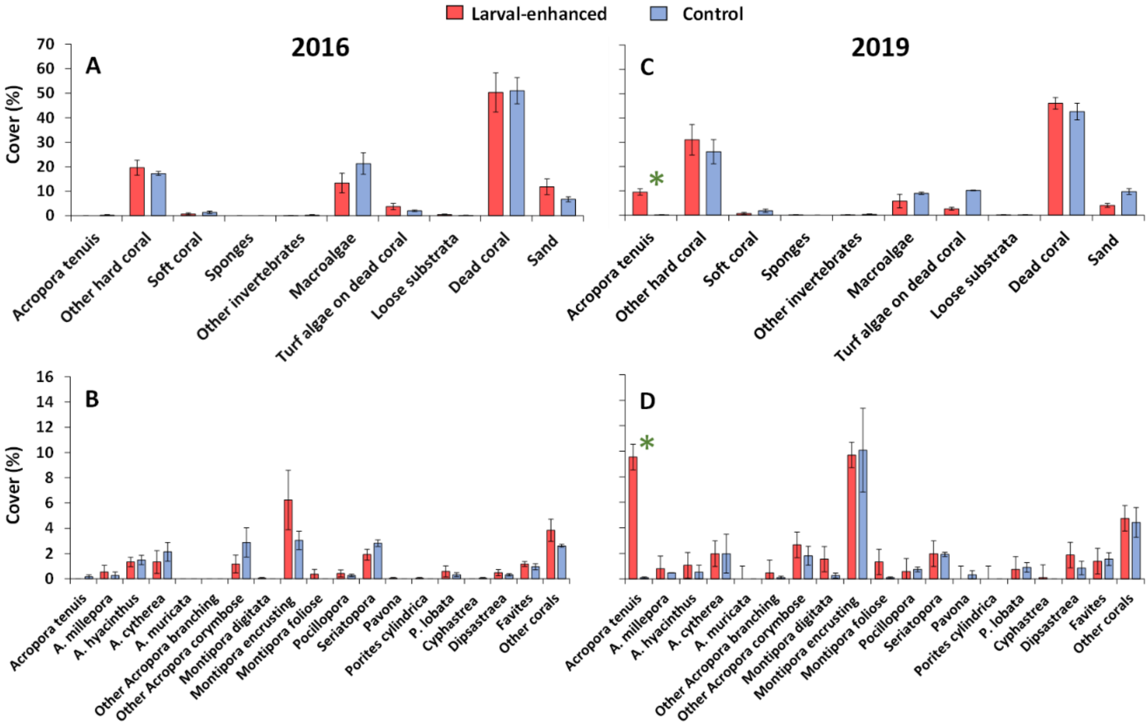



Figure 7.14. Mean percentage cover of major benthic categories prior to larval enhancement in 2016 (A) and 35 months after larval enhancement in 2019 (B), also mean percentage cover of coral categories prior to larval enhancement in 2016 (C) and 35 months after larval enhancement in 2019 (D). Error bars are ± SE. N=3 for both larval enhanced and control plots. Asterisk denotes significant difference in mean cover of *A. tenuis* between larval-enhanced and control plots. (Source: Harrison et al. 2021).

The significant increase in coral cover resulting from coral larval restoration corresponded with, and is likely to have influenced, some changes in reef fish assemblages through time. A small but significant increase in fish abundance occurred in larval plots in 2018 compared with control plots (Figure 7.15). A higher abundance of pomacentrids that shelter within coral branches (Coker et al., 2013) and an increase in chaetodontids that mainly feed on coral polyps (Cole and Pratchett, 2011) coincided with the growth of *A. tenuis* colonies (Figure 7.16).

Although the Magsaysay reef sites are included in the designated Magsaysay MPA, there is still no enforcement of fishing restrictions on the reef and some fishers continue to fish in the MPA. Therefore, it is not clear how the ongoing fishing pressures will affect the fish assemblages at the restoration sites in future. Further community engagement and education about the need to protect the Magsaysay MPA reef sites, combined with increased local management and enforcement of fishing restrictions, is needed to enable fish communities to fully recover and provide increased fish resources to other reef areas nearby.

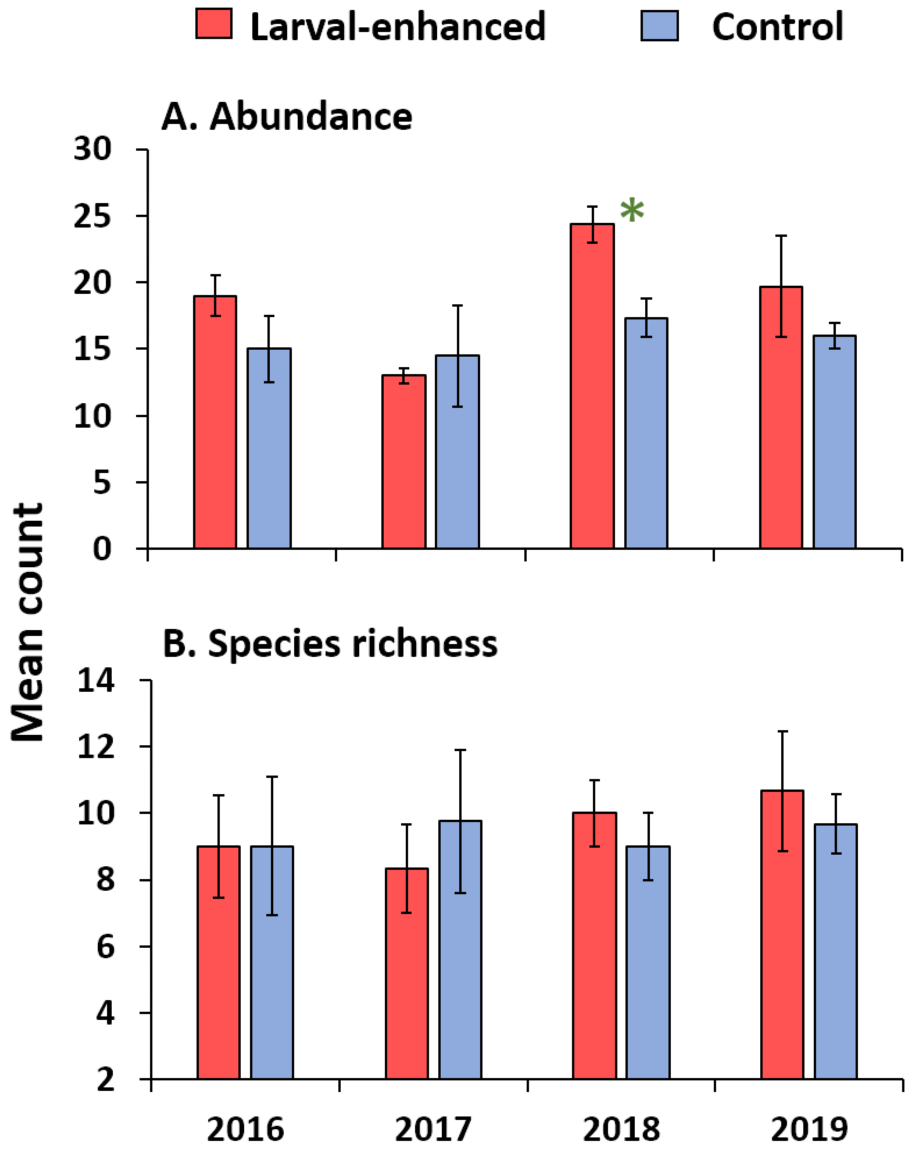



Figure 7.15. Mean total fish abundance (A) and mean species richness (B) in larval enhanced (N = 3) and control (N = 3) plots before the larval restoration experiment in April 2016, and during annual surveys up to 2019. Error bars are ± SE. Asterisk denotes significant difference in mean fish abundance between larval-enhanced and control plots during 2018. (Source: Harrison et al. 2021).

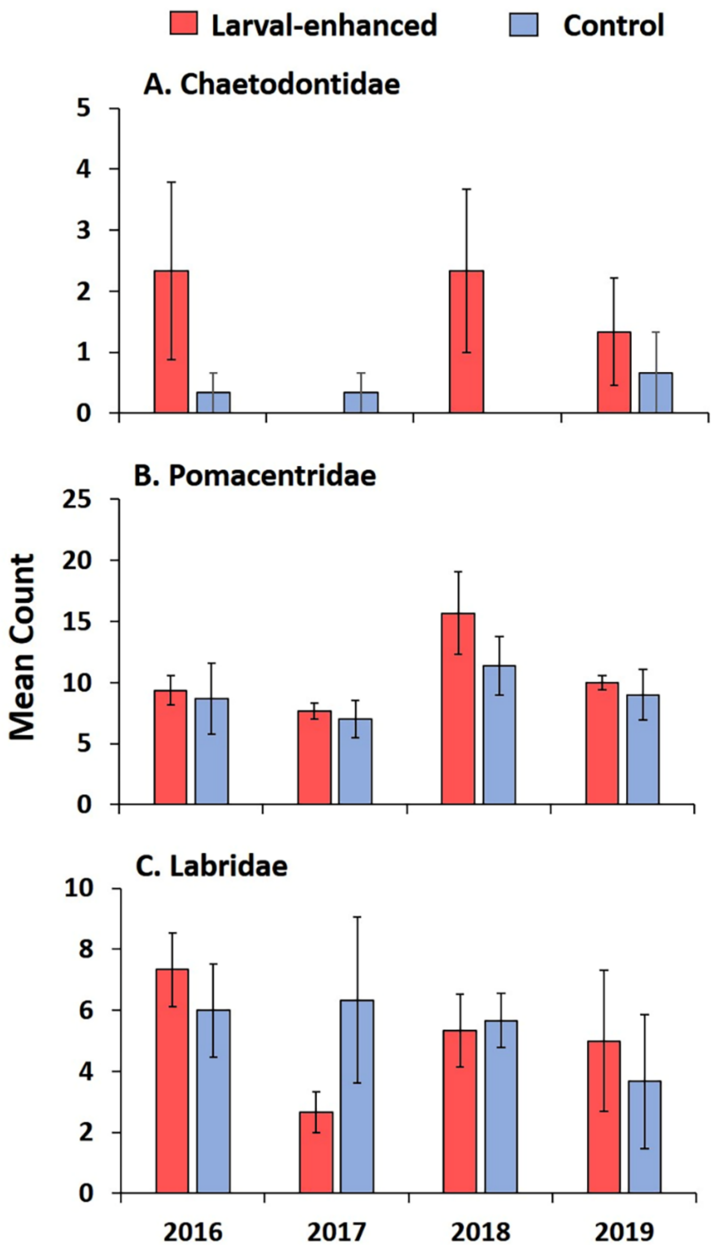



Figure 7.16. Mean abundance of three commonly occurring fish families in larval enhanced (N = 3) and control (N = 3) plots before the larval restoration experiment in April 2016, and during annual monitoring surveys until 2019. Error bars are ± SE. (Source: Harrison et al. 2021).

The 2016 larval restoration experiment has resulted in the restored *A. tenuis* colonies now dominating the larval enhancement plots (Figure 7.17). The high densities of breeding colonies established during this reef trial are likely to enhance fertilization rates on Magsaysay reef from high sperm and egg concentrations following synchronous spawning events (Oliver and Babcock, 1992; Levitan and Petersen, 1995).These breeding populations now also contribute to the depleted natural larval supply in the Lingayen Gulf, and some of these genetically diverse larvae are likely to disperse to other reefs and enhance recruitment and reef connectivity at larger scales over time (Harrison, 2006; Jones et al., 2009; Randall et al., 2020). As these breeding colonies grow and their spawning biomass increases, they become more fecund and hence their ecological value increases.

Figure 7.17. High densities of *A. tenuis* colonies growing on a larval enhancement plot 34 months after larval settlement. (Image: P. Harrison).

The average production costs for each *A. tenuis* coral colony at 10 months was US$13.70, and was US$17.80 for each of the 220 colonies in the restored breeding population at 34 months age. These costs were lower than for the 2013 pilot study US$21.00 per colony at 35 months (dela Cruz and Harrison, 2017) and for *A. loripes* US$35.00 at 35 months (dela Cruz and Harrison, 2020b), largely as a result of significantly increased larval supply and higher numbers of recruits and adult colonies surviving in the present study. Therefore, the cost-effectiveness of larval restoration should increase as mass larval production increases for larger-scale delivery onto damaged reefs. These production costs per colony for direct larval settlement onto degraded reef areas are substantially lower than for colonies reared in nurseries for extended periods prior to outplanting on reefs (Guest et al., 2014, Humanes et al., 2021). It is also important to note that these simple production cost metrics do not take into account the growing ecological and socio-economic values of these restored breeding colonies, which provide critical habitats for fish and other reef organisms, and annual increases in fecundity and production of millions of larvae.

Planned monitoring of restoration and control plots for this and ACIAR project reef restoration trials was delayed in 2020 and early 2021 due to COVID-19 pandemic and related travel and fieldwork restrictions. Monitoring resumed in May 2021, recorded 104 colonies were recorded alive inside the three larval restoration plots. The mean diameters ranged from 13 cm to 61 cm, and 67% of the colonies measured between 20 to 49 cm diameter (Figure 7.18). In April 2021, 91 of these colonies were gravid and spawned, and the gametes were collected, cultured, and the larvae were used for another larval enhancement coral restoration in Anda, Pangasinan.

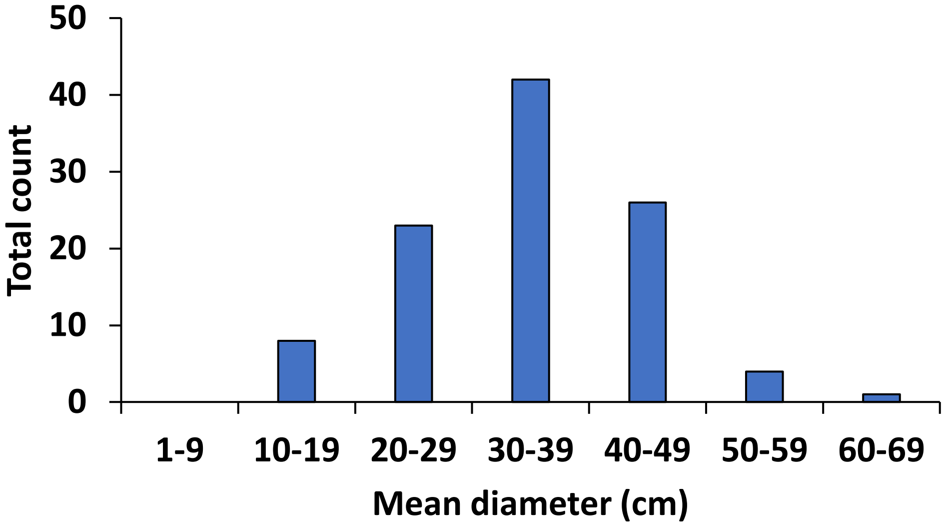



Figure 7.18. Size frequency distribution of *A. tenuis* colonies from May 2021 monitoring of the 2016 larval restoration plots on Magsaysay reef.

Conclusions: The results of this study have confirmed that increasing larval supply and direct settlement on degraded reef areas can rapidly re-establish coral colonies and abundance on highly degraded and algal-phase-shifted reef areas. High coral growth rates resulted in a breeding population of *A. tenuis* within two to three years, leading to significantly increased coral cover on restoration plots compared with control reef plots reliant on depleted natural larval supply. The higher densities of larvae supplied in this study significantly increased larval settlement, recruitment and production of adult corals at higher densities on larval restoration plots, and at reduced cost compared with earlier studies. In addition, the increased cover of branching coral colonies corresponded with increased fish habitats and abundance of pomacentrids reliant on sheltering in branches, and increased chaetodontid corallivores on the larval restoration plots. Ongoing artisanal fishing pressures in the Magsaysay MPA will need to be managed in order to increase the abundance of fish and spawning stocks within the restoration areas, that could potentially increase fish recruit 'spill-over' effects into nearby reef areas (Russ et al. 2015, 2021).

### *2017 Larval density and recruitment experiment*

This experiment formed part of Kerry Cameron's PhD research (Cameron 2021), and was published in 2020:

Cameron, K. and Harrison, P.L. (2020). Density of coral larvae can influence settlement, post-settlement colony abundance and coral cover in larval restoration. **Scientific Reports 10**: 5488. https://www.nature.com/articles/s41598-020-62366-4

The key outcomes from this research are summarised below.

The aim of this research was to determine optimal larval densities for supplying larger-scale field trials. The larval density field experiment was initiated in May 2017 and examined the effects of supplying different densities of *A. tenuis* larvae on initial settlement success and subsequent survival. Thirty replicate small scale larval settlement chambers with fine mesh panels to allow seawater exchange were deployed on Magsaysay reef areas. Each chamber contained a biologically conditioned settlement tile (Figure 7.19), and each chamber was supplied with a different larval density ranging from 10 to 5,130 larvae to enable linear regression analyses.

Figure 7.19. Experimental settlement chambers for testing larval density on Magsaysay reef in May 2017 (Image: Kerry Cameron)

After a five-day settlement period, tiles were carefully collected and numbers of settled spat on each tile were recorded under a microscope and LED lights. Settlement rates varied from ~2-30%, with only a weak positive correlation between increasing larval density and initial % settlement success (Figure 7.20A). Tiles were then returned to their original reef locations and survival and growth of juvenile corals on the tiles were monitored after two, five, eight, 12 and 24 months.

The results indicate some density-dependent effects on survivorship, with optimal rates (%) of settlement and highest total survival to 12 months in densities with ~800-2200 larvae/tile, and greatest coral growth at 24 months on tiles supplied with ~1000-2000 larvae (Figure 7.20). Therefore, larval supply at very high densities was inefficient, and could also have negative outcomes on subsequent colony survival and coral cover.

The results indicate that *A. tenuis* larval densities from the lower end of the optimal range found in this study should provide improved outcomes for larval restoration of degraded reefs. These densities led to settler densities that did not impede larval preference for substratum selection, and with increased likelihood of colonies persisting for two years. Larval supply density also significantly influenced larval settlement positions, with proportionately fewer larvae settling in advantageous positions around the outer areas of the lower tile surfaces as density increased. Overall, these results indicate that settlement and recruitment rates can be controlled by manipulating larval supply density, which will enable future larval restoration reef trials to be optimised.

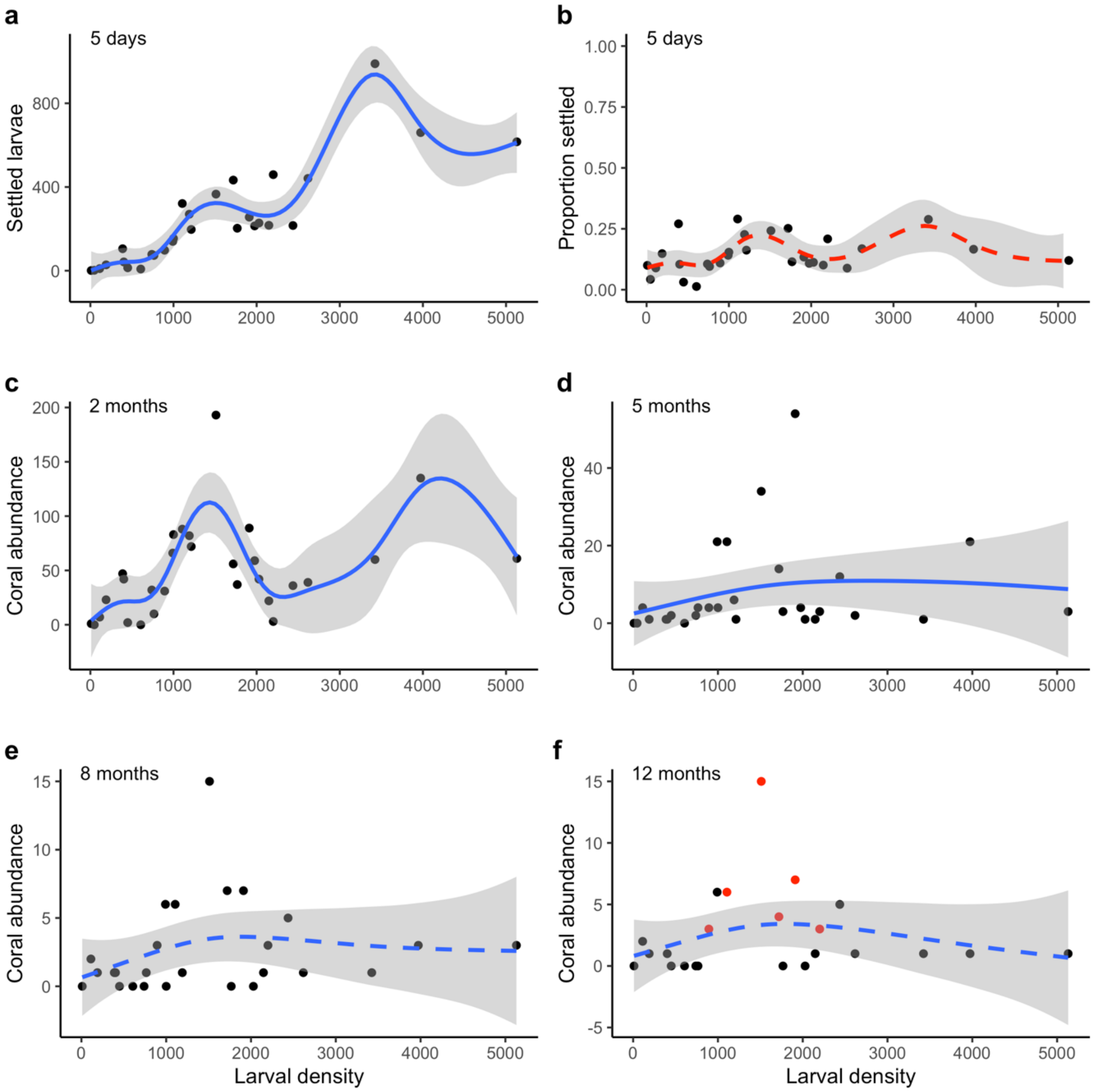



Figure 7.20. Relationship between larval density and initial settlement patterns and subsequent survival of *A. tenuis* juveniles to 12 months age on settlement tiles on Magsaysay reef (a) total settlement after five days, (b) proportion of larvae settled (%) after five days, (c) post-settlement colony abundance after 2 months, (d) colony abundance after 5 months, (e) after 8 months, and (f) after 12 months (visibly fusing colonies highlighted with red data points). Solid lines indicate significant model fits, dashed lines represent non-significant model fits, and shaded areas represent 95 % confidence intervals. (Source: Cameron and Harrison 2020).

A conceptual diagram highlighting the key outcomes from this research is shown in Figure 7.21 below.

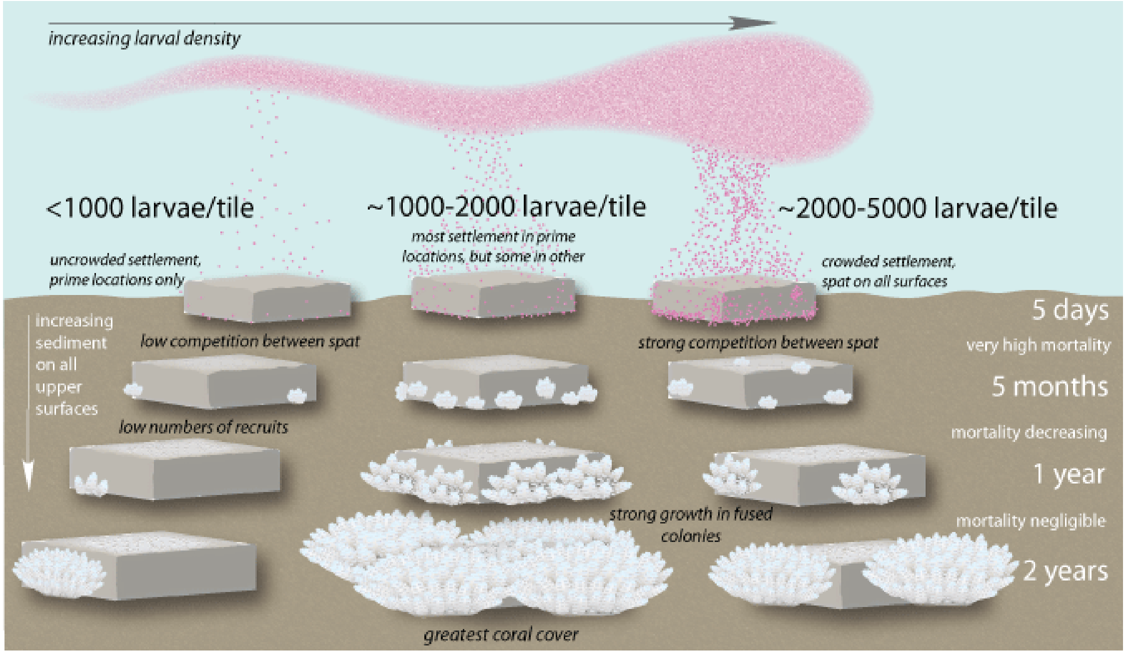



Figure 7.21. Diagram summarising effects of different *A. tenuis* larval supply densities on initial settlement and subsequent survival of juveniles on settlement tiles on Magsaysay reef up to two years (Source: Cameron and Harrison 2020).

### *March 2018 Acropora millepora larval restoration trial*

In March 2018, a larval restoration trial was initiated on Magsaysay reef, Anda, Pangasinan (16°19'36" N, 120°02'01" E), using ~1 million larvae cultured from gametes from *A. millepora* colonies that spawned in March 2018. Nine days after the first full moon of March 2018, 27 gravid *A. millepora* colonies (12-25 cm in diameter) were collected in Magsaysay and Caniogan reefs and were brought back to the BML hatchery facility. On March 27, ten colonies partially spawned and one colony fully spawned, with an estimated 1,693,000 eggs collected with 90.2% mean fertilization. On the following night, 8 colonies partially spawned and 1 fully spawned with ~856,000 eggs collected with 86% mean fertilization. After 6 and 7 days of larval culture, larvae were concentrated and transferred to Magsaysay reef where they were deployed in four larval restoration plots covered with fine mesh nets, with two control plots that were not supplied with cultured larvae.

Two types of nets were used to compare their performance and efficiencies on these exposed reef areas, with two plots covered with each net type. Two plots were covered with 5x5 m by 60 cm high mesh 'tent' enclosures made from 200 μm plankton mesh that were designed for use in the 2016 *A. tenuis* larval restoration field trial (Harrison et al. 2021). The second net design was a 5x5 m flat sheet with an additional 1 m vinyl skirt along the four sides to allow for 3D reef complexity, and is similar to the 6x4 m flat mesh sheet enclosures used in the initial 2013 and 2014 larval restoration trials (dela Cruz and Harrison 2017, 2020), but with Velcro opening portals adapted from the 2016 mesh tent nets. The second modified net design was developed as part of Kerry Cameron's PhD research following coral larval settlement experiments at the Australian Institute for Marine Science (AIMS) in 2017 (Cameron et al. in prep).

The flat mesh sheet design has potential advantages of reduced drag from currents and wave action compared with the 2016 mesh tent design, whereas the 2016 mesh tent was designed to reduce abrasion from live corals and three-dimensional reef structures. Ten biologically conditioned 10x10 cm natural coral skeleton tiles were attached on posts in each plot to quantify initial larval settlement after larval supply. After 24 hours settlement period, 1 settled spat was found on a tile in one plot covered with the flat mesh sheet, with

21 spat on tiles in plots covered by the mesh tents. No settled spat were present on tiles from control plots (Figure 7.22).

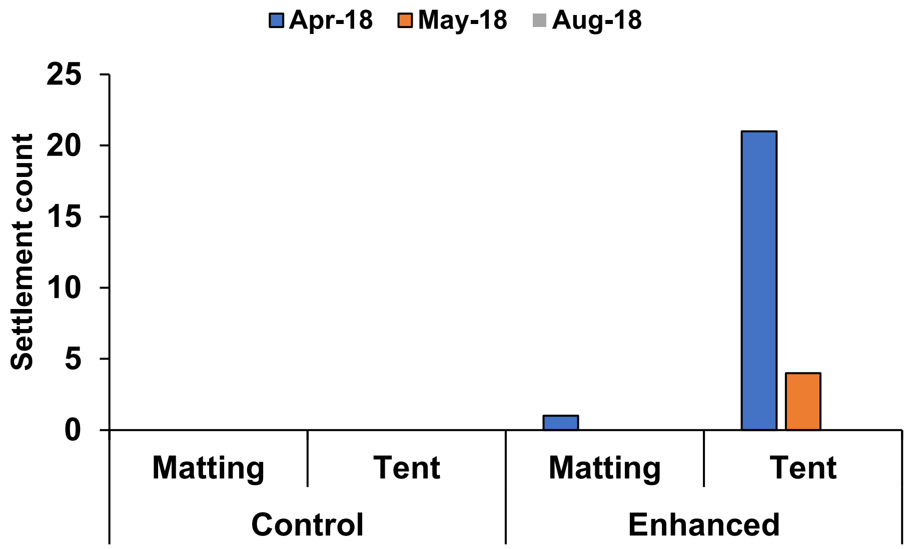



Figure 7.22. Initial settlement and after one month and four months of *A. millepora* on the deployed settlement tiles insides the control and treatment plots.

After one month, three juvenile corals remained alive on the tiles in the mesh tent enclosure treatment, but none were alive on tiles in the flat sheet plots. After one year, eight colonies were growing on the natural reef substrata in the mesh sheet plots and five were recorded on the mesh tent plots (Figure 7.23). No *A. millepora* juveniles were recorded in the control plots. However, subsequent periodic monitoring of *A. millepora* both on tiles and natural substrata showed increased numbers of colonies as the previously cryptic juveniles became conspicuous.

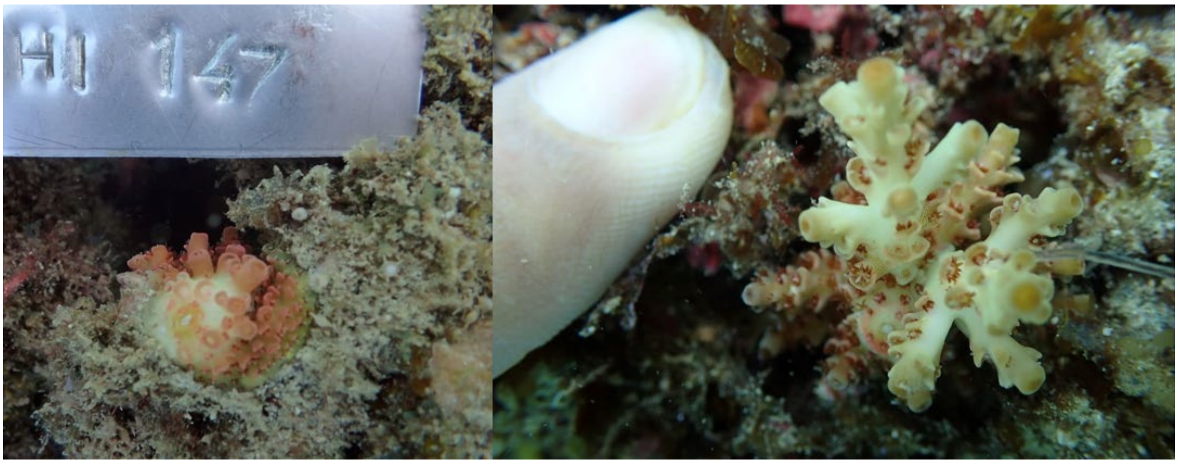



Figure 7.23. One year old juvenile *A. millepora* corals growing on natural substrata on the larval enhancement plots in Magsaysay reef (Images: Elizabeth Gomez).

After 36 months, a total of 11 remaining colonies were growing on the tiles and 24 colonies on the natural substrata (14 on plots with flat mesh sheet treatment, and 10 plots with the mesh tent treatment). Survival data analysis showed that there was no significant difference in the survival of corals on the tiles and natural substrata (Log rank test, *p* =

0.130, $X^2 = 2.298$, *df* = 1; Figure 7.24A) and between the matt and tent treatments (Log rank test, $p = 0.289$, $X^2 = 1.126$, *df* = 1; Figure 7.24B).

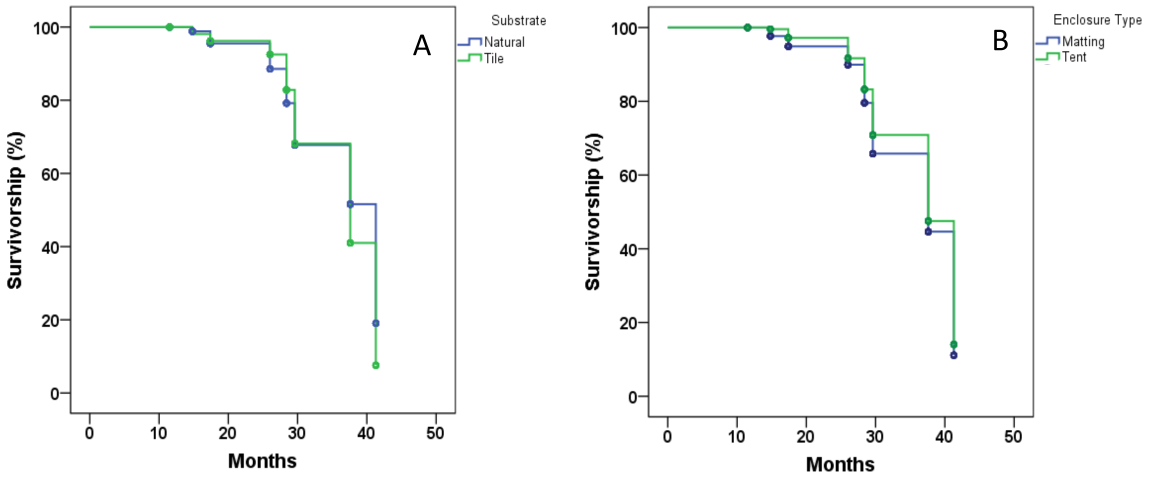



Figure 7.24. Kaplan-Meier survival curve of *A. millepora* corals that were settled onto degraded reef plots at Magsaysay reef (A) natural substrata and tiles, and (B) on the matting and tent treatment.

Initial mean diameter of corals was 2.7 ± 0.43 cm on the tiles, and 2.1 ± 0.21 cm on the natural substrata. Mean diameter of the majority of the corals was 5 cm after one year, and increased to 10 cm after 2 years and 15 cm after 3 years (Figure 7.25). The largest colony recorded after 36 months was 30 cm mean diameter. The reproductive status of corals was checked after 23 months, one month prior to the potential spawning period, however no sexually reproductive colonies were found. Due to the COVID-19 pandemic and fieldwork restrictions in 2021, the reproductive status of the corals could not be monitored.

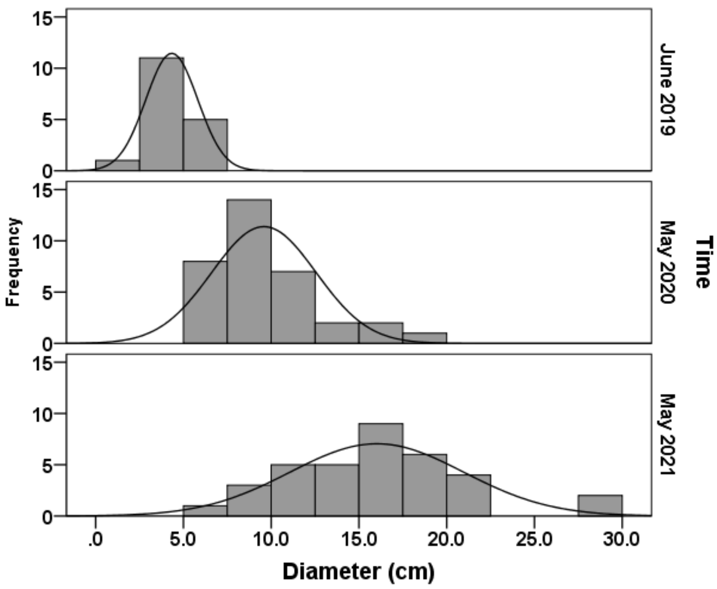



Figure 7.25. Size frequency distributions of mean diameters of *A. millepora* corals in 2019, 2020 and 2021, from Magsaysay reef.

### *May 2018 multi-species larval restoration at Hundred Islands National Park (HINP).*

In May 2018, a multi-species larval enhancement experiment was initiated on degraded fringing reef areas at Quezon Island in the Hundred Islands National Park (HINP). Expansion of the research into HINP was enabled through ACIAR team member meetings and discussions with Mayor Celeste of the City of Alaminos in March 2018, resulting in strong support and approval for the larval restoration research. Subsequent approval was given by the HINP management committee and Protected Management Board of the Department of Environment and Natural Resources in April 2018. The reef substratum adjacent to Quezon Island is composed mainly of consolidated coral rubble and dead coral skeletons resulting from previous blast fishing and coral bleaching events. These reef areas are now protected from direct human impacts and no fishing is allowed, however live coral cover is very low with relatively few surviving corals present on the reef areas.

On 7 May 2018, an estimated total of ~715,000 *Favites colemani* brain coral larvae were collected from larval cultures in the BML hatchery, and combined with ~2.7 million *A. tenuis* larvae collected from *in situ* cultures in larval pools moored near Quezon Island. Larvae were deployed under mesh sheets in three 7x7 m plots and under one 4x20 m mesh sheet on degraded reef areas on Quezon Island. A total of 262 settled spat were recorded on settlement tiles in the 7x7 m plots, of which 143 were *F. colemani* spat and 119 were *A. tenuis* spat. The mean settlement per tile was 17.5 (9.5 for *F. colemani* and 7.9 for *A. tenuis*). In the 4x20 m plot, there were 524 spat recorded (347 *F. colemani* and 202 *A. tenuis*). The average settlement per tile was 42.2 (26.7 *F. colemani* and 15.5 *A. tenuis*). After one year, 51 juvenile *A. tenuis* corals with mean diameter of 3.9 ± 0.9 cm (Figure 7.26) and two small juvenile *F. colemani* colonies were recorded growing in the three 7x7 m plots. In the 4x20 m plot, 16 *A. tenuis* colonies were recorded growing on the natural substrata, with an average mean diameter of 3.2 ± 0.8 cm.

Subsequent monitoring showed an increase in number of restoration colonies inside the plots due to the previous cryptic recruits became visible, especially for the slow growing *F. colemani* recruits. On May 2021, a total of 108 *A. tenuis* colonies were recorded growing on the larval plots. These consisted of 29 *A. tenuis* colonies were found in plot 1, 26 colonies in plot 2, 36 colonies in plot 3, and 17 colonies on the 4 x 20 plot. However, there was observable size differences among the colonies, and during previous monitoring periods we observed several loose colonies were found close to some larger colonies. Due to the shallow reef location of the experimental site, it is possible that occasional strong winds and larger waves during typhoon seasons might have fragmented some of the original colonies. The newly formed “fragmented colonies” were tagged and measured through time. From the total 108 colonies found in May 2021, 27 of these were newly fragmented colonies with sizes ranging from 2-18 cm mean diameter, while the larger original colonies ranged in size from 8-25 cm diameter. Monitoring of reproductive status from broken sections of branches showed that 35 colonies were gravid during the April 2021 spawning period, and the gametes were collected and cultured for another coral restoration intervention experiment. This Quezon Island reef trial confirmed previous experiments and demonstrated that the coral larval restoration method can increase coral cover and aid reef recovery through both sexual and asexual reproduction of newly established coral colonies.

The May 2021 monitoring surveys also showed that a total of 50 *F. colemani* brain coral colonies were found inside the treatment plots. Due to the very small size of colonies, ranging from 1.35 to 8.5 cm mean diameter, colonies were not sampled for sexual reproductive status. However, based on earlier studies conducted on BARC reefs, *F. colemani* can be reproductively mature at a mean diameter of less than 3 cm (Baran et al., in prep). Therefore, it is likely that the larger *F. colemani* colonies were reproductive at three years of age, but subsequent cessation of fieldwork due to COVID-19 restrictions prevented further monitoring of these colonies in 2021.


Figure 7.26. 10 month old juvenile *A. tenuis* colony growing on natural substrata on the larval enhancement plots in Quezon Island reef, HINP (Images: Peter Harrison)

### *2019 larger-scale controlled larval cloud and LarvalBot restoration trials*

During 2019, two 1,250 $m^2$ larger-scale larval restoration field trials were successfully initiated in March and April at Braganza Island HINP (Figure 7.27), and a multi-hectare scale reef trial was completed at Caniogan reef, Anda in April.

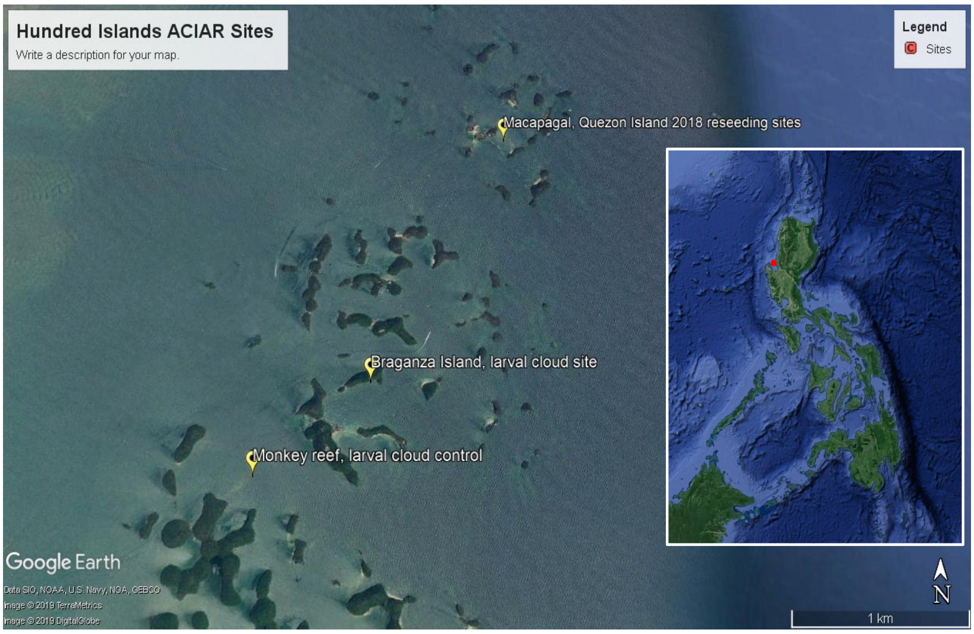



Figure 7.27. Images showing the locations of the 2019 larval enhancement plots in Braganza Island and the control plots in Monkey Island, Hundred Island National Park, and the location of the 2018 Quezon Island larval restoration sites (Source: Google Earth).

### *March 2019 Braganza Island piped larval release*

On 8-10 March 2019, coral spawn was collected in spawn catchers after multispecific *Acropora* spawning events on Magsaysay reef (Section 7A above). The spawn catchers were attached to 5x5 m welded steel frames with a fine mesh net extending about 1.8 m below the sea surface. Spawn samples were transferred by vessels to floating larval culture pools moored near Quezon Island, HINP (Figure 7.5 above) and reared for 4-6 days until larvae were competent to settle. Four 25x50 m plots were demarcated on degraded reef areas at Braganza Island characterised by low live coral cover and low macroalgae and turf algae cover making this reef site suitable for larval enhancement intervention. Two plots were designated as larval enhancement areas and two plots were procedural controls without larvae added (Fig. 7.27). Another two 25x50 m plots were demarcated on Monkey Island reef about 1 km southwest of Braganza Island, and served as experimental controls (Figure 7.27). Twenty biologically conditioned 10x10 cm natural coral skeleton tiles were deployed in each of the plots prior to the introduction of competent larvae.

The larvae were carefully filtered to concentrate them, sampled to quantify abundance, then placed in durable plastic bags. An estimated 134,450 larvae were introduced into the two larval enhancement plots using a new controlled larval cloud supply method, whereby larvae were squirted from the bags through a short hosepipe directly onto the reef areas to increase the chance of successful larval attachment and settlement.

After 24 hours, 18 settled spat were recorded on settlement tiles with an average of 9 ± 1.2 per plot (Figure 7.28). One settled spat was found in one of the procedural control plots adjacent to the larval enhancement plot, and is likely to have been from a larva that drifted onto the control site and settled. No settlement was recorded on tiles from the Monkey Island control plots (Fig. 8).

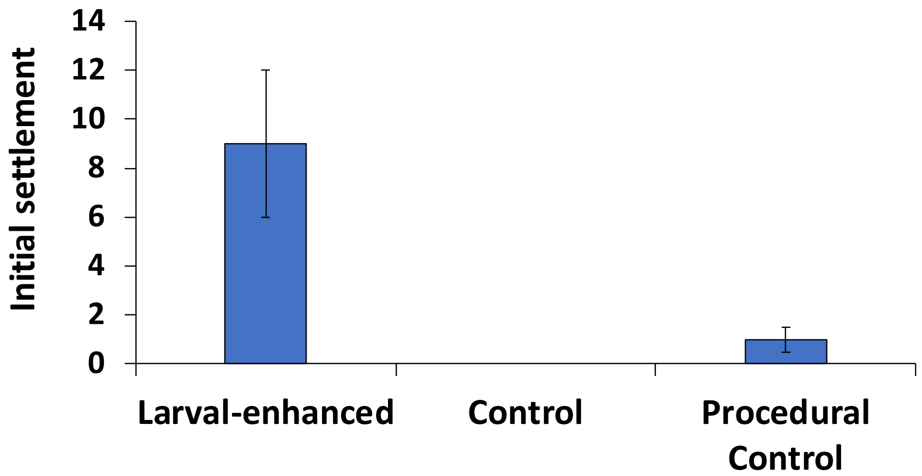



Figure 7.28. Mean (± s.d.) number of settled spat on tiles in Braganza Island larval enhancement plots and procedural control plots and Monkey Island control plots after controlled larval cloud release through pipes in March 2019.

### *April 2019 Braganza Island LarvalBot release*

In April 2019, two reef experiments were completed using *A. tenuis* larvae delivered onto degraded reef areas using an autonomous underwater vehicle (AUV), called LarvalBot. The LarvalBot concept is an adaptation of QUT Professor Matt Dunbabin's RangerBot UAV and was funded by an international grant competition in 2018 won by Harrison and Dunbabin and funded by Tiffany & Co. Foundation through the Great Barrier Reef Foundation, Australia.

Gametes were collected in April 2019 from *in situ* spawning of *A. tenuis* 2013 and 2016 cohort larval restoration colonies from the Magsaysay restoration sites using large spawn cones (Figure 7.29), and from additional colonies that spawned at the BML hatchery. For the hatchery cultured larvae, 11 gravid *A. tenuis* colonies that had been collected in 2018 for spawning and gamete collection and re-attached on Magsaysay reef were collected again four nights before the full moon of April 19, 2019. Another three wild colonies of *A. tenuis* from Magsaysay reef and 14 colonies from Caniogan reef were also collected and temporarily transferred to the BML hatchery. On April 21, four colonies fully spawned, and one colony partially spawned resulting in an estimated 793,000 eggs with 97.3% fertilization. On the night of April 23, a total of 19 colonies spawned and about 1.8 million eggs were collected with 97.1% fertilization.

For the larvae reared from *in situ* collection of gametes from *A. tenuis* restored colonies that spawned, a total of 72 gravid colonies were monitored from the 2013 cohort colonies (dela Cruz and Harrison 2017) and 77 gravid colonies from the 2016 colonies (Harrison et al. 2021). During the dusk crepuscular period around 18:00 hr, spawn cone collectors with a diameter of either 40 or 60 cm were carefully placed over the gravid colonies (Figure 7.29). Following spawning, the floating egg-sperm bundles collected in the jar located at the top of the spawn collector. The jars were then sealed and brought on the surface for the fertilization process. The collected sperm-egg bundles were mixed in a separate fertilization container for the 2013 and 2016 cohorts.

On the spawning night of April 22, 16 colonies from 2013 spawned and 6 colonies from 2016 spawned. Due to bad weather conditions, the egg-sperm bundles were retained in the collection jar and transported by land to the BML hatchery facility for standard laboratory fertilization and culture processes (dela Cruz and Harrison 2017). The estimated number of eggs collected from 2013 colonies was one million, with 48.5 % fertilization, while 260,000 eggs were collected from 2016 colonies withs 55.3% fertilization.

For the major spawning nights on April 23 and 24, the fertilization process was conducted on board the research vessels while gametes were being transported to the larval rearing pools moored near Quezon Island in the Hundred Islands National Park. Total travel time from Magsaysay reef to Hundred Island National Park was approximately 30 min during good weather and calm sea conditions. Excess sperm was removed from the fertilized eggs on a floating pontoon at Quezon Island by gently skimming the embryos off the water surface and transferring them to tubs filled with clean seawater, to avoid problems associated with high sperm densities inducing polyspermy and reduced water quality (Willis et al. 1997, dela Cruz and Harrison 2020a).

On the night of April 23, a total of 23 colonies from the 2013 cohort spawned with 3.2 million eggs collected, with 94.4% fertilization. A total of 319,000 eggs were collected from spawning of a few 2016 colonies, with 77.8% fertilization. All the eggs and embryos were mixed together, divided into two and placed into two of the moored 5 x 5 m larval pool rearers at Quezon Island. On the night of April 24, 42 of the 2016 colonies spawned with a total of 5 million eggs collected, with 91.2% fertilization. A total of 22 of the 2013 colonies spawned, with an estimated 6 million eggs collected, with 90.3% fertilization. The eggs and embryos were transferred by vessels to Quezon Island and cultured in two additional larval rearers separated according to the source colonies (2013 or 2016).

Embryos and larvae were reared for 4-6 days within *in situ* larval pools moored near Quezon Island, and additional larvae from the 22 April spawning night were reared in the BML hatchery.

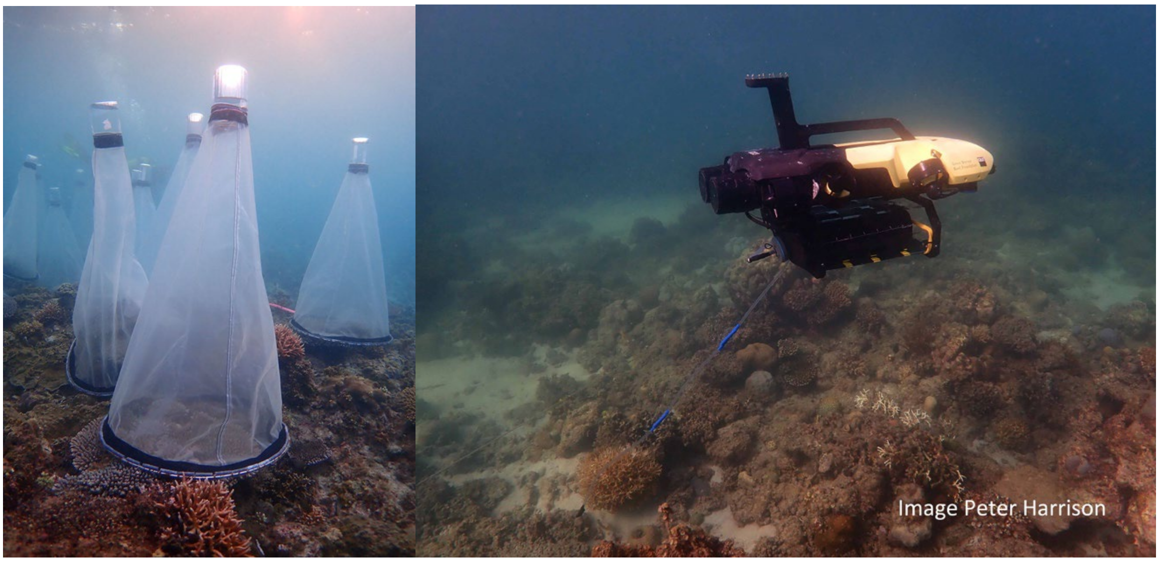



Figure 7.29: Coral spawn collection cones placed over 2013 *A. tenuis* restoration colonies just prior to spawning (left image), and LarvalBot dispersing larvae onto degraded reef sites along GPS controlled pathways in April 2019 (right image) (Images: Peter Harrison).

A pilot study was initiated at Braganza Island on 26 April, using 5-day old larvae reared at the BML hatchery from the April 21 spawning. The larvae were delivered into the 25x50 m plots used as larval enhancement areas in the March 2019 experiment (detailed above), with two plots as controls without larvae added. Twenty biologically conditioned 10 x 10 cm natural coral skeleton tiles were deployed in each of the plots prior to the introduction of larvae. Cultured larvae were carefully filtered to concentrate them, sampled to quantify abundance, then divided equally and placed into durable plastic bags at BML that were supplied with oxygen before being sealed and transported to HINP.

Larvae were added into 8 litre compressible bladders attached under LarvalBot and a small electric pump was used to carefully draw the larvae down a clear hose that trailed behind the UAV as it delivered larvae directly onto the degraded reef areas, along predetermined GPS controlled pathways within each of the two larval enhancement plots (Figure 7.29). Bladders were refilled with larvae when emptied resulting in an estimated 211,000 larvae delivered onto plot one using LarvalBot, and 298,000 larvae delivered onto plot two using LarvalBot. In addition, manual squirting of some remaining excess larvae via the controlled larval cloud bag and pipe method used in March 2019 (described above), was done at plot two. After 24 hours, 410 settled spat were recorded on settlement tiles in larval plots with an average of 205 ± 192SE per plot, whereas no spat were recorded on tiles from control plots (Figure 7.30).

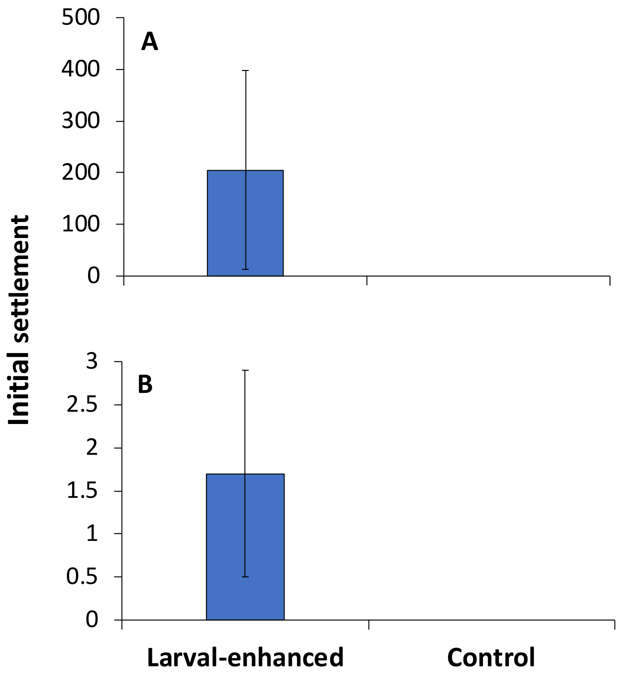



Figure 7.30. Initial mean settlement of *Acropora* spp. spat on tiles monitored 24 hours after larval supply on (A) 1250 m$^2$ plots on Braganza Island reef, Hundred Island National Park on 26 April 2019; and on (B) one-hectare plots on Caniogan reef, Anda on 28 April 2019 supplied with *A. tenuis* larvae.

Monitoring planned for 2020 was impacted by the COVID-19 pandemic and field work and travel restrictions, so monitoring had to be delayed by a year and was done in April 2021. In the Braganza Island plots, a 50 metre line transect was laid out every five metres and a diver swam along the transect while searching for *A. tenuis* colonies covering 2.5 metre reef areas on both the left and right sides of the transects.

A total of 13 *A. tenuis* colonies were found in the two Braganza Island larval plots, and all colonies were recorded growing on the settlement tiles. No visible *A. tenuis* colonies were found on the natural substrata in the two larval plots, and no *A. tenuis* colonies were found in the control plots. The average mean diameter of the colonies was 8.3 ± 1.9 cm, and none of the colonies sampled were gravid. These colonies were below the minimum size of 13 cm mean diameter recorded for *A. tenuis* colonies that had grown large enough to be sexually reproductive after two years from the 2016 larval restoration reef trial (Harrison et al. 2021, Figure 7.13 above).

### *April 2019 Caniogan reef LarvalBot release*

On 28 April, the world's first larger-scale larval restoration trial was initiated using LarvalBot to deliver 4-6 day old *A. tenuis* larvae onto three one hectare plots on Caniogan reef, with three one-hectare plots demarcated as controls (Figure 7.31). Caniogan reef is a subtidal reef located in the southeast section of the Bolinao Anda Reef Complex in the Municipality of Anda. The reef system is located close to the shore and is influenced by inputs of fresh water from a nearby river and periodic poor water quality during the monsoon season (June – October). Earlier surveys recorded mean coral densities of 10 adult colonies per m$^2$ (Baria 2009), however, impacts from flooding and anoxic 'black-water' and high sedimentation events in more recent years killed many of the corals, resulting in reef degradation and poor natural recovery.

Larval cultures at HINP and BML were combined for use in the Caniogan reef trial, and consisted of larvae from the April 22 Magsaysay reef spawning (reared in the BML hatchery), April 23 and 24 Magsaysay reef spawning (reared *in situ* in HINP) and April 23 hatchery spawning (reared in the BML hatchery). Before all the larvae were mixed together in one pool, larvae from each culture period and location were filtered and three subsamples taken using 15 ml tubes. An estimated 295,000 larvae were collected from the April 22 Magsaysay reef spawning, 1.1 million and 670,500 larvae from the April 23 to 24 Magsaysay reef spawning, respectively, and 795,000 larvae from the April 23 hatchery spawning. The larvae were then combined into a large plastic culture pool on a vessel near the Tanduyong Island ACIAR project field camp, subsampled, and carefully transported to Caniogan reef in the research vessel before being added into the 8 litre compressible bladder attached under LarvalBot (Figure 7.29).

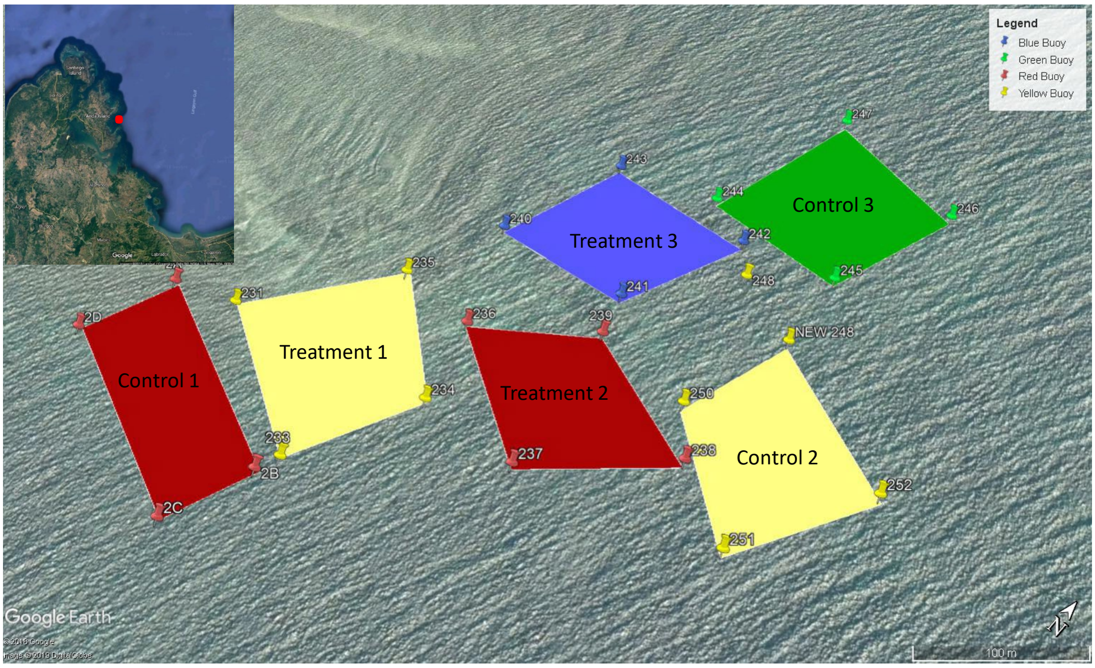



Figure 7.31. Map showing the locations of the six 1 hectare plots in Caniogan reef, Anda, in the northwestern region of the Lingayen Gulf (inset).

Just prior to larval release, a total of thirty biologically conditioned 10x10 cm natural coral skeleton tiles were deployed in each of the plots along the path of the LarvalBot in the larval restoration plots, and similarly in the control plots without cultured larval supply. Larvae were delivered directly onto the degraded reef areas at Caniogan reef along predetermined GPS controlled pathways within each of the three one-hectare larval enhancement plots in the same manner as the pilot study at Braganza Island (described above), and bladders were sequentially refilled with a known volume of larvae after each deployment run on the reef.

Larval Plot 1 had an estimated 757,850 larvae supplied, Larval Plot 2 had an estimated 829,150 larvae supplied, and Larval Plot 3 had an estimated 788,900 larvae supplied. with the larval enhancement trial finishing after dark about 8.30 pm. The remaining excess larvae were transported and released onto the coral garden at Magsaysay reef. Given the large one-hectare reef areas in the larval enhancement plots and relatively very small area of the settlement tiles, it was predicted that low numbers of larval settlers would be detected on the settlement tiles when they were monitored after 24 hours. Subsequently, a total of five settled spat were recorded on settlement tiles with an average of 1.7 ± 1.SE per larval enhancement plot, whereas no settlers were recorded on tiles from control plots (Figure 7.30).

The Caniogan reef plots were also planned to be monitored in 2020 but monitoring was impacted by the COVID-19 pandemic and field work and travel restrictions, so monitoring had to be delayed until April 2021. The large hectare plot sizes make detailed monitoring of coral restoration outcomes difficult, and it is likely that some coral colonies may be present but not readily observed on these large plots. For the April 2021 surveys, divers slowly swam around the plot and attempted to observe the whole hectare area of each of the reef plots. A total of six putative *A. tenuis* colonies were observed growing in two of the larval plots. These colonies had a mean diameter of 10.4 ± 1.07SE cm, and none of the colonies were gravid. This is consistent with the non-reproductive status of the two year old colonies recorded at Braganza Island reef plots, and is also consistent with the minimum 13 cm diameter colony size recorded for the gravid colonies from Magsaysay reef plots in the 2016 larval restoration reef trial (Harrison et al. 2021, Figure 7.13 above).

### *April 2019 Magsaysay reef timing of larval settlement*

This experiment formed part of Kerry Cameron's PhD research (Cameron 2021), and a manuscript has been prepared for publication in 2022.

Scaling up of larval restoration requires improved understanding of optimal times of larval release to promote increased rates of rapid settlement by competent coral larvae. Initial PhD research by Kerry Cameron examining timing of larval settlement at AIMS SeaSim in 2017 indicated that periods around midday had higher rates of settlement compared with earlier and later daylight periods for some *Acropora* larvae (Cameron 2021).

Building on these results, a reef-based experiment was initiated at Magsaysay reef in April 2019, to test peak larval settlement rates during reduced deployment times and periods of the day. Preconditioned settlement tiles were fixed directly to the reef substratum and then temporarily enclosed by spawning cones made of plankton mesh attached to metal frames (see above). Approximately 2000 competent *A. tenuis* larvae were injected under each spawning cone (Figure 7.32).

Figure 7.32. Larvae being injected into spawning cones for 3-9 hours by Kerry Cameron, with one preconditioned settlement tile inside each spawning cone (Source: Cameron 2021).

Three time periods and three times of day were tested, with a total of five larval treatments and a control treatment (tiles with no enclosing nets and no larvae supplied). A total of ten replicates were used for each treatment to increase statistical power. These treatments comprised of three staggered three hour settlement periods, commencing at 9 am, 12 pm or 3 pm, as well as a six hour settlement period commencing at 10.30 am, and a 9 hour settlement period commencing at 9 am.

The day after larval deployment, and allowing time for settled larvae to have completed metamorphosis, the tiles were collected and examined under microscopes at the ACIAR field research station at Tanduyong Island. Highest settlement occurred on the tiles where larvae were released closest to the middle of the day, with the highest number of settlers found on tiles with larvae contained under cones from 12-3 pm. The second highest number of larval settlers were recorded on tiles with larvae contained under cones from 10.30 am to 4.30 pm, also encompassing the midday period. No larval settlement occurred on the control tiles, indicating low natural larval supply during the experimental period.

A conceptual diagram illustrating the experimental design and mean settlement per treatment is shown in Figure 7.33. These results are consistent with the previous experiment conducted at AIMS SeaSim in 2017, which resulted in highest rates of settlement around midday (Cameron 2021). This result is highly relevant to field applications of coral larval restoration methods using enhanced larval supply, where creating a tight seal with containment nets against the natural reef substratum is difficult. Selecting time periods for larval deployment when competent larvae are most likely to settle quickly could maximise settlement rates on target reef sites. This issue was further highlighted by the results from this experiment, which showed that significantly less larval settlement occurred in the nine hour treatment than in the midday three hour treatment, even though the nine hour period encompassed midday and all of the other treatment periods. This suggests that many larvae had drifted out of the nets due to the irregular reef topography preventing strong seals of the base of the spawn cone nets against the reef, before the period when larvae were most likely to be actively settling.

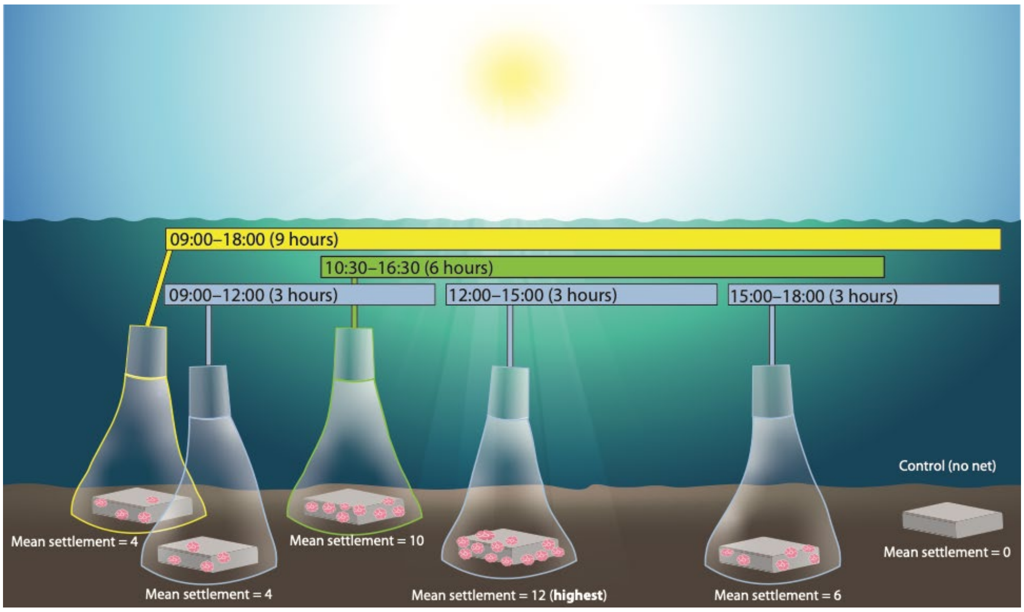



Figure 7.33. Visual representation of the experimental design and key results. Larval containment periods are indicated in the coloured boxes and correspond to the coloured outline of each containment net. Mean larval settlement for the 10 tiles in each treatment is indicated below the tiles. Note that the relative size of tiles, nets and settled larvae are not to scale. (Source: Cameron 2021).

### *Effect of fish farm effluent on the settlement and survivorship of cultured coral larvae 2021*

The planned activities for Objective 2 included an experiment to test the ability of coral larvae to settle and survive along a gradient of higher quality reef sites to more degraded reef areas near Bolinao that are subject to chronic stressors from fish-farming and poorer water quality. This experiment was designed to quantify the impacts of reduced environmental conditions on settlement and survival of reef corals in chronically polluted reef areas, and therefore determine which types of badly degraded reef systems might not be 'recoverable' (sensu Harrison et al. 2021) using current coral larval restoration methods.

The intensive mariculture of *Chanos chanos* (milk fish) and current fish farming practices in the coastal town of Bolinao significantly increase organic matter and nutrient loading, mainly from unconsumed fish feed and faecal material in the marine environment (Holmer et al. 2003, San Diego-McGlone et al. 2008). This has resulted in the deterioration of reef water quality causing negative impacts on the marine environment and important marine organisms including corals (Licuanan et al. 2017). During the past decade, there was a steep decline in coral cover recorded around Bolinao reef areas coinciding with the expansion of the mariculture activities (Licuanan et al. 2019). Previous studies have shown detrimental effects on the survivorship of coral juveniles, and reduced settlement of some brooding coral larvae that are likely to significantly reduce the recovery and maintenance of coral population in these reef areas (Villanueva et al. 2005, Quimpo et al. 2020). Therefore, this pollution gradient experiment was designed to investigate the effect of fish farm effluent on larval settlement and survivorship at different reef locations at varying distances from the polluted mariculture area, using larvae of the broadcast spawning coral *Acropora tenuis*.

Five sites with varying distances to the mariculture area in Bolinao were selected (Figure 7.34). The Tomasa point reef is the closest to the mariculture area, Malilnep reef is 10 km north away from fish farm area, and Lucero reef is located in between the Tomasa and Malilnep reefs. To the east, the Cangaluyan reef is located approximately 9 km away from the mariculture area, and Magsaysay reef is about 20 km southeast, and these reefs served as the control site and source site of corals used for the experiment. Surface water flow models show water enters from Cangaluyan reef to the mariculture area in Tomasa reef and flows out towards Lucero and Malilnep reef during the dry season in the Philippines.

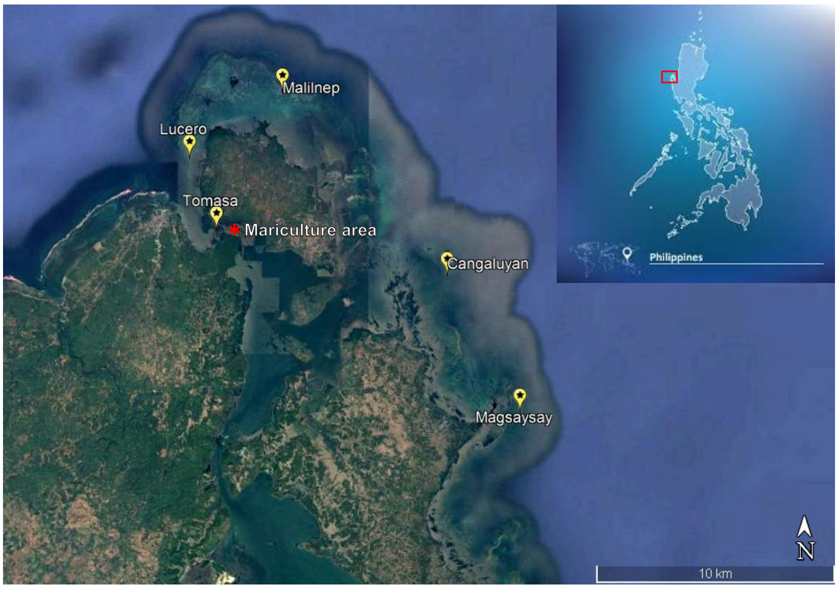



Figure 7.34. Locations of reef areas in relation to the mariculture area for the larval settlement experiment using *A. tenuis* larvae in 2021.

At each reef location, twenty 5x5 cm by 0.5 cm thick fibre-cement tiles were deployed using a stainless steel baseplate tile attachment system (after Mundy 2000) three weeks before the expected April coral spawning period. This deployment allowed for the tiles to be biologically conditioned and acquire biofilms necessary for larvae to settle (Webster et al. 2004, Randall et al. 2020). On the night of April 24, 2021 (3 nights before full moon), at 1820 hr, 8-year-old *Acropora tenuis* colonies from the 2013 larval enhancement experiment at Magsaysay reef (dela Cruz and Harrison 2017) spawned. Coral egg-sperm bundles were collected *in situ* from 16 colonies using spawn cone mesh collectors placed on top of the colonies. After spawning, the jars containing coral gametes were transported to the BML hatchery facility for larval culture following the standard procedure (dela Cruz and Harrison 2017). In total, approximately 5.1 million eggs were collected with 80% fertilization. After 6 days, 75 sets of 500 competent larvae were manually counted, and each set of 500 larvae was placed in 60 ml sterilized syringes.

Prior to the larval release, 15 of the tiles at each location were placed in small settlement enclosure systems with plankton mesh windows to allow water exchange through the chamber (after Cameron and Harrison 2020). Larvae were slowly released from the syringes through a resealable hole located on top of each enclosure (Figure 7.35). After three days settlement period, tiles were collected, and larval settlement was counted under microscopes, and the locations of settlers were mapped onto monitoring sheets. Tiles were then redeployed to their original locations and sites for further monitoring.

Figure 7.35. Settlement tile inside the settlement chamber attached to the reef substrata.

The remaining five tiles in each reef location were used for biofilm analysis to determine differences in the microbial community among reef locations, and relate the biofilm patterns to the settlement of coral larvae. Settlement tiles were collected and gently washed with UV-filtered seawater. The biofilm materials were scraped off into sterile cryogenic vials using sterile blades (n = 4 slides per site) and stored using RNAlater® RNA Stabilization Solution (AmbionTM) until further processing. Genomic DNA will be extracted using Qiagen DNeasy PowerSoil® following the manufacturer's standard protocol. DNA concentrations will be quantified and checked for purity using Nanodrop 2000C. DNA samples will be sent to Macrogen, South Korea, for library preparation and sequencing on the Illumina MiSeq platform with 300 bp paired end reads. The V3-V4 hypervariable region of the 16S rRNA gene will be sequenced using primer set primers Bakt_341F (5′-CCTACGGGNGGCWGCAG-3′) and Bakt_805R (5′-GACTACHVGGGTATCTAATCC-3′) (Herlemann et al. 2011).

Raw sequences from 16S rRNA will be processed and analyzed using Quantitative Insights Into Microbial Ecology (QIIME2) (Bolyen et al. 2019). DADA2 (Callahan et al. 2016) package will be used to remove low quality reads and chimeric sequences. 16S rRNA sequence reads will be trimmed. Naïve Bayes sequence classifiers for 16S rRNA will be trained separately using SILVA release 132 reference database (Quast et. al., 2013). Amplicon Sequence Variant (ASV) sequences will be then taxonomically classified based on the SILVA release 132 reference database (Quast et al. 2012) based on 97% similarity using the trained classifier. 16S rRNA sequences classified as belonging to chloroplasts and mitochondria will be removed from the dataset.

Alpha and beta-diversity of the bacterial ASVs of the marine biofilms will be assessed. ASV counts will be rarefied to the smallest sample size in calculating alpha-diversity metrics. Alpha diversity indices including observed ASVs, Chao 1, Shannon-Weiner, and Inverse Simpson index of diversity, will be calculated using the Phyloseq package (McMurdie and Holmes 2013).

Initial larval settlement of *A. tenuis* on tiles was lowest in Tomasa reef, which is the reef closest to the mariculture area, followed by Cangaluyan reef (Figure 7.36). The more distant reefs of Malilnep, Lucero and Magsaysay had higher mean larval settlement than Tomasa reef. This indicates that environmental conditions and water quality in Tomasa reef are less suitable for *A. tenuis* larval settlement than on less polluted reefs further from the mariculture activities. After 1 month, the expected decline in survivorship of recruits in all the sites was recorded. However, higher survivorship was recorded on reef sites further from the mariculture area (Figure 7.36), indicating a gradient effect of environmental conditions on post-settlement survival.

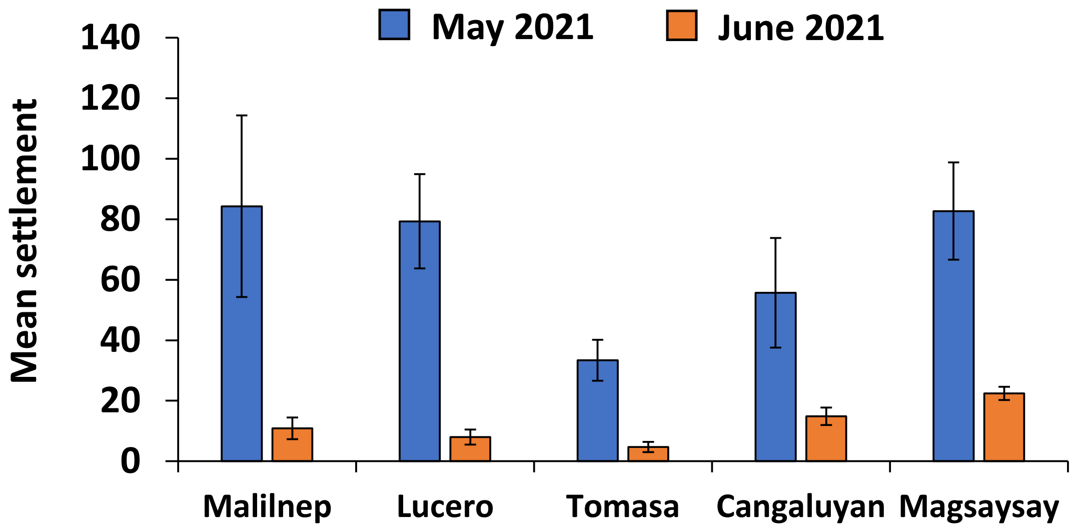



Figure 7.36. Initial mean settlement and survivorship after one month of *A. tenuis* larvae in different reef location.

### *Longer-term monitoring of 2013 and 2014 Larval Restoration Pilot Studies*

In addition to the extensive larval restoration trials initiated during this ACIAR project (described above), this project also supported ongoing monitoring and publication of the longer-term outcomes from Dexter dela Cruz's pilot studies initiated during his PhD (dela Cruz 2019), which were supported by the initial ACIAR Project SRA FIS/2011031 (Harrison et al. 2016). The main results and more recent outcomes from those two pilot studies are presented below.

### *2013 Acropora tenuis larval restoration reef trial*

The results from the first *A. tenuis* larval enhancement experiment on Magsaysay reef that was initiated in 2013 by PhD student Dexter dela Cruz were published in 2017.

dela Cruz, D. and Harrison, P.L. (2017). Enhanced larval supply and recruitment can replenish reef corals on degraded reefs. **Scientific Reports 7**: 13985 https://www.nature.com/articles/s41598-017-14546-y

Abstract

Foundation species have essential roles in ecosystems but are often highly susceptible to disturbances. Reef-building corals are foundation species on reefs however increasing anthropogenic and natural disturbances are eroding coral community resilience leading to declining reef ecosystem function and status in many regions. Successful reproduction and recruitment is essential for restoring coral populations but recruitment-limitation can constrain recovery. We supplied ~400,000 *Acropora tenuis* larvae in fine-mesh enclosures on each of four larval-enhancement sites to significantly increase larval settlement and recruitment on degraded reef areas in the northwestern Philippines. Initial settlement was high and juvenile survivorship began stabilising after five months, with recruits becoming visible at nine months. After three years a mean of 2.3 $m^{-2}$ colonies survived on available reef substrata within each larval-enhancement site. Most colonies grew rapidly and spawned successfully at three years, thereby quickly re-establishing a breeding population. In contrast, natural recruitment failed to produce any new visible *A. tenuis* colonies at these sites. These results demonstrate that mass settlement of coral larvae can rapidly enhance recruitment and coral recovery on degraded but recoverable reef areas, and provides an important option for active reef restoration where key threats are managed but larval supply and recruitment success are limiting.

Updates

Subsequent annual monitoring of the longer-term outcomes from this 2013 study showed high ongoing survival and growth of colonies at the degraded Magsaysay Reef site through to 2019. Colony size ranged up to 50.6 cm mean diameter (overall colony mean diameter = 27.8 ± 1.8 SE) in February 2018, and colonies increasingly dominated the coral assemblages in the larval restoration plots (Figure 7.37). Surveys in 2019 showed that 50 of the six-year old *A. tenuis* colonies were growing on the larval restoration plots, with sizes ranging from 17 cm to half a metre in mean diameter. In contrast, there have been no new natural *A. tenuis* recruits recorded in either the larval plots or the control plots during subsequent monitoring surveys. In addition, the lack of natural recovery of coral communities in the control plots since the baseline surveys in 2013 indicates that the Magsaysay reef system continues to have limited natural larval supply that is not sufficient for reef recovery without active intervention (Figure 7.38).


Figure 7.37. Six year old *A. tenuis* colonies dominating the reef areas in one of the 2013 larval enhancement plots, taken in March 2019 (Image: Peter Harrison).

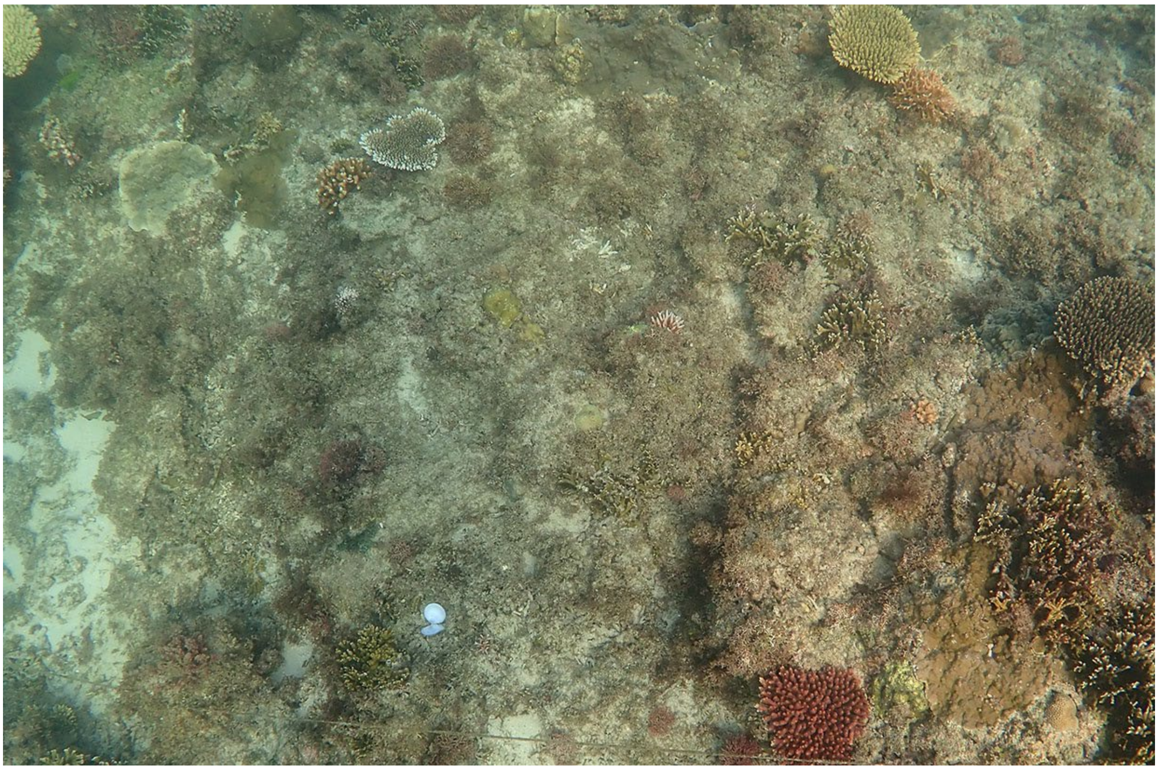


Figure 7.38. Image of part of a control plot in March 2019 taken six years after the 2013 larval restoration experiment showing very low coral cover compared with larval enhancement sites, indicating that the reef system is still larval limited (Image: Peter Harrison).

Of particular significance was the establishment of a new breeding population from the 2013 experiment. In 2016 after three years growth, the majority of the 2013 cohort colonies were larger than 12.5 cm mean diameter and were sexually reproductive (dela Cruz and Harrison 2017). All of the larger colonies spawned after the April 2016 full moon for the first time, and gametes were viable enabling 1.6 million larvae to be reared for the 2016 *A. tenuis* larval restoration experiment (Harrison et al. 2021, see above). More of the colonies spawned in 2017 and recent years, and ongoing monitoring indicates that most colonies are now large enough to be sexually reproductive. These colonies spawned again for the fourth consecutive year after the April 2019 full moon (Figure 7.39), and are now contributing significantly to larval production and potential settlement on nearby reefs in the Lingayen Gulf. These outcomes are globally significant as it was the first time that a breeding population of *Acropora* reef corals was re-established on a degraded reef system using mass larval enhancement, with the lifecycle closed within three years (dela Cruz and Harrison 2017).

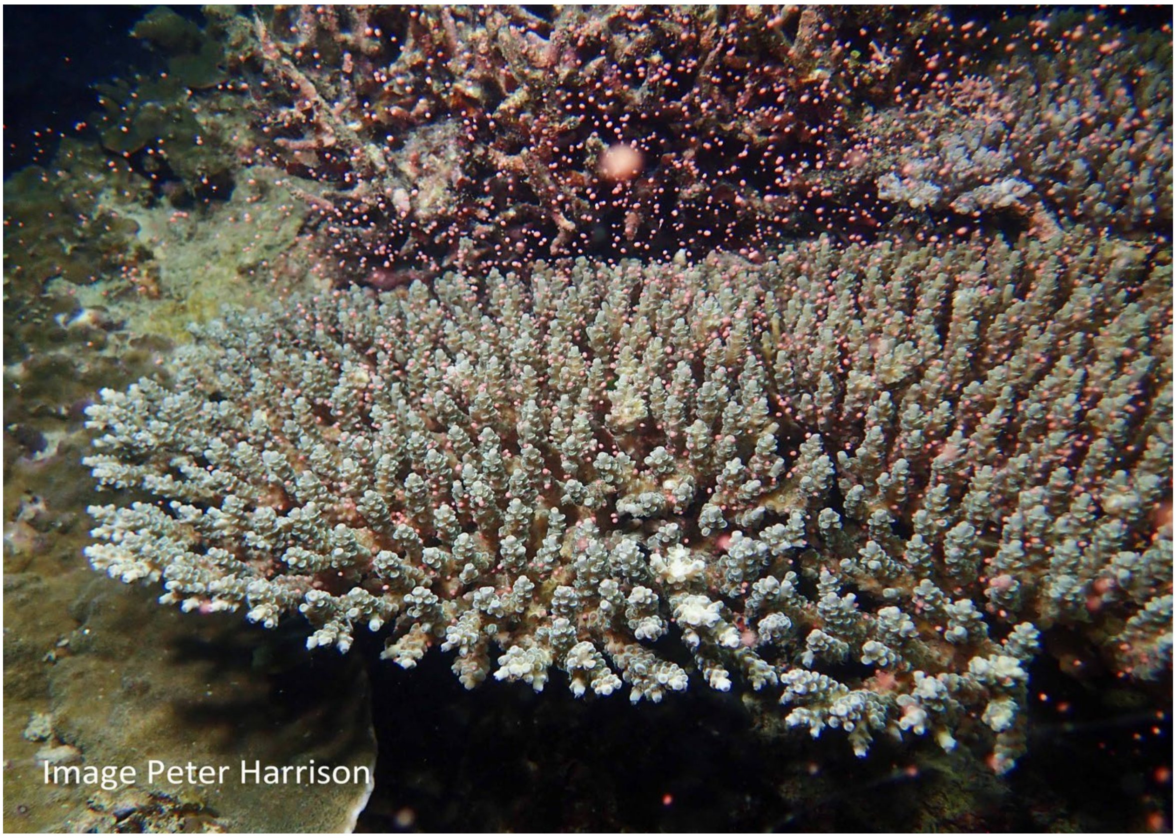



Figure 7.39. Six year old *A. tenuis* colonies growing in larval enhancement plots on Magsaysay reef spawning egg-sperm bundles on 24 April 2019 (Images: Peter Harrison).

### *2014 Acropora loripes larval restoration reef trial*

The results from the *A. loripes* larval enhancement experiment on Magsaysay reef that began in 2014 by PhD student Dexter dela Cruz were published in 2020.

dela Cruz, D. and Harrison, P.L. (2020). Enhancing coral recruitment through assisted mass settlement of cultured coral larvae. **PloS ONE, 0242847** https://doi.org/10.1371/

Abstract

The escalating rate at which coral communities are declining globally requires urgent intervention and new approaches to reef management to reduce and halt further coral

loss. For reef systems with limited natural larval supply, the introduction of large numbers of competent coral larvae directly to natural reef substrata provides a potentially useful approach to replenish adult coral populations. While few experiments have tested this approach, only one experiment has demonstrated its long-term success to date. Given the differences in life-history traits among corals, and different sensitivities of larvae to abiotic and biotic factors, coupled with the dynamic nature of post-settlement survivorship and recruitment processes, trials of the larval enhancement technique with larvae of different coral species are needed to test the broader applicability and viability of this approach.

Accordingly, in this paper we examine the applicability of the larval enhancement technique to restore a population of *Acropora loripes* in the Bolinao-Anda Reef Complex, Pangasinan, northwestern Philippines. Larvae were cultured ex situ following spawning of collected *A. loripes* colonies in June 2014. Competent larvae were transported to degraded reef areas and approximately 300,000 larvae were introduced in each of three 6 × 4 m plots directly on the reef. Fine mesh enclosures retained the larvae inside each treatment plot for five days. Three adjacent 6 × 4 m plots that served as controls were also covered with mesh enclosures, but no larvae were introduced. Each plot contained ten 10 × 10 cm conditioned settlement tiles cut from dead tabulate *Acropora* that were used to quantify initial larval settlement. After allowing larval settlement for five days, mean settlement on tiles from the larval enhancement plots that were monitored under stereomicroscopes was significantly higher (27.8 ± 6.7 spat per tile) than in control plots, in which not a single recruit was recorded.

Post-settlement survivorship and growth of spat and coral recruits on tiles and reef substrata inside the experimental plots were monitored periodically for 35 months. After 35 months, the mean size of each of the remaining 47 *A. loripes* coral colonies surviving on the reef substrata was 438.1 ± 5.4 $cm^3$, with a mean diameter of 7.9 ± 0.6 cm. The average production cost for each of the surviving *A. loripes* colonies at 35 months was USD 35.20. These colonies are expected to spawn and contribute to the natural larval pool when they become reproductively mature, thereby enhancing natural coral recovery in the area. This study demonstrates that mass coral larval enhancement can be successfully used for restoring populations of coral species with different life-history traits, and the techniques can rapidly increase larval recruitment rates on degraded reef areas, hence catalysing the regeneration of declining coral populations.

<u>Updates</u>

Most of the *A. loripes* colonies continued to survive and grow on Magsaysay reef plots during 2018 and 2019 (Figure 7.40), but monitoring in June 2019 showed that none of the colonies were sexually reproductive. Ongoing COVID impacts on planned fieldwork prevented further monitoring during the likely reproductive period in 2020 and 2021.

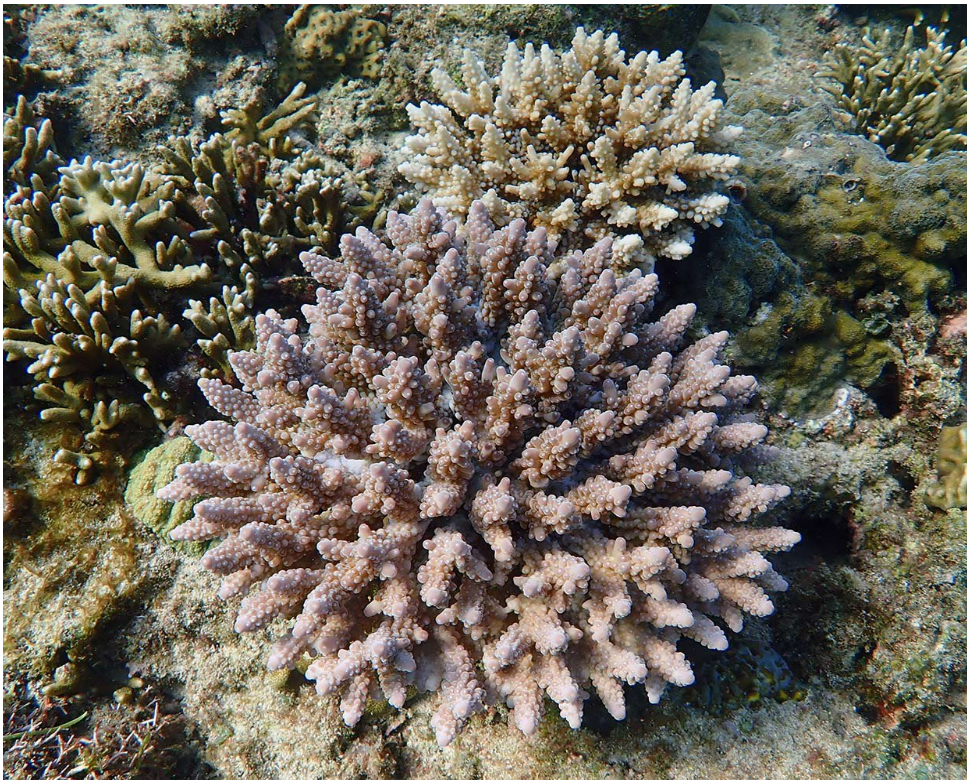


Figure 7.40. Colonies of *Acropora* cf. *loripes* grown from settled larva in June 2014 photographed in March 2018 at age 3 years 9 months (Image: Peter Harrison).

## *Summary of larval restoration research outcomes*

The results of the many larval enhancement field trials from these ACIAR projects clearly demonstrate that coral larval settlement and recruitment can be significantly enhanced compared with natural background levels using mass larval supply and settlement to rapidly initiate coral population restoration and fast growth, even on degraded reef areas. The natural loss of juvenile coral recruits after larval settlement can be offset through the use of increased concentrations of competent coral larvae to substantially increase initial settlement rates and recruitment overall (Harrison 2021, Harrison et al. 2021). Therefore, mass larval enhancement is a viable and effective active reef restoration option for initiating foundation coral population recovery where environmental conditions are suitable for reef corals to survive and grow, but natural larval supply and recruitment are limited. Furthermore, the demonstrated success of these relatively low-cost mass larval settlement techniques will enable this approach to be used in initiating coral restoration at larger scales in a wide range of other degraded but recoverable reef areas around the world, including elsewhere in the Philippines. This approach is also applicable in other regions where most reefs are under increasing threat or already seriously degraded.

Similar larval restoration experiments have now been successfully completed on the Great Barrier Reef (GBR) led by Harrison with colleagues including Dr Dexter dela Cruz and other HDR students supported by this ACIAR project. Therefore, the ACIAR project outcomes have resulted in significant project uptake and further development of methods and equipment in Australia. A small-scale larval restoration project was initiated in 2016 at Heron Island Reef in the southern Great Barrier Reef, supported by philanthropic funds through the Great Barrier Reef Foundation, and the larger restored *Acropora* colonies were confirmed to be reproductive in 2021 (Harrison et al. in prep). In 2017, larger scale larval supply to degraded reef patches was trialed using a new method at reef sites with low coral cover at Heron Island Reef and One Tree Island reef in the southern Great Barrier Reef, supported by funding through Great Barrier Reef Marine Park Authority (GBRMPA), and logistical support from Queensland Parks and Wildlife Service (QPWS) marine operations team (Harrison 2018). These outcomes resulted in successful Government grant applications for further larval restoration projects on the northern GBR on reefs off Cairns in 2018 and 2019, led by Harrison with colleagues from JCU and UTS (Harrison et al. 2019, 2020). These projects confirmed that enhanced larval supply results in significantly higher larval settlement on larval restoration plots compared with control plots, and the research has been highlighted in successful coordinated media campaigns resulting in substantial national and international interest in the ACIAR and GBR project outcomes.

More recently, a larger-scale GBR coral larval restoration project (Moving Corals) has been funded through the Australian Government GBRF Reef Restoration and Adaptation Program, co-led by Harrison and Dr Chris Doropoulos from CSIRO. The coral larval restoration method has also been trialed on reefs in the southern Caribbean in collaboration with researchers from SECORE, and will also be trialed in new international reef restoration projects in 2022 and beyond.

## Section 7C: Objectives 2 and 3 Coral larval laboratory experiments

Substantial research has also been completed in laboratory based experiments with coral larvae as part of Objectives 2 and 3, which has supported research by HDR students.

### *Aggregated larval settlement research*

With support from this ACIAR project, Charlon Ligson investigated the performance of early *Acropora verweyi* coral recruits in varying group size levels (Figure 7.41), as part of his UP Masters research (Ligson 2021) and project work.

A key project objective is to improve the survival and growth of coral recruits resulting from sexual propagation. The early life-history stages of coral recruits suffer from significant mortality due to multiple factors, which represents a bottleneck in coral recruitment and reef restoration (Bostrom-Einarsson et al. 2020, Randall et al. 2020). Hence, there is a need to better understand and improve the post-settlement survival and growth of coral juveniles for larger-scale coral and fish habitat restoration.

One of the interesting attributes of coral spat is the tendency of coral larvae to settle in aggregations, especially where those coral larvae are reared and settled in higher densities (dela Cruz and Harrison 2017, Cameron and Harrison 2020, Harrison et al. 2021). Coral larvae that settle in aggregates may fuse to form coral spat that are larger than solitary spat. Larger coral spat may provide advantages for survival and growth and reach size-escape thresholds sooner (Raymundo and Mapa 2004). However, the performance of coral spat in different group sizes, especially during the early post-settlement phase, has not been fully investigated in broadcast spawning corals that dominate tropical coral reefs.

The research examined the survival and growth rate of coral spat, with four group size levels: solitary spat, 2, 3-5, 6-9, and 10-28, and outcomes were monitoring over 21 weeks post-settlement. The highest survival was detected in the 6-9 aggregated spat group, followed by the 3-5 and 10-28 groups, with lower survival in the 2-polyp group and the solitary spat (Figure 7.42). Overall, 7.4% of the 338 coral spat reared in *ex situ* BML hatchery conditions survived up to the last 21 weeks of monitoring.


Figure 7.41. Charlon Ligson, ACIAR student researcher, examined how varying group sizes influence the survival and growth of *Acropora verweyi* early coral recruits. Charlon collected coral gamete bundles (left photo) after spawning and reared larvae for settlement experiments. One month-old *A. verweyi* coral recruits settled on a tagged rubble piece for monitoring (right photo). (Source: C. Ligson)

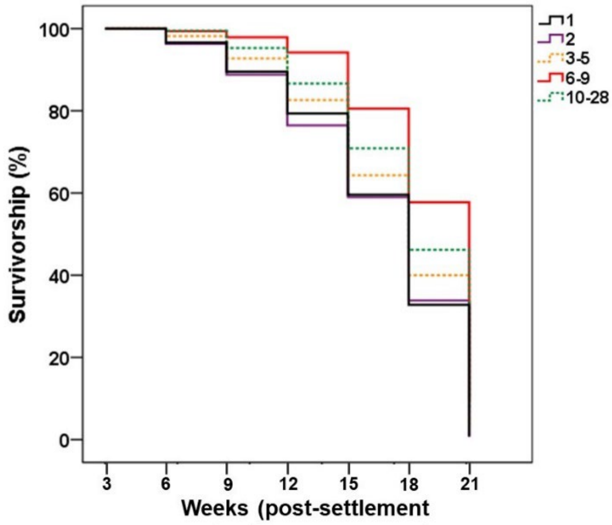



Figure 7.42. Survivorship of *Acropora verweyi* coral individuals (N=338) at varying group size levels over 21 weeks post-settlement. (Source: Ligson 2021)

Growth rates were significantly higher in the 6-9 and 10-28 group sizes (~0.016 $mm^2$/week and ~0.042 $mm^2$/week, respectively) than in smaller group sizes (~0.002 to ~0.007 $mm^2$/week). In addition, the mean surface area of solitary spat (~0.35 $mm^2$) was two- to ten-fold smaller than spat in larger aggregations (Figure 7.43). The results revealed that aggregations of at least six *A. verweyi* spat performed better in terms of survival and growth rate than smaller aggregations and solitary polyps, at least in the first few months after settlement. Hence, larger aggregations may enhance survival of spat during the critical period of early post-settlement. These results suggest that aggregated settlement of *A. verweyi* coral spat provides potential benefits for methods that use coral larvae as material for reef restoration, however additional research is needed to verify these trends for other species used for larval restoration.

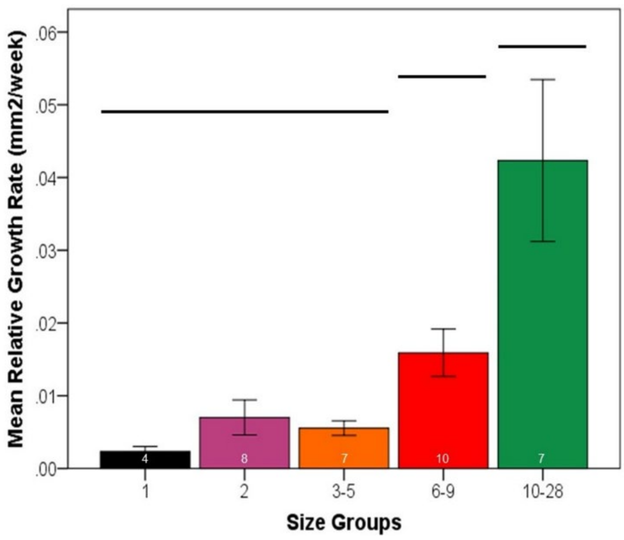



Figure 7.43. Mean relative growth rate (mm$^2$/week) of *Acropora verweyi* coral individuals of varying group size levels at 15 weeks post-settlement. Group sizes joined by the same horizontal black line are not statistically different (Mann-Whitney U test, $p > 0.05$). Error bars are standard error of the means. (Source: Ligson 2021)

### *Settlement surface microtopography and biological conditioning effects*

Settlement surface microtopography effects

Katy Horan's Honours research experiments (Horan 2017) examined the effects of settlement surface microtopography and biological conditioning on coral larval settlement and survival. The experiments were done at the BML hatchery facility, supported by this project.

Sets of 3D settlement tiles were printed from computer aided drawing (CAD) designs and 3D scans of *Platygyra* brain coral and *Turbinaria* coral skeletons to mimic natural reef features. Experiments used six different tile designs (control flat surface, large indents, small indents, vertical grooves, brain coral and *Turbinaria* skeleton) each printed in PLA and ABS (Figure 7.44). One set of each of the six PLA and ABS tiles were placed into 40 litre plastic tubs containing clean filtered seawater, each with 1,000 *Favites colemani* brain coral larvae that had been reared from colonies that spawned at BML in April 2016.

Settlement patterns after the five-day settlement period showed that microtopography significantly influenced settlement preferences of *F. colemani* brain coral larvae, but there were no significantly different preferences for settlement between the two types of plastic tiles (two way ANOVA microtopography design $p = 0.010$, $F_{(48,59)} = 3.42$; material $p = 0.246$, $F_{(48,59)}=1.37$). Most larvae strongly preferred to settle in cryptic indentations with very few larvae settling on exposed surfaces on tiles on either plastic (two way ANOVA $p = 8.29E^{-11}$, $F_{(116,119)} = 3.922$, *post hoc* Tukey HSD PLA $p = 0.00015$; ABS $p = 0.00005$). Settlement was 269% and 378% higher in cryptic locations compared to exposed locations on PLA and ABS tiles, respectively. Highest mean larval settlement occurred in small 2 mm indents on ABS tiles 54.0 ± 15.90 and PLA tiles 58.6 ± 5.99, and settlement rates were lowest on flat control tile surfaces 12.6 ± 5.90 (ABS) and 13.6 ± 5.87 (Tukey HSD $p < 0.05$) (Figure 7.44).

These results confirm that the two commonly used 3D printing plastics PLA and ABS are not toxic to *F. colemani* larvae and that settlement rates can be significantly increased when cryptic microhabitats are provided. Therefore, 3D printing technology can be used to produce complex settlement surfaces that enhance larval settlement and could potentially lead to increased coral recruitment for more effective reef restoration in future. Further development of 3D printing methods should enable calcium carbonate based settlement device structures to be developed that could be used for future reef trials.

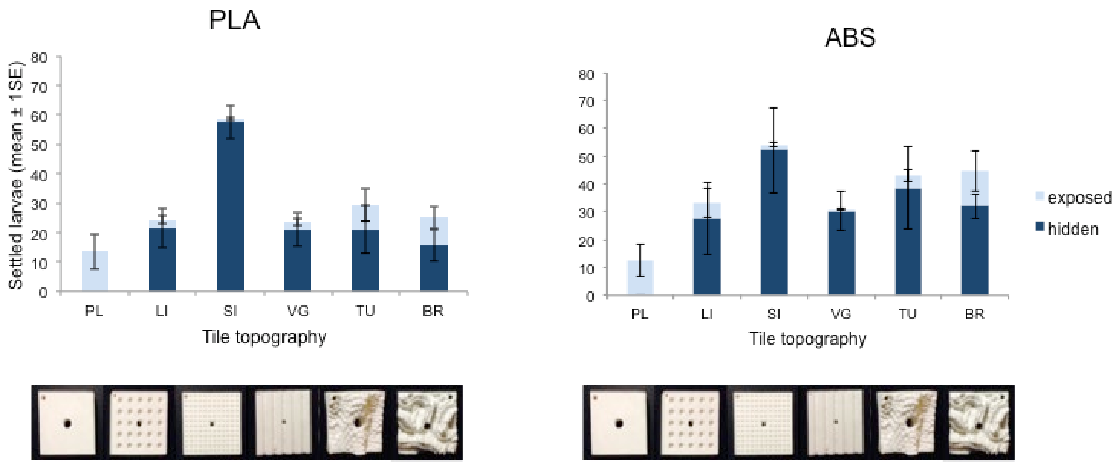



Figure 7.44: Numbers of *F. colemani* larvae (mean ± 1 SE, *n* = 5) settled on substrata 3D printed in PLA or ABS, using six designs (from left to right: PL, plain; LI, large indent; SI, small indent; VG, vertical groove; TU, *Turbinaria*; BR, brain coral). Data show larval settlement in exposed locations or hidden locations on each tile (Images and data from Horan 2017).

## Biological conditioning effects

Settlement rates and preferences of *A. gemmifera* larvae were investigated using 10x10 cm tiles cut from dead *Acropora* coral skeletons (after dela Cruz and Harrison 2017), and replicates of these natural tiles that were 3D scanned and 3D printed from PLA and ABS plastics (Figure 7.45). Five replicate groups of tiles were conditioned for four weeks in one of two locations (Magsaysay reef or the BML hatchery) prior to the experiment, hence the effects of initial conditioning location were also analysed.

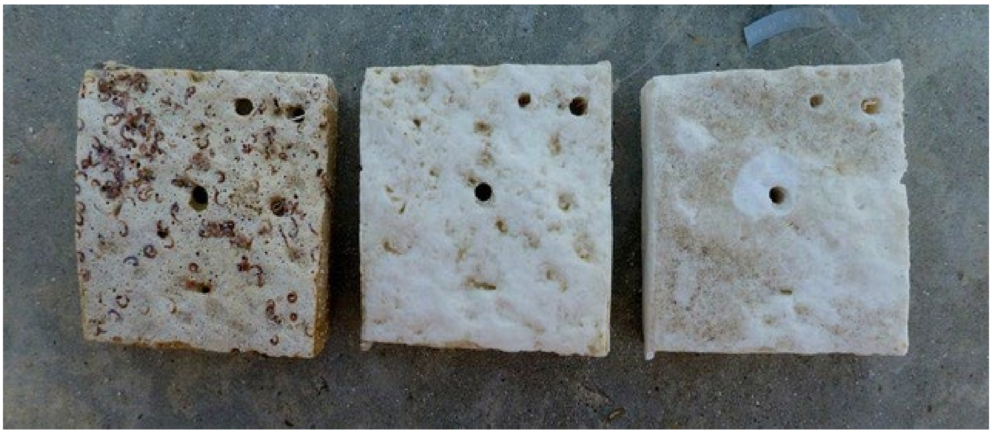


Figure 7.45. Examples of a settlement tile cut from dead plate *Acropora* spp. (left) and 3D printed replicas from PLA (middle) and ABS (right). (Image: Katy Horan).

Approximately 1,000 *A. gemmifera* larvae were added to each experimental tank containing replicate sets of coral skeleton, PLA and ABS tiles. Larval settlement was monitored after three days, and post-settlement survival was monitored after nine months.

Larvae settled on 3D printed tiles in similar numbers to those on reef-conditioned coral tiles and there was no preference for either plastic material. Highest mean settlement rates were recorded on hatchery-conditioned coral tiles (Figure 7.46).

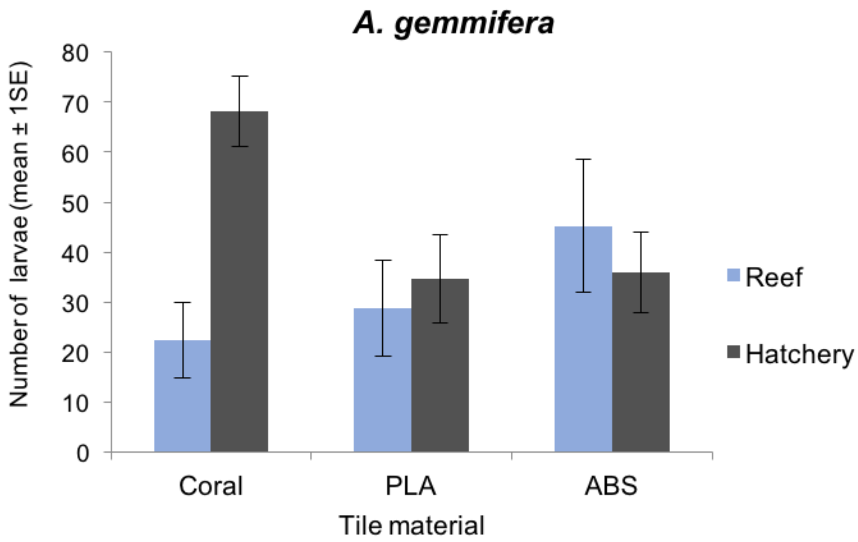



Figure 7.46. Mean number of *A. gemmifera* larvae (± SE, *n*=5) settled on tiles cut from dead plate coral, and replicas 3D printed in PLA or ABS, conditioned for four 4 weeks at Magsaysay reef (reef) or the BML hatchery. (Source: Horan 2017).

However, monitoring after nine months revealed nearly 100% mortality of juveniles from the hatchery-conditioned coral tiles (Figure 7.47). In contrast, a clear benefit of the plastic tiles for post-settlement survival was observed in the hatchery-conditioned group, with ~30% of settled larvae surviving to nine months on the plastics, compared to <2% survival on the coral tiles (Figure 7.47). These data also show that initial conditioning location can significantly affect post-settlement survival with <8% survival on reef-conditioned substrata regardless of the type of settlement tile material. The results of this experiment have important implications for designing coral larval settlement surfaces and monitoring recruitment, and indicate that the tile conditioning location can significantly affect larval settlement and juvenile survival.

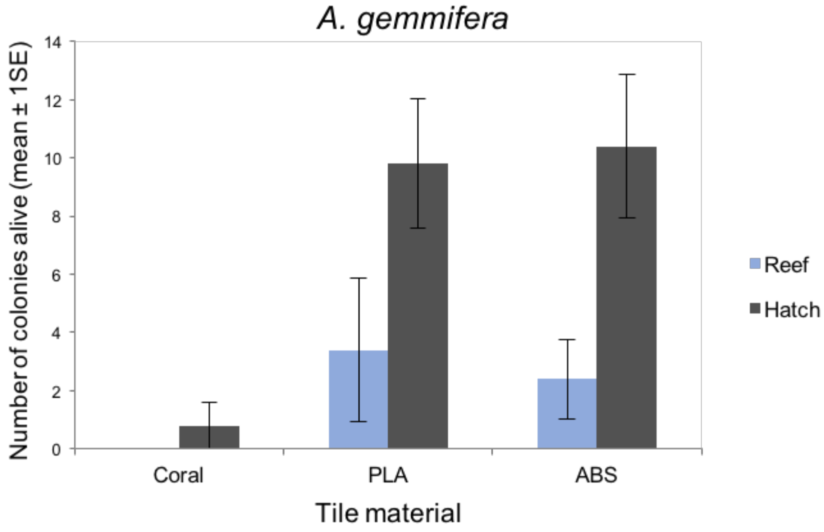



Figure 7.47. Mean number of *A. gemmifera* juveniles (± SE, *n*=5) alive on tiles cut from dead plate coral, and replicas 3D printed in PLA or ABS, after nine months monitoring. (Source: Horan 2017).

### *Larval conditioning and microalgal symbiont experiments*

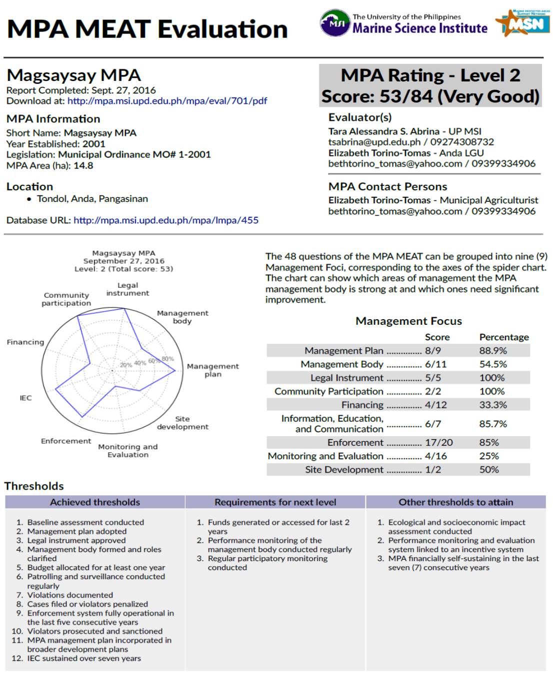
Experiments on larval feeding, and supplying larvae with Symbiodiniaceae microalgae, were completed as part of Nadine Boulotte's PhD research (Boulotte 2021), supported by this ACIAR project and in conjunction with related larval research projects on the GBR (Harrison et al. 2019, 2020). Analyses of samples of *Acropora* larvae supplied with cultured microalgae indicate that feeding increased larval nutrient stores. Provisioning larvae could therefore potentially enhance their settlement and recruitment rates. Additional larval settlement experiments completed at AIMS SeaSim examined the effects of supplying *Acropora* larvae with Symbiodiniaceae symbionts during settlement. Post-settlement survival was higher in juveniles derived from larvae supplied with symbionts, hence supplying settling larvae with Symbiodiniaceae may enhance recruitment success for coral restoration. The outcomes from this PhD research are planned for publication in 2022.

## Section 7D: Objective 4 Evaluating social, environmental and financial impacts of alternative reef restoration strategies

Research for this Objective was led by Jeff Bennet and UP Research Master's student Tara Abrina. An overview of the outcomes is presented first, followed by a detailed report prepared by Abrina and Bennett.

The Aim of the research for Objective 4 was to compare the social, environmental, and financial impacts of different reef restoration strategies, including the coral larval restoration method, referred to as mass larval enhancement (MLE) reef restoration strategy in this section, and other strategies. This was accomplished by conducting valuation studies on the use and non-use values of coral reef restoration in the context of the MLE method used in this project in the Northwestern Philippines (Section 7B above).

Initial analysis of the Magsaysay reef MPA restoration site was completed using the MPA Management Effectiveness Assessment Tool, currently being used nationwide throughout the Philippines to assess the status of local management of MPAs (Figure 7.48). The assessment indicated an MPA rating for Magsaysay reef of Level 2 with an overall score of 53/84 (Very Good).



**MPA MEAT Evaluation**

The University of the Philippines Marine Science Institute

**Magsaysay MPA**
Report Completed: Sept. 27, 2016
Download at: http://mpa.msi.upd.edu.ph/mpa/eval/701/pdf

**MPA Rating - Level 2**
**Score: 53/84 (Very Good)**

**MPA Information**
Short Name: Magsaysay MPA
Year Established: 2001
Legislation: Municipal Ordinance MO# 1-2001
MPA Area (ha): 14.8

**Evaluator(s)**
Tara Alessandra S. Abrina - UP MSI
tsabrina@upd.edu.ph / 09274308732
Elizabeth Torino-Tomas - Anda LGU
bethtorino_tomas@yahoo.com / 09399334906

**Location**
- Tondol, Anda, Pangasinan

Database URL: http://mpa.msi.upd.edu.ph/mpa/lmpa/455

**MPA Contact Persons**
Elizabeth Torino-Tomas - Municipal Agriculturist
bethtorino_tomas@yahoo.com / 09399334906



The 48 questions of the MPA MEAT can be grouped into nine (9) Management Foci, corresponding to the axes of the spider chart. The chart can show which areas of management the MPA management body is strong at and which ones need significant improvement.

**Management Focus**

| | Score | Percentage |
|---|---|---|
| Management Plan | 8/9 | 88.9% |
| Management Body | 6/11 | 54.5% |
| Legal Instrument | 5/5 | 100% |
| Community Participation | 2/2 | 100% |
| Financing | 4/12 | 33.3% |
| Information, Education, and Communication | 6/7 | 85.7% |
| Enforcement | 17/20 | 85% |
| Monitoring and Evaluation | 4/16 | 25% |
| Site Development | 1/2 | 50% |

**Thresholds**

| Achieved thresholds | Requirements for next level | Other thresholds to attain |
|---|---|---|
| 1. Baseline assessment conducted<br>2. Management plan adopted<br>3. Legal instrument approved<br>4. Management body formed and roles clarified<br>5. Budget allocated for at least one year<br>6. Patrolling and surveillance conducted regularly<br>7. Violations documented<br>8. Cases filed or violators penalized<br>9. Enforcement system fully operational in the last five consecutive years<br>10. Violators prosecuted and sanctioned<br>11. MPA management plan incorporated in broader development plans<br>12. IEC sustained over seven years | 1. Funds generated or accessed for last 2 years<br>2. Performance monitoring of the management body conducted regularly<br>3. Regular participatory monitoring conducted | 1. Ecological and socioeconomic impact assessment conducted<br>2. Performance monitoring and evaluation system linked to an incentive system<br>3. MPA financially self-sustaining in the last seven (7) consecutive years |

Figure 7.48: Magsaysay Reef MEAT Summary Page

That assessment highlighted two use values for Magsaysay reef: fisheries and tourism. Therefore, to estimate tourism values a modified Travel Cost Method with Contingent Behaviour survey was initiated with Bennett and Abrina at Tondol White Sands Beach, adjacent to Magsaysay reef area. Bennett met with and trained survey enumerators during the first week of April (Figure 7.49), and the survey data acquisition was completed in May 2017.

Figure 7.49. Bennett (ANU) and Ms. Mai Alagcan (ACIAR) with the Tourism Officers of Anda during the Orientation Day training for TCM Enumerators.

Table 7.2: Average Consumer Surpluses and marginal benefits (per person per visit*)

| | Current | Improved | Marginal benefit |
|---|---|---|---|
| βTC | -0.0003 | -0.0002 | |
| Std. Err. | $5.57 \times 10^{-5}$ | $4.81 \times 10^{-5}$ | |
| Consumer Surplus (Mean) | US$ 63.37 | US$ 113.18 | US$ 49.81 |
| Consumer Surplus (Lower 95% CI) | US$ 47.12 | US$ 73.88 | US$ 26.76 |
| Consumer Surplus (Upper 95% CI) | US$ 96.74 | US$ 241.86 | US$ 145.12 |
| Annual Visits | 17,240 | 20,688 | 3,448 |
| Mean Economic Value of Annual Visits | US$ 1,092,467.84 | US$ 2,341,530.95 | US$ 1,249,063.11 |
| Economic Value of Annual Visits (Lower 95% CI) | US$ 812,282.86 | US$ 1,528,382.93 | US$ 716,100.07 |
| Economic Value of Annual Visits (Upper 95% CI) | US$ 1,667,724.91 | US$ 5,003,609.14 | US$ 3,335,884.23 |

*significant at the 1% level*

The results demonstrate that a significant recreational benefit, equivalent to about twice the current value of the reef, will be generated by restoring Magsaysay reef (Table 7.2). A paper based on these findings was published 2018.

Abrina, T. A. S., & Bennett, J. (2018). Estimating the recreational benefits of coral restoration in Northwestern Philippines. *Journal of Environmental Science and Management*. *21*(2).

Abstract

In this paper, the recreational value of restoring corals reefs is estimated in the context of a site in Northwestern Philippines. The authors apply the travel cost method with a variation that integrates a contingent behavior question. This allows for the estimation of marginal benefits in the context of a change in recreational asset quality. The results show that the recreational study site, including the reef in its damaged state, gives rise to average per visit benefits of around US$63.00. With a restored reef, that average value increases to approximately US$113.00 per visit. Hence, the average marginal benefits associated with an investment in reef restoration for this case study site is in the order of US$50 per visit, with a ninety-five percent confidence interval of US$0.72 million to US$3.34 million per year.

These findings were presented as a poster at the Asia-Pacific Coral Reef Symposium in June 2018.

Following the initial research at Anda, a choice modelling (CM) workshop was conducted by Bennett at the University of the Philippines' School of Economics. This workshop was in preparation for the second study on non-market valuation of coral reef restoration using a Choice Modelling (CM) approach. The research questions for the CM survey were:

1. What is the marginal non-use value of coral restoration (a change in coral reef quality) in the Philippines?
2. Does the scale of restoration effort make a difference in how people value/how much people are willing to pay for such an effort (i.e. is there a bias related to scale)?
3. Does the distance from restoration site make a difference in how much people are willing to pay (i.e. is there a bias related to proximity)?
4. Are people's utility functions (graphical representation of people's preferences for coral restoration) non-linear in scale?

The Choice Modelling exercise was conducted in May-June 2018 to inform the Benefit Cost Analysis of social and financial costs of reef restoration strategies. The survey was designed by Abrina and Bennett with projections about reef status provided by the ACIAR Project's coral scientists. Brandworks, a Manila-based market research company, was hired and trained (funded by ACIAR funds) to conduct the surveys (Figure 7.50). The Choice Modelling results also allowed an analysis of the distribution of benefits across different segments of the population (local vs Manila metro) for different scales of reef restorations (local vs national). Significant benefits were estimated at both the national and local scales for the Metro Manila population, which indicates a potential source of future funding for restoration investments.

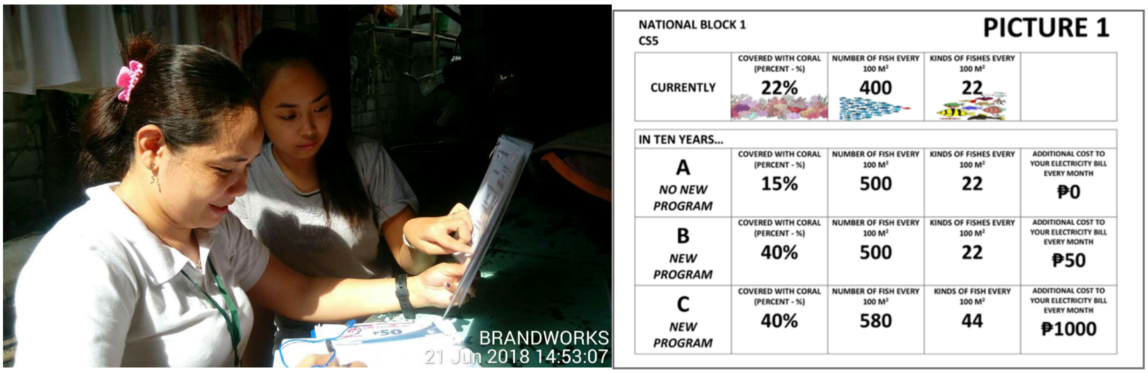



Figure 7.50. Field enumerators conducting the household surveys in Metro Manila and Dagupan City (left, Brandworks) and Sample choice set used in the Choice Modelling (right).

The output of the study was published in 2020.

Abrina, T. A. S., & Bennett, J. (2020). Using choice modelling to estimate the non-market benefits of coral reef restoration in the Philippines. *Ocean and Coastal Management*. https://doi.org/10.1016/j.ocecoaman.2019.105039

Abstract

Coral reef health decline in the Philippines provides an impetus for reef restoration investments. A benefit-cost analysis can be used to support policy-relevant decisions on such investments. However, to our knowledge, most benefit-cost analyses conducted for coral reef investments in the Philippines have been inadequate because they have used total economic values, proxies and benefit transfers as benefit estimates or have been cost-effectiveness studies. To overcome this information inadequacy, this paper reports estimates of coral reef restoration non-market values in the context of an investment in

Mass Larval Enhancement on two scales in the Philippines – restoration on a single coral reef and restoration on a nation-wide scale. Using choice modeling for two split samples (locals living near the single coral reef and those living in Metro Manila), willingness to pay values for coral reef attributes that have been improved through restoration were estimated. At the single reef scale, respondents from the Manila sample were, on average, willing to pay Php 1.41 per percentage increase in coral cover, Php 0.93 per additional individual fish, and Php 1.17 per marginal increase in fish species per household monthly for ten years (Php 1.40, Php 0.62, and Php 1.15 for the same respective attributes within the local sample). At the nation-wide scale, the equivalent value estimates for the Manila sample were Php 8.70 and Php 8.13 for coral cover and fish species respectively (Php 33.06 and Php 27.05 for the local sample). Respondents overall were not willing to pay for increases in fish individuals on a national scale. Differences in the attribute value estimates between the two restoration scales provide evidence of the validity of the results. The differences in value estimates between the local and Metro Manila samples varied depending on the coral reef attribute. These results should be taken into consideration when using benefit transfer to inform benefit-cost analyses across differing populations.

The final aspect of this research was a benefit-cost comparison of varying scales and methods of coral reef restoration in the Philippines. The outcomes from this study were published in 2021.

Abrina, T. A. S., & Bennett, J. (2021). A benefit-cost comparison of varying scales and methods of coral reef restoration in the Philippines. *Science of The Total Environment*, *799*, 149325.

<u>Abstract</u>

The slow rate of recovery in some reefs around the Philippines has prompted the widespread investment in active reef restoration in the country. However, from the point of view of society, these different coral reef restoration investments have not yet been fully compared in a benefit-cost analysis. In this paper, the economic efficiencies of four coral reef investments are compared – at two different scales (local and national) and two different technologies ('coral gardening' and 'mass larval enhancement'). The values are derived from a previous valuation study that used the Choice Modelling method of estimating non-market values of coral reef restoration. The capacity of these values to facilitate comparisons among reef investments is thus assessed in this paper. Based on predictions from reef restoration scientists the Philippines, the mass larval enhancement investments are estimated to produce higher net benefits and benefit-cost ratios compared to those of coral gardening. In terms of scale, higher net social outcomes for the local-scale investments support more localized approaches to coral restoration.

### *Detailed report on Objective 4 research and outcomes*

This research addresses two policy issues and a methodological challenge. The economic efficiency of coral reef restoration investments at different scales (local and national) and the use of two different technologies ('coral gardening' (CG) and coral larval restoration, herein referred to as 'mass larval enhancement' (MLE)) are addressed using benefit cost analysis in the context of reef management in the Philippines. The capacity of the Choice Modelling method of estimating non-market values to generate data that are useful for evaluating alternative reef restoration techniques applied at different scales (local and national) is also assessed.

## 1. Background

Globally, the condition of coral reefs has been in decline due to a range of causes including global climate change causing mass coral bleaching, dynamite fishing, poor water quality, and predator and disease outbreaks (Licuanan et al., 2017; Sully et al., 2019). In response, governments have sought to improve reef management by passive means such as the declaration of reef protected areas (Aliño, 2001). However, the rate of recovery in these areas has been slow and therefore active restoration techniques have been developed ( Rinkevich, 2005, Edwards, 2010, Bostrom-Einarsson et al. 2020). Two such techniques are:

1. 'coral gardening' (CG) – which involves the transplanting of live coral pieces from healthy reefs to degraded reefs (Reyes et al., 2017); and,
2. 'mass larval enhancement' (MLE) – by which coral spawn is harvested from healthy corals, larvae are reared, and then reintroduced to degraded reefs (dela Cruz and Harrison, 2017, 2020, Harrison et al. 2021).

Three policy issues arise in this context. First, it is yet to be ascertained if coral restoration is economically efficient from the point of view of society. Second, if it is, which method of restoration is the most efficient option? Third, at what scale is the preferred option best carried out?

To address these policy issues, this research takes a case study approach. Specifically, we conduct Benefit Cost Analyses (BCAs) of two reef restoration investments that were conducted at a local reef scale: a community CG project and an MLE experiment. Both focused on areas within the Bolinao-Anda Reef Complex (BARC) in Northwestern Philippines. A comparison between the results of these two BCAs permits an assessment of the viability, from a net social benefit perspective, of coral reef restoration and the determination of a preferred technique.

Then, to consider the issue of the appropriate scale of investment, the results of two further BCAs are outlined. The first is an *ex post* evaluation of a national scale CG investment. The second is an *ex ante* BCA of a nation-wide MLE investment.

The four BCAs reported thus provide information relevant to policy makers deciding on the viability of a reef restoration investments, which technique to use, and which scale is optimal.

To conduct the four BCAs, information regarding the values of non-market benefits generated by reef restoration is required (Scarborough and Bennett, 2008). A choice modelling study of these values conducted previously by Abrina and Bennett (2019) is used as a source of value estimates used for benefit transfer. Of particular importance is that study's capacity to provide information that is useful to the process of extrapolating value estimates across differing scales, using a set of attributes suited to describing the outcomes of alternative reef restoration investments. This study explores some of the complexities involved in the process of extrapolating non-market values across different scales.

This report is structured as follows. In section 2, an introduction to the techniques used for coral reef restoration is provided and the four investments subjected to BCA are outlined. Section 3 sets out the fundamentals of the BCA method. Special attention is given to challenges that are of specific interest to this case; notably, non-market values, and the extrapolation of results to differing investment scales. The elements of the BCAs are then assembled: the benefits in section 4 and the costs in section 5. Next, the results of the BCAs are reported in section 4. Within these BCAs, we present analyses of result sensitivity to uncertainties regarding the restoration value estimates. Finally, in section 6, conclusions are drawn regarding the efficiency of restoration investments and the capacity of choice modelling to produce value estimates that are useful where scale is a policy parameter.

## 2. Investing in reef restoration

Four different investments in coral reef restoration are compared in this study:

(1) a local CG project;

(2) a local-scale MLE experiment ;

(3) a national-scale CG concept developed by the Philippine Department of Science and Technology called *Filipinnovation*; and,

(4) a national scale MLE based on an extrapolation of the local-scale MLE experiment.

A summary of the four cases and their associated data sources are set out in Table 7.3, and is examined in detail below.

Table 7.3. Four coral restoration investments subjected to benefit-cost analysis

| **Scale** | Local | Local | National | National |
|---|---|---|---|---|
| **Technology** | Coral Gardening (Asexual) | Mass Larval Enhancement (Sexual) | Coral Gardening (Asexual) | Mass Larval Enhancement (Sexual) |
| **Type of Impact Evaluation** | Projections of ex-post monitoring data | Projections of ex-post monitoring data | Authors' Estimate | Ex-ante |
| **Reference Study** | dela Cruz et al. 2014 | dela Cruz & Harrison 2017 | N/A; Authors' Estimates of the Filipinnovation Ancog et al. 2019; Carlos et al. 2016 | Extrapolation of dela Cruz & Harrison 2017 |

### 2.1 Local scale coral gardening

Coral gardening is a restoration technique that requires affixing live coral fragments onto suitable coral reef substrata (Reyes et al., 2017). Gardening takes advantage of a live coral fragment's ability to regrow as long as conditions allow. This 'transplantation' of coral fragments is an asexual method of coral propagation (Edwards, 2010).

For the case study considered in this paper, dela Cruz et al. (2014) chose a degraded reef within the BARC reef system off Lucero, which is a village located in the municipality of Bolinao (Figure 1). Previous studies showed that this site was suitable for restoration but had not been able to recover naturally post-degradation (dela Cruz et al., 2014).

Thirty volunteers from the nearby coastal community were trained to provide the necessary labour for the transplantation. They collected 450 fragmented coral colonies from a source reef 21 kms away, and then transplanted the fragments at the restoration site in six 16m$^2$ plots. Because the species they chose is capable of colonizing sandy substrate, there was no need to set up a coral nursery unit (CNU) nor have a grow-out phase. The transplants were monitored every two months for the first year. The last monitoring activity was conducted 19 months after the restoration activity.


Figure 7.54. Map of local scale coral restoration sites in Northern Luzon

2.2 Local scale mass larval enhancement

The Magsaysay reef, also part of the BARC, is located off the village of Tondol in the municipality of Anda. It was chosen as a restoration site because of its damaged condition and relatively low mean hard coral cover of about 15.6% (dela Cruz and Harrison, 2017). Fourteen hectares of the reef were declared a marine protected area (MPA) in 2001. Despite the low mean coral cover, some areas of the reef are able to support hard coral cover of up to 98%. However, like the reef in Lucero, the degraded sections have not been able to recruit new corals naturally at a rate that enables recovery (dela Cruz and Harrison, 2017, dela Cruz, pers.com.).

To restore Magsaysay reef MPA, the MLE technique was applied. This technique involved the collection and transfer of gravid parent *Acropora tenuis* coral colonies from a healthy reef to the BML outdoor hatchery, where they spawned and the larvae were cultured to produce coral offspring. These larvae were then reintroduced to damaged reef areas using eight 24 $m^2$ larval enclosures on top of suitable coral substrate (dela Cruz & Harrison, 2017). Monitoring was continued for three years post-enhancement. The larger coral colonies that remained alive three years after the 2013 MLE experiment were observed to be reproductive (dela Cruz & Harrison, 2017). Larvae cultured from these restored colonies were also used for the subsequent 2016 high density larval restoration experiment (detailed above, Harrison et al. 2021).

2.3 National scale coral gardening

From 2011 to 2018, a coral gardening investment was implemented across 20 sites located throughout the Philippines (Figure 7.52). Known as 'Filipinnovation on Coral Restoration' (Ancog et al. 2019; Carlos et al. 2016), this programme was designed to address national coral reef degradation and support local fishing and tourism industries. Led by the Philippine Department of Science and Technology (DOST), the programme was a national-scale collaboration among government agencies, private organisations and civil society groups.

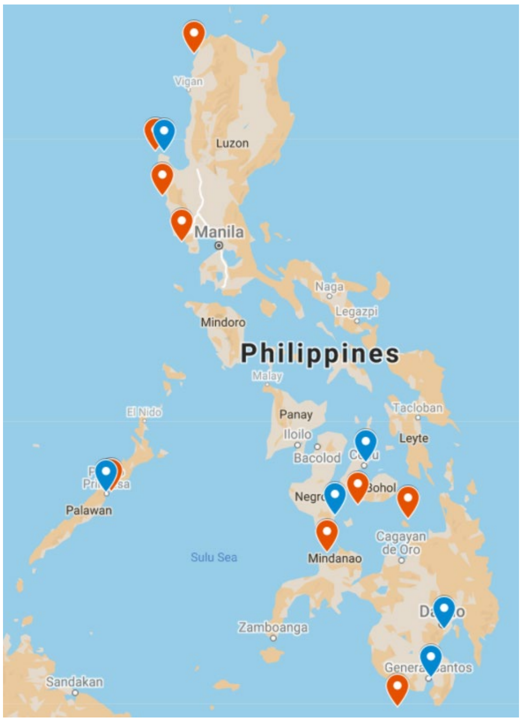



Figure 7.52 Map of national scale coral restoration sites. Red pins indicate 2.3 coral gardening (Carlos et al. 2016), blue pins indicate 2.4 mass larval enhancement. [Image from Google Maps]

From 2011 to 2013, coral gardening activities were conducted in eight sites. These sites were chosen based on their suitability for coral restoration, the available supply of coral fragments, and reefs where some management provisions in place. After two years of evaluations and adjusting the plans accordingly, the programme was extended to an additional 11 sites from 2016-2018.

The method of coral gardening was essentially the same as that used in the BARC case. However, the program used corals already fragmented as a result of physical damage to a reef, called corals of opportunity (COPs). This meant that the program was not be able to choose the species of coral used for restoration. Moreover, it needed a search phase to collect already fragmented corals and, unlike the local scale project which used a species that would grow out of sand, the national scale method required a ‘grow-out phase’ that took place in a nearby coral nursery unit (CNU) before transplantation. For this study, we used the outcomes reported for one site (Balicasag Island, Panglao, Bohol) as a representative.

2.4 <u>National scale mass larval enhancement</u>

While the three coral restoration investments so far outlined have already occurred, no national scale application of the MLE has yet been conducted. To enable comparisons across scale and technique, a potential national scale MLE investment is investigated in this paper. Such an investment would involve the MLE being implemented at selected restoration sites across the Philippines. Specifically, the sites would need to have conditions that support coral recruitment despite a lack of natural coral larvae supply, as is the case at Magsaysay reef (dela Cruz and Harrison, 2017). To facilitate a comparison to the national CG programme, the sites chosen for MLE would be comparable to the CG sites. Lastly, the MLE sites, like the CG sites, would be subject to on-going management programmes that counter reef threats through ongoing management interventions.

The technique used for the national MLE case would be a scaled-up version of the method used for the Magsaysay reef MLE investment. The crucial difference is the time needed for setting up outdoor hatcheries near the sites and training technicians across the country in MLE. In the Magsaysay case, the nearby Bolinao Marine Laboratory already provided the needed facilities and skilled labour. Timelines for the four restoration investments are presented in Table 7.4.

Table 7.4 Timeline of activities for four coral restoration techniques.

| | Restoration Activities | | | |
|---|---|---|---|---|
| Year | Local Scale (Ex-post)<br>Coral Gardening<br>(dela Cruz et al. 2014) | Local Scale (Ex-post)<br>Mass Larval Enhancement<br>(dela Cruz and Harrison 2017) | National Scale (Ex-ante)<br>Coral Gardening<br>(Ancog et al. 2019; Carlos et al. 2016) | National Scale (Ex-ante)<br>Mass Larval Enhancement |
| 0 | 2010<br>• Proposals and planning<br>• Partnership building<br>• Site selection<br>• Baseline survey<br>• Training | Jan-March 2013<br>• Site selection<br>• Administrative Preparations<br>• Baseline survey<br>• Parent coral selection and collection<br>• Coral larvae rearing in hatchery | 2011<br>• Proposals and planning<br>• Partnership building<br>• Site selection<br>• Baseline survey<br>• Procurement of equipment<br>• Training | 2022<br>• Proposals and planning<br>• Partnership building<br>• Site selection<br>• Procurement of equipment<br>• Training |
| 1 | 2010<br>• Fragment collection<br>• Coral transplantation<br>• Monitoring<br>• Maintenance | April 2013<br>• Enhancement Activity<br>• Monitoring<br>• Maintenance | 2012<br>First four sites<br>• Training<br>• Coral nursery set-up<br>• Coral transplantation<br>• Monitoring | 2023<br>• Training<br>• Outdoor hatchery set up<br>• Procurement of equipment<br>• Hatchery testing<br>• Baseline surveys |
| 2 | 2011<br>• Fragment collection<br>• Coral transplantation<br>• Maintenance<br>• Monitoring | 2014<br>• Monitoring<br>• Maintenance | 2013<br>Next four sites<br>• Training<br>• Coral nursery set-up<br>• Coral transplantation<br>• Monitoring | 2024<br>• Baseline Surveys<br>• Training<br>• Parent coral collection<br>• Coral larvae rearing in hatchery<br>• Enhancement activity |
| 3 | | | 2014<br>Evaluations | 2025<br>• Monitoring<br>• Maintenance |
| 4 | • Maintenance<br>• Monitoring<br>• Evaluation<br>• Proposals and planning<br>• Partnership building<br>• Site selection<br>• Training | 2016<br>• Monitoring<br>• Maintenance<br>• Enhanced corals from first batch reproduce (growth exponentially increases) | | |

| | | | | |
|---|---|---|---|---|
| | | • Evaluations<br>• Site selection<br>• Administrative Preparations | | |
| 5 | • Fragment collection<br>• Coral transplantation<br>• Maintenance<br>• Monitoring | • Parent coral selection and collection<br>• Coral larvae rearing in hatchery<br>• Enhancement | 2016<br>• Reapplication for funding<br>• Proposals and Planning<br>• Partnership building | 2026<br>• Monitoring<br>• Maintenance<br>• Evaluations<br>• Proposal and planning |
| 6 | • Maintenance<br>• Monitoring | • Monitoring<br>• Maintenance | 2017<br>Next five sites<br>• Coral nursery set-up<br>• Coral transplantation<br>• Monitoring | |
| 7 | | | 2018<br>Last six sites<br>• Coral nursery set-up<br>• Coral transplantation<br>• Monitoring | 2028<br>• Parent coral collection<br>• Coral larvae rearing in hatchery<br>• Enhancement activity |
| 8 | • Fragment collection<br>• Coral transplantation<br>• Maintenance<br>• Monitoring | • Monitoring<br>• Maintenance | 2019<br>• Monitoring<br>• Maintenance<br>• Evaluations | 2029<br>• Monitoring<br>• Maintenance |
| 9 | | | | |
| 10 | • Maintenance<br>• Monitoring<br>• Evaluation | • Monitoring<br>• Maintenance<br>• Evaluation | • Monitoring<br>• Maintenance<br>• Evaluation | • Monitoring<br>• Maintenance<br>• Evaluations |

## 3. Benefit cost analysis

Benefit Cost Analysis (BCA) is widely used internationally as a means of assessing the impact on social welfare of proposed investments or policies. With an established conceptual base in welfare economics, BCA requires that the positive and negative impacts on social welfare of a change in resource use, relative to a counterfactual, are estimated in monetary terms and aggregated according to the timing of the impacts through discounting (Mishan, 1971). Where a proposed change in resource use yields a net present value greater than zero, it can be concluded that an improvement in social well-being would be achieved if the proposed change was enacted. The change would be potentially Pareto improving (i.e. a change in allocation of goods that harms no one and benefits at least one person).

The application of BCA to the context of assessing the social welfare impacts of coral reef restoration investments presents two specific challenges that are the foci of this study. First, the restoration of a coral reef system produces environmental benefits that are not exchanged in markets. To implement BCA in this context requires the estimation of these non-marketed benefits in monetary terms. An array of non-market valuation techniques is available including revealed preference techniques and stated preference techniques (Hanley & Barbier, 2009). All of these techniques face problems in implementation. In the context of reef restoration where non-use benefits are involved, the application of stated preference techniques such as the Contingent Valuation Method and Choice Modelling are required to provide conceptually consistent monetary estimates. Because these techniques involve survey respondents being asked questions regarding their preferences under hypothetical circumstances, care must be taken to avoid the creation of bias in estimates (Johnston et al. 2017). Sensitivity of the BCA findings to variations in the non-market value estimates is thus an appropriate strategy to acknowledge the potential of bias.

The second issue of specific interest in the reef restoration context is scale. BCA is an analysis of investments at the margin. Values estimated at the margin are likely to vary depending on the scale of the margin under investigation. For instance, as more and more area of reef is restored, it is likely that the marginal benefit from an extra hectare of restored reef will decline in line with the law of diminishing marginal utility. Furthermore, as the scale of restoration investment increases, marginal costs may decrease as economies of scale are achieved. BCAs conducted across differing scales must allow for such variations at the margin.

This can be achieved on the benefit side through the application of stated preference results that have integrated tests for scale sensitivity. Put simply, extrapolation of results from one scale to another must account for those scale differences. This is a variant on the process of benefit transfer (Rolfe and Bennett, 2006). On the cost side, non-linear extrapolations of costs should be incorporated.

In the Philippine literature, BCAs for coral reef restoration either did not analyse any specific investments or used non-marginal values, and are thus incompatible with the theoretical framework of a BCA for policy analysis.

## 4. The benefits

The benefits of coral reef restoration encompass both use and non-use values (Turner and Schaafsma, 2015). Use values occur when the restored reefs provide benefits to people who have first-hand contact with the reef. Such values include recreation enjoyment and extractive activities whereby people harvest the products of the reef (such as fish) either for commercial sale or for private consumption. On the other hand, non-use values arise when people who do not have contact with the reef environment gain enjoyment from the knowledge of its restoration or from the reassurance that the reef will be available in the future for use by themselves or by people who are important to them (such as their descendants).

To our knowledge, Abrina & Bennett (2018) and Abrina & Bennett (2019) are the only two valuation studies that have sought to estimate these values in the context of a specific active reef restoration in the Philippines.

In terms of use values, the recreational benefits derived from improved reef conditions have been estimated for MLE investments by Abrina & Bennett (2018). Fish species that are associated with reef restoration in the Philippines are generally not commercial (target) species (Cabaitan et al., 2015; Raymundo et al., 2007; Seraphim et al., 2020; Yap, 2009). Therefore, the conclusion drawn has been that any surpluses in reef values that arise from extractive uses of fish are almost negligible and was not included in the estimation (Abrina & Bennett, 2018). This study used a well-established revealed preference technique, the Travel Cost Method (TCM) with a contingent behaviour modification (Hanley & Barbier, 2009). In this study, it was found that a restored site is valued more highly per visit in its restored state than when left unrestored. Specifically, Abrina and Bennett (2018) found that restoration generates USD50 more per visit (95% upper and lower confidence intervals of USD27 and USD145 respectively) than its future conditions without restoration. It is important to note that the TCM is designed to estimate only the benefits associated with recreation at the site. It does not address non-use values.

Choice Modelling (CM), a stated preference technique, has also been applied to estimate the non-marketed benefits of reef restoration (Abrina & Bennett, 2019). Because the good outcome presented to the respondents in the CM application was restored reefs, the application estimated the full suite of benefits enjoyed by the survey respondents. Hence, if a respondent was a visitor to the reef in question and they also enjoyed the knowledge of its restoration without visiting, their responses to the CM questionnaire would have embodied both their use and non-use values.

The implication from these previous studies is that the results of the CM application are more relevant. Not only do they cover both use and non-use benefits but they have been estimated at varying scales of investment (local and national) and for differing groups within the overall population. Furthermore, the results are transferable across the outcomes of the two different restoration techniques (MLE and coral gardening) given that value estimates are made for reef attributes that can be aggregated according to the specific physical context at hand. In Abrina & Bennett's (2019) CM application, the three reef condition attributes used were (1) percent coral cover, (2) individual fish within a $100m^2$ area and (3) fish species within a 100 $m^2$ area. The per unit attribute willingness to pay estimates from Abrina & Bennett (2019) are set out in Table 7.5.

Table 7.5. Willingness-to-Pay (WTP) for coral restoration, per attribute per household per month (PHP 2018)

| **Values - Local Dagupan** | | | |
|---|---|---|---|
| HH Region 1 2015 | 1,151, 629 | Response Rate | 0.52 |
| | | | |
| | Coral | Fish Pop | Fish Spec |
| Mean | 1.4 | 0.62 | 1.15 |
| Upper | 2.27 | 0.93 | 2 |
| Lower | 0.5 | 0.3 | 0.36 |

| **Values - National Dagupan** | | | |
|---|---|---|---|
| HH Region 1 2015 | 1,151, 629 | Response Rate | 0.52 |
| | | | |
| | Coral | Fish Pop | Fish Spec |
| Mean | 33.06 | -1.98 | 27.05 |
| Upper | 72.64 | -0.37 | 56.83 |
| Lower | 13.7 | -4.7 | 9.77 |

| **Values - Local Manila** | | | |
|---|---|---|---|
| HH Metro Manila 2015 | 3,095, 766 | Response Rate | 0.67 |
| | | | |
| | Coral | Fish Pop | Fish Spec |
| Mean | 1.41 | 0.93 | 1.17 |
| Upper | 2.6 | 1.33 | 2.14 |
| Lower | 0.15 | 0.52 | 0.26 |

| **Values - National Metro Manila** | | | |
|---|---|---|---|
| HH Metro Manila 2015 | 3,095, 766 | Response Rate | 0.67 |
| | | | |
| | Coral | Fish Pop | Fish Spec |
| Mean | 8.7 | ns | 8.13 |
| Upper | 11.91 | ns | 11.42 |
| Lower | 5.29 | ns | 5.15 |

Notes: PHP100 = USD1.92; ns: not significantly different from zero

Based on the outcomes of existing Philippine coral restoration projects and consultations with reef scientists and managers, estimate four different reef "futures," or combinations of attribute levels that would describe a restored reef in 10 years, were defined. These reef futures are labeled from 1 to 4 in Table 7.6. Level 1 (status quo) describes a local reef in BARC in ten years without restoration, *ceteris paribus*. Levels 2 to 4 are the alternative futures of that same reef ten years after the restoration project is applied. These levels are ordered by increasing optimism across all attributes.

The attribute levels are further assigned two probability distributions, also displayed in Table 7.6, which represent the outcomes of two potential management scenarios A and B. Scenario B's central tendency is more skewed towards the status quo level than scenario A. This allows the calculation of restoration benefits to be based on *expected* values.

Table 7.6. Four coral restoration outcomes (10 years) with probability distributions under two management scenarios

| Levels | Attributes | | | Probability Distributions | |
|---|---|---|---|---|---|
| Local Coral Gardening | | | | | |
| | Coral Cover (%) | Fish Population | Fish Species | Management Plan A | Management Plan B |
| Pre-restoration | 0 | 14 | 9 | | |
| 1 (Status Quo) | 3 | 20 | 10 | 0.75 | 0.90 |
| 2 | 8 | 44 | 11 | 0.20 | 0.05 |
| 3 | 23.5 | 88 | 13 | 0.047 | 0.045 |
| 4 | 39 | 142 | 20 | 0.003 | 0.005 |
| Local Mass Larval Enhancement | | | | | |
| Pre-restoration | 15 | 68 | 18 | | |
| 1 (Status Quo) | 15 | 75 | 18 | 0.75 | 0.90 |
| 2 | 25 | 100 | 22 | 0.20 | 0.05 |
| 3 | 35 | 120 | 24 | 0.047 | 0.045 |
| 4 | 60 | 152 | 30 | 0.003 | 0.005 |
| National Coral Gardening | | | | | |
| Pre-restoration | 22 | 380 | 22 | | |
| 1 (Status Quo) | 12 | 285 | 21 | 0.90 | 0.950 |
| 2 | 22 | 319 | 21 | 0.05 | 0.035 |
| 3 | 25.5 | 351 | 22 | 0.045 | 0.010 |
| 4 | 29 | 373 | 23 | 0.005 | 0.005 |
| **National Mass Larval Enhancement** | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Pre-restoration | 22 | 380 | 22 | | |
| 1 (Status Quo) | 12 | 285 | 21 | 0.90 | 0.950 |
| 2 | 25 | 333 | 22 | 0.05 | 0.035 |
| 3 | 32 | 366 | 22 | 0.045 | 0.010 |
| 4 | 44 | 415 | 23 | 0.005 | 0.005 |

The first step in estimating the expected value of an outcome is to calculate for each attribute $k$, the difference between each level $i$ and the status quo level $sq\ k$ (attribute change, $\Delta A_{ik}$), we r:

$$\Delta A_{ik} = i_k - sq_k$$

For example, for the coral cover attribute at the local MLE scale, the Level 2 attribute change from restoration is 10 percent $(25\ (Level\ 2) - 15\ (Level\ sq) = 10)$. The same is done for the two fish attributes. The attribute changes are then multiplied by their respective WTP values from Table 3 to calculate the per unit attribute change values:

$$x_k = WTP_k * \Delta A_{ik}$$

The expected value $E(\chi_{mk})$ of an attribute $k$ for a particular management scenario $m$ is estimated by multiplying the outcome value $x_k$ by its probability $P$:

$$E(\chi_{mk}) = \sum x_k * P(x_{mk})$$

These per household expected values are then aggregated to the number of households predicted to enjoy a benefit. Using the populations surveyed in Abrina & Bennett (2019), the aggregation extends to Region 1 (1m households, includes the following provinces: Ilocos Norte, Ilocos Sur, La Union, and Pangasinan. This region was chosen as the beneficiary population because the local scale restoration projects were conducted in Pangasinan); and Metro Manila (3m households). This aggregated benefit is adjusted by the response rates of Abrina and Bennett's (2019) survey (52% and 67% for Region 1 and Metro Manila, respectively) using the assumption that households that were not willing to participate in the survey hold zero value for reef restoration.

To take account of time, the adjusted aggregate values were multiplied by 12 to convert the monthly estimates to an expected value per annum. These values form the base for the annual benefit stream used for the BCAs. A social discount rate of seven per cent for ten years was used to calculate the present values of the benefits.

## 5. The costs

The costs of each management scenario are based on the actions set out in the table of activities (Table 7.4). The general activities under the coral gardening projects include (1) administration and analysis, (2) collection, and (3) transplantation; while the activities under the mass larval enhancement projects are (1) administration and analysis, (2) collection, (3) hatchery work, (4) larval enclosures production, (5) site selection &

preparation, and (6) larval enhancement activity. Costs were also delineated following the Philippine Government format of separating capital, labour, maintenance and other operating expenses. Project costs from dela Cruz et al. (2014) and dela Cruz and Harrison (2017) served as the basis for the cost computations. Table 7.7 outlines the details of the cost estimation process.

Table 7.7. Basis for cost estimation across coral reef restoration types and scales

| | Local CG | Local MLE | National CG | National MLE |
|---|---|---|---|---|
| Activities | (1) administration and analysis, (2) collection, and (3) transplantation | (1) administration and analysis, (2) collection, (3) hatchery work, (4) larval enclosures production, (5) site selection & preparation, and (6) larval enhancement activity | (1) administration and analysis, (2) collection, and (3) transplantation | (1) administration and analysis, (2) collection, (3) hatchery work, (4) larval enclosures production, (5) site selection & preparation, and (6) larval enhancement activity |
| Reference Studies for Costs | dela Cruz et al. (2014) | dela Cruz and Harrison (2017) | dela Cruz et al. (2014) | dela Cruz and Harrison (2017) |
| Area Restored in Reference Study | 1 ha (62,500 fragments) | 0.0192 ha (24 $m^2$ x 8 plots) | 1 ha (62,500 fragments) | 0.0192 ha (24 $m^2$ x 8 plots) |
| Target Restoration Area | 1 ha | 1 ha | 65 ha | 65 ha |

Costs per project area were multiplied by the estimated number of projects necessary to cover the degraded reef area to achieve the outcomes under each scale of restoration. For example, dela Cruz and Harrison (2017) applied the MLE restoration treatment to 0.0192 hectares (24 $m^2$ x 8 plots) of the Magsaysay reef and is considered one project. Re-seeding one hectare of reef is assumed to be sufficient to achieve stated outcomes and objectives for the entire 14 hectares of Magsaysay Reef, considering that fast-growing corals on a reseeded plot are likely to become sexually reproductive after about three years and produce benefits exponentially. Therefore, in order to cover re-seed one hectare of degraded reef, the dela Cruz and Harrison (2017) project is assumed to be replicated 52 times within ten years.

The MOOE costs reported in dela Cruz and Harrison (2017) were multiplied 26 times on the first and fifth years, multiplying costs linearly for a total of 52 times to estimate the costs for a local scale MLE. Meanwhile, capital costs, which include the costs of building a working hatchery, sleeping quarters, and culture tanks (at USD 104 each), are estimated at USD 20,104 with a useable life of 10 years.

In addition to the costs reported by the reference studies, two other costs were included for this analysis. The first is the professional fees for administrative preparations, such as preparing contracts, permits, accounting, logistics, as well as analysis and evaluations. The second is the assumed cost for MOOE of 1,000 USD (compounded by 7%) on years without restoration activity to account for the maintenance and monitoring provided by the Bolinao Marine Laboratory for both local scale projects. In the national scale projects, the MOOE is assumed to be 3,000 USD per person, considering travel expenses, plus 180,000 for annual monitoring costs (2019 PHP; Ancog et al. 2019).

These costs, calculations, and assumptions mostly apply to all four BCAs. When extrapolating the costs to the national scale however, capital costs vary greatly among regions. For instance, the Bolinao Marine Laboratory provided the facilities and skilled labour for the local scale projects that would not be available for projects in other regions of the Philippines. Lastly, given that the costs were reported in USD in the reference studies, all prices were converted to PHP and adjusted for inflation.

## 6. Results

The two scales (local and national) and two techniques (CG and MLE) of reef restoration were assessed in four benefit cost analyses. The possible levels taken by the attributes at each scale for the two restoration techniques are reported in Table 7.6. One management strategy was investigated: it yielded probability distribution A for the coral attribute and B for the two fish attributes as set out in Table 7.6. It was assumed to be the same across all treatments and scales. The attribute values used to estimate the expected benefits are the mean willingness to pay values set out in Table 7.5, with the local values applied to the local CG and MLE cases and the national values being applied to the national CG and MLE cases. In this way, the Choice Modelling derived value estimates reported in Abrina and Bennett (2019) take into account the differing scales of the restoration actions.

The results of the four benefit cost analyses are presented in summary in Table 7.8. Benefit cost ratios are used as the test metric in order to facilitate comparison across the differing investment scales.

Table 7.8 Benefit cost analysis results (billion PHP, 2018)[1.]

| | Costs | Benefits[2] | Net Benefit | Benefit-Cost ratio |
|---|---|---|---|---|
| CG local | 0.02 | 0.86 | 0.84 | 37.3 |
| MLE local | 0.03 | 2.27 | 2.42 | 87.4 |
| CG national | 0.23 | 2.62 | 2.39 | 11.5 |
| MLE national | 0.25 | 5.25 | 5.00 | 21.0 |

1. Present values using a seven per cent discount rate.
2. Note that the negative values for the fish population attribute recorded in the source choice modelling study have been set to zero for this exercise.

To account for the possibility that the estimates of the reef attribute values were biased upwards due to biased responses from the choice modelling survey participants, a sensitivity test was performed using the lower bounds of the 95 per cent confidence intervals reported in Table 7.5. The results of that analysis are presented in Table 7.9.

Table 7.9 Lower bound value estimates, benefit cost analysis results (billion PHP, 2018)[1.]

| | Costs | Benefits[2] | Net Benefit | Benefit-Cost ratio |
|---|---|---|---|---|
| CG local | 0.02 | 0.29 | 0.27 | 12.85 |
| MLE local | 0.03 | 0.54 | 0.52 | 20.89 |
| CG national | 0.23 | 1.33 | 1.10 | 5.83 |
| MLE national | 0.25 | 2.66 | 2.41 | 10.64 |

1. Present values using a seven per cent discount rate.
2. Note that the negative values for the fish population attribute recorded in the source choice modelling study have been set to zero for this exercise.

All four reef restoration cases are shown to provide improvements in net social welfare for the people of the Philippines: positive net present values are produced at local and national scales with both the CG and MLE techniques. The analysis demonstrates that the willingness to pay for the reef condition improvements exceed the costs of the projects. This result appears to be robust in so far it applies even when the lower bound willingness to pay estimates are used as the basis for the benefit calculations.

Comparing the results across the two restoration techniques using the benefit cost ratios as a guide indicates that MLE provides some advantage over CG. The MLE benefit cost ratios are higher at both the local and national scales.

A comparison of the BCR results across the two scales of application (local and national) shows that the local investments perform better. Given their smaller scale, the local net benefit present values of the local scale projects are lower than the national scale estimates, as would be expected *a priori*. However, the benefit cost ratio difference across scale is largely due to the difference in the per unit attribute values estimated in the choice modelling application: the small scale projects have higher per unit attribute value estimates, reflecting the diminishing marginal value experienced with scale increases.

## 6. Conclusions

The results from this research show that a programme of coral reef restoration in the Philippines would generate net social welfare gains. This conclusion holds for both CG and MLE techniques and at both local and national scales. Determining the best technique to be used and the optimal scale of the programme is more difficult to determine largely because the benefit cost comparison presented in this study is across projects that are not identical apart from the variation in technique and scale. However, the evidence presented suggests that MLE, while being the more expensive technique, does produce superior outcomes compared to CG: the benefit cost ratios for the MLE projects are greater than those of the CG projects. In terms of scale, the higher net present values of the national projects compared to the local projects would suggest that the returns to the community from reef restoration investments would warrant the nationwide approach.

This paper has also demonstrated the capacity of choice modelling as a tool for estimating non-market values that are well suited to application in benefit cost analysis. The reef restoration attribute values estimated in Abrina and Bennett (2019) provided the basis for an examination of the impact on reef restoration viability across two very different project scales. It also allowed the benefit cost analysis results to be tested for sensitivity to the potential for biased estimates.

# 8 Impacts

## 8.1 Scientific impacts – now and in 5 years

The research from this project has resulted in substantial scientific outputs and significant scientific outcomes and international impacts. The project has resulted in 12 new research publications (Section 10.2 below), with additional manuscripts being finalised for submission. These publications include papers published in high-ranking international journals including Nature *Scientific Reports*, *PloS ONE*, *Frontiers of Marine Science*, and highlight the world's first successful mass larval restoration trials and direct larval settlement on degraded reefs. Furthermore the research and experimental reef trials have resulted in seven new coral larval restoration reef trials, and resulted in multiple new breeding coral populations on reefs in two regions in Northern Luzon. Many of the restored corals grew to sexually reproductive size within only 2-3 years, with two years growth to reproductive size from the 2016 *A. tenuis* reef trial representing a world record among broadcast spawning reef corals. In addition, ongoing monitoring of fish communities demonstrated increased fish abundance and average species richness in coral restoration plots compared with control plots, coinciding with increased coral cover and fish habitat availability resulting from the larval restoration reef trials.

Other scientific breakthroughs include the development of innovative methods for collecting coral spawn slicks in floating spawn catchers on reefs, and mass larval culture in newly designed larval culture pools moored on reefs. These reef based approaches avoid the need for collecting gravid corals, transferring them to laboratory hatchery systems for coral spawning and tank culture of larvae, which require large financial investments in infrastructure, staff salaries, power and water, and maintenance. Therefore this reef-based approach for mass larval restoration provides a more cost-effective method for producing many millions of larvae that can be used for larger-scale restoration projects in future. Project research also trialed two innovative methods for larval delivery onto target reefs using a low-cost bag and pipe method to squirt concentrated larvae onto reefs, and mass larval release over multiple hectare plots using an autonomous underwater vehicle LarvalBot in collaboration with Matt Dunbabin from QUT. Socio-economic analyses using benefit cost analyses showed that coral restoration would generate net social welfare gains, with benefit-cost ratios likely to be higher for larval enhancement restoration methods than for the traditional coral fragmentation and coral gardening approaches.

The success of the larval restoration reef trials from this project have also enabled Harrison to develop and lead a series of new funded research projects on larval restoration on the GBR from 2016 to 2021, and larval restoration is now one of the tools being trialed at larger scales on the GBR as part of the Australian Government Reef Restoration and Adaptation Program. These GBR projects have enabled further development of equipment and new techniques to optimise coral spawn slick capture and mass larval rearing in pools on reefs, which are being integrated back into the ACIAR project research activities in the Philippines. The co-development of research in the Philippines during coral spawning periods from March to July and on the GBR from October to December each year, has enabled much faster evolution of successful techniques due to the offset spawning periods in each region. The integration between the ACIAR Philippines project and the GBR funded projects is exemplified by the Tiffany Foundation and GBRF funded GBR collaborative project with Harrison and Dunbabin, which has led to the world's first successful multihectare-scale larval deployment using LarvalBot on degraded reefs in the Philippines in April 2019.

Following a conference presentation of ACIAR project outcomes in Hawai'i in 2016, Harrison was invited to the Kuwait Institute for Scientific Research (KISR) in July 2016 and conducted a training course on reef restoration and coral larval restoration techniques with 10 KISR researchers. Harrison has also been collaborating with senior coral reef research colleagues from other institutions overseas, leading to larval restoration reef trials in Curacao in the southern Caribbean, and a new collaborative project between Dunbabin and Harrison that will be initiating the mass larval restoration and robot larval delivery methods in multiple overseas regions during 2022. These outcomes clearly show that the results from this ACIAR project are having very significant impacts in Australia and internationally, and these techniques can be applied to many other reef regions around the world in future. It is anticipated that the scientific impacts from this project will continue to grow rapidly in the next few years as more reef scientists, managers and other stakeholders adopt these larval restoration methods and innovative equipment designs for reef restoration projects in other regions around the world.

Scientific impacts also include the significant increase in scientific research capacity of the five PhD and Masters and Honours research students and the many technical and research assistants who have been actively engaged in this project. Their scientific expertise has been substantially strengthened through development of rigorous research plans and experimental designs, publications, theses and written scientific research summaries, as well as public presentations at scientific conferences, stakeholder and public research presentations and training workshops.

## 8.2 Capacity impacts – now and in 5 years

This project and the associated research and training opportunities have resulted in substantial capacity building impacts among research students, technicians and research assistants, and volunteer participants in relation to their improved scientific practices, statistical analyses and other research skills, and self-confidence that is essential for early career development. In addition, ACIAR project team members have developed important skills for project planning, implementation, team-building activities, budgeting, time-management and some practical building skills such as those acquired from participation in building the larval rearers and the mesh enclosure frames in 2016 and 2017.

Key capacity impacts have included research participants from the Philippines including mentoring and supporting SCU PhD graduate Dr Dexter dela Cruz (Figure 8.1) who was awarded a John Allwright Fellowship from the Philippines and graduated April 2019 (and subsequently employed as a Postdoctoral researcher and project officer on this project), and UP Masters graduates Charlon Ligson and Tara Abrina, and UP Masters student Elizabeth Gomez who will complete her degree in 2022.


Figure 8.1. Dr dela Cruz PhD graduate (with PhD supervisor Harrison) at Southern Cross University, April 2019

The project has also provided training and capacity building opportunities for other UP postgraduate students including Timothy Quimpo (graduated in 2019) and Laurence Robles (graduated in 2018), and Joey Casaban and Sheldon Boco in 2016 who subsequently enrolled in higher degrees on other marine ecology topics. In addition, the project has provided essential support for PhD research students from SCU Australia including graduates Dr Kerry Cameron (completed in 2021) and Dr Nadine Boulotte (completed in 2021), and SCU Honours student Katy Horan (completed in 2017), who have all benefitted directly from research training and capacity-building during this project.

The project also provided research support for PhD student Dr Wing Chan (University of Melbourne/AIMS) and Isabel Nunez (Masters graduate, Wageningen University), and training and capacity building for Mikaelan dela Cruz, the designated marine biologist of the Hundred Island National Park. Additional capacity building outcomes include training of survey enumerators for the reef use socio-economic values surveys at Tondol White Sands Beach, Anda, in 2017, and participants of the choice modelling (CM) workshop conducted by Bennett at the University of the Philippines' School of Economics in 2017.

Capacity building outcomes are also evident among the many research technicians and support staff from BML who have participated in this project, who have gained valuable experience with scientific research diving practices and construction of research infrastructure (Figure 8.2). This project also enhanced the research capacity at BML through provision of project equipment including new microscopes and high intensity light sources, multiprobe water quality meters and software, hatchery tanks and equipment, dive gear, cameras, refurbished research boats and the ACIAR project field station hut on Tanduyong Island that are also supporting participants on other research outside the scope of this project.

Figure 8.2. Members of the ACIAR Coral reef restoration team from BML UP-MSI/MERF and SCU at Tanduyong Island, Anda during one of the intensive fieldwork and capacity training periods.

Capacity impacts have also resulted from participation and mentoring of staff from local government units (LGUs) in the Municipalities of Bolinao, Anda, and the City of Alaminos in Northern Luzon during five coral reef restoration workshops. These include an initial workshop led by Cabaitan in May 2017 attended by about 50 DENR staff, and four project workshops held in 2018 and 2019 by ACIAR project staff. Project researchers provided key lectures on coral reefs, human impacts, coral reproduction and coral restoration methods, as well as hands-on practical training at BML training workshops on 28-30 May 2018 attended by 13 staff from Bureau of Fisheries and Aquatic Resources Region 5, and Local Government Unit (LGU) and Bantay Dagat from the provinces Bani, Sarangani and City of Alaminos (Figure 8.3). A subsequent training workshop was held at BML from 15-17 May 2019, attended by 15 LGU representatives from Ilocos Sur, Sarangani, Legaspi City and private sectors from Surigao.


Figure 8.3. Participants of the Coral Reef Enhancement training workshops at BML in 2018 (A) and 2019 (B).

Two larger coral reef restoration and Policy guidelines workshops organized and led by the ACIAR project team were successfully completed on 27-28 September 2018 at Alaminos attended by 112 participants (Figure 8.4). The 27 September workshop was attended by 59 participants from diverse sectors in local government departments from Anda and Alaminos City including the Vice Mayor of Anda, representatives from the Philippine National Police, PNP Maritime Group, Philippine Coast Guard, Bantay Dagat - Task Force Isla, Department of Environment and National Resources – Protected Area Management Bureau, CMAS Philippines and Alaminos Tourism office and other agencies. During the open forum, the participants asked detailed questions about the ACIAR Project coral larval restoration work and raised issues concerning how to properly manage and protect coral reefs of Anda and Alaminos. One of the important outcomes from this workshop was an agreement between Alaminos and Anda municipalities to draft a joint resolution to patrol and catch illegal fishers in their waters, with the help of the Coast Guard and Police. On the 28 September, 53 participants attended the workshop, including Barangay officials of Alaminos and Anda, fishers, boat and tourism operators.


Figure 8.4. Invitation to the training workshop (left image) and some of the participants attending the workshops at Alaminos City in September 2018 (right image).

Three students from the Philippine Science High School, Alexander Hernandez, Makyla Santos and Ay Kau, completed a summer internship in BML gaining knowledge of coral reproduction and spawning. Project researchers and staff have also continued to have very productive meetings with Mayors and other local Municipality representatives at Bolinao, Anda, and the City of Alaminos. These meetings have resulted in very strong support for the project and the reef restoration plans, and resulted in permission and approvals for new coral restoration sites being developed at the Hundred Islands National Park since 2018 (Figure 8.5). A formal proposal to initiate larval restoration at two sites in the Hundred Islands National Park was submitted in March 2018 and was approved by the HINP Management Authority, enabling the HINP larval restoration trials in 2018 and 2019.

The project team also regularly join and participate in the meetings of the Department of Environment and Natural Resources, Protected Area Management Bureau and Alaminos City officials to provide updates on the coral restoration activities and outcomes in the HINP, further strengthening the links between the ACIAR project activities and key LGUs and continuing to engage with capacity-building activities.

Figure 8.5. Project team members meeting with the City of Alaminos Mayor Celeste and Colonel Velasco in the Hundred Islands National Park in March 2018, which resulted in full support to initiate coral larval restoration trials on degraded reef areas in the HINP in April 2018.

These capacity building training activities and the increased research, technical and management skills and knowledge of the researchers, students and staff who participated in this project, were designed to sustain the outcomes from this project after it was completed, and to support the application of this knowledge to other reef restoration and coral mariculture projects in future. It is predicted that these impacts will be increasingly evident within the next five years as the coral larval restoration techniques are applied to new restoration in other regions of the Philippines, and on reefs in Australia and in other reef regions around the world.

## 8.3 Community impacts – now and in 5 years

Broader community impacts from this project include the wide dissemination of information about the project outcomes to diverse stakeholder groups including detailed discussions with reef managers and research coordinators from the Great Barrier Reef Marine Park Authority and the Great Barrier Reef Foundation, which resulted in new coral larval restoration projects in the Great Barrier Reef region. In addition, presentations to coral reef and restoration networks through international conferences, workshops and through media stories have transferred new knowledge and innovative approaches from this project to an increasing global network of colleagues and reef restoration practitioners that is likely to keep building in future years.

### 8.3.1 Economic impacts

The economic impacts from this project have not yet been fully quantified, however, the Travel Cost Method analyses of tourism values demonstrated that a significant recreational benefit will be generated by restoring Magsaysay reef, equivalent to about twice the current value of the reef. Furthermore, the results from the socio-economic analyses indicate that coral reef restoration programme in the Philippines would generate net social welfare gains, and that both coral larval restoration and coral gardening techniques provide net benefits at both local and national scales. The benefit-cost ratios for the larval restoration methods are greater than those for coral gardening approaches. In addition, the higher net values of the national projects compared to local projects suggest that the returns to the broader community from reef restoration investments do warrant a nationwide approach to active reef restoration in the Philippines.

Having re-established multiple new breeding populations of ecologically important foundation corals on degraded reef areas at Magsaysay Reef and HINP, many more coral colonies are predicted to grow on nearby reef areas resulting from larval recruitment as the reef restoration outcomes expand into other reef areas in the Lingayen Gulf. Consequently, some direct flow-on effects of increased fish habitats and spill-over of fish and other reef resources are predicted to occur in future. This in turn could potentially promote improved fisheries production and other reef resources that could lead to increased food security in future for local communities who rely on these coastal reef systems. Improved reef status could also enhance tourism activities that could be carefully managed to avoid adverse impacts on restored and surviving healthy reef patches, thereby providing new employment opportunities. Based on the successful and rapid growth of juvenile corals in this project, new enterprises and employment opportunities for local people could be developed to enable juvenile corals to be cultured for use in other reef restoration activities in future, and potential for other commercial coral mariculture activities such as supplying juveniles to the expanding international coral aquarium trade to avoid collection of wild colonies from natural reefs.

This project has also provided significant employment opportunities for many BML staff who were directly employed in the ACIAR project diving teams, BML hatchery, construction of larval rearers and field logistical support, and as skilled boat operators. The project has also provided employment for local fishers from Tanduyong Island and

Tondol, Anda who were employed to guard the larval restoration sites during some critically important larval settlement phases of the coral restoration experiments. In addition, local businesses in Bolinao, Anda, Alaminos and other regional centres in Pangasinan, and in Manila have benefited from significant expenditure on research support and infrastructure during this project.

### 8.3.2 Social impacts

Healthy coral reefs provide a wide range of valuable goods and services that are socially and economically important at local and regional scales. Coral reefs in the Philippines are very important to local families and coastal communities, as they provide essential fish food and other reef resources for dependent people (Alcala and Russ 2006, Cruz-Trinidad et al. 2011). The degraded status of many of coral reefs in the Bolinao-Anda region and associated loss of fish production and tourism values are likely to have had a direct negative effect on the well-being and social welfare of local communities who depend heavily on these reefs. The social impacts of this project will require more time to become evident, but the initial responses of coral recovery and fish assemblages in coral restoration plots at Magsaysay reef are encouraging, with significantly increased fish abundance in 2018 and higher species richness of fish in larval enhancement plots compared with controls. These benefits to local communities and businesses and the social impacts of this project are predicted to increase as the coral populations continue to grow to provide improved reef habitats for fish and other reef biota. This could increase food resources and other ecosystem services in future, leading to some social benefits including fishers spending more time onshore in the community and with their families due to reduced travel times to healthy reef systems for fishing.

### 8.3.3 Environmental impacts

The re-establishment of multiple breeding coral populations on degraded reef sites and the likely development of many other corals recruiting from the successful larval restoration experiments on degraded reefs are providing significant positive environmental impacts. The increased fish abundance and the trend of increasing fish species richness in larval enhancement plots also indicate positive environmental impacts are occurring from the larval restoration activities. Therefore this project has had positive environmental impacts by initiating the restoration of some key foundation coral species on degraded reef areas. Based on current trends it seems likely that the restored coral populations will become increasingly important habitats for reef fish and other coral-associated reef organisms, leading to improved biodiversity on these reefs in future.

In addition, the educational activities and training workshops for local communities and ongoing discussions with local Mayors and other municipal staff in the Bolinao and Anda regions and the City of Alaminos, are all leading to improved understanding of the critical importance of maintaining healthy coral communities for effective management of these local reef resources in future. An example of these outcomes was the agreement between Alaminos and Anda municipalities during the 2018 ACIAR project workshop to draft a joint resolution to patrol and catch illegal fishers in their waters, with the help of the Coast Guard and Police. This should lead to long-term improved and sustainable use of these local reef areas, particularly in the highly-protected reef sites within the HINP and hopefully improving management of Magsaysay reef MPA and other nearby MPAs.

## Policy impact

The outcomes from this ACIAR project are likely to have significant policy impacts for developing active management practices in reef management in future. For example, the

Great Barrier Reef Marine Park Authority recently developed a new policy for active coral and reef restoration, and Harrison provided feedback on the draft policy based on outcomes from the ACIAR and GBR projects. The ongoing decline and loss of >50% of average coral cover on the GBR in recent decades coupled with the recent severe 2016, 2017 and 2020 mass coral bleaching and mortality events in the GBR have catalysed discussions within the GBRMPA and the Australian Government about the need for active coral and reef restoration on the GBR. The ongoing success of the mass coral larval restoration reef trials from this project have provided key evidence to inform discussions with senior GBRMPA staff, and also informed the discussions and supported the inclusion of the larval restoration research program within the Reef Restoration and Adaptation Program (RRAP) for the GBR.

## 8.4 Communication and dissemination activities

The key results from this ACIAR project have been communicated to a wide range of stakeholders including many scientists, reef managers and practitioners, and more broadly to local municipal authorities and the public through publications, presentations at many national and international conferences and workshops, Australian Embassy meeting in April 2019, and through highly successful targeted multi-media campaigns and news stories and documentaries.

The twelve publications supported by this project are listed in Section 10.2 below, with additional manuscripts planned for submission in 2022.

In addition, a popular science article was published in 2021 that included images and outcomes from the ACIAR projects.

Harrison, P.L. (2021). More Sex on the Reef: Can coral spawning help save reefs? Feature Article **Ocean Geographic 56**: 25-33. April 2021

http://www.ogsociety.org/journal/featured-articles/360-more-sex-on-the-reef.html

International Conference and Workshop presentations

The key results from this project and the initial SRA project have been presented at the following international and national scientific and management conferences:

- Society for Ecological Restoration in Manchester in August 2015 (dela Cruz)
- Two presentations (dela Cruz, Harrison) in the Reef Restoration session co-chaired by Harrison at the 13th International Coral Reef Symposium in Hawaii in June 2016 (ICRS was attended by more than 3,000 leading reef scientists and managers)
- Presentation at the GBR Foundation Science Forum, August 2016 (Harrison)
- Presentation at Biodiversity and Chemical Ecology conference, Bohol, Philippines (Cabaitan and Boco)
- Presentation at the Australian Coral Reef Society in July 2017, and award for Outstanding Student Presentation for Field-based Research to Kerry Cameron
- Invited Keynote talk by Harrison at the Coastal Restoration Conference at JCU, Townsville in September 2017
- Presentation at the European Coral Reef Symposium, Oxford, UK in December 2017 (Harrison)
- Six presentations by postgraduate students (dela Cruz, Cameron, E. Gomez, Ligson, Abrina) and an invited Keynote presentation by Harrison at the Asia Pacific Coral Reef Symposium at Cebu in June 2018
- Invited presentation by Harrison at the Great Barrier Reef Restoration Symposium, hosted by the NESP Tropical Water Quality Hub in Cairns, July 2018

- Invited Keynote talk by dela Cruz during the first year anniversary of Batangas State University's Verde Island Passage Center for Oceanographic Research and Aquatic Life Sciences, February 2018
- Invited plenary presentation by dela Cruz during the International Conference on Pangasinan Studies in Lingayen, Pangasinan, October 2018
- Seven oral presentations by ACIAR team members (Cabaitan, dela Cruz, E. Gomez, R. Gomez, Abrina, Quimpo) during the Philippine Association of Marine Science Conference in Aklan State University, July 2019.
- Presentation (Harrison) in the Reef Restoration session co-chaired by Harrison at the 14th International Coral Reef Symposium in Bremen, originally planned for 2020, then delayed and converted to an online webinar presentation conference during July 2021.
- Presentation (Harrison) in the Reef Futures conference in Florida, originally planned for 2020, then delayed and converted to an online webinar presentation conference during December 2021.

These conference presentations have stimulated substantial scientific, management and media interest, with new collaborative projects emerging as a result of discussions during and after these conferences, including new plans to use mass larval restoration to enhance reef recovery on impacted and degraded reefs in other reef regions.

Results from the project were also highlighted by Harrison at an invited international workshop on Assisted Evolution in Townsville during February 2016, resulting in the following publication on reef restoration that is becoming widely cited:

- van Oppen MJH, Gates RD, Blackall LL, Cantin N, Chakravarti LJ, Chan WY, Cormick C, Crean A, Damjanovic K, Epstein H, Harrison PL, Jones TA, Miller M, Pears RJ, Peplow LM, Raftos DA, Schaffelke B, Stewart K, Torda G, Wachenfeld D, Weeks AR, Putnam HM (2017). Shifting paradigms in restoration of the world's coral reefs. ***Global Change Biology 23***: 3437–3448. doi: 10.1111/gcb.13647

Harrison also presented outcomes from this project at the international workshop on Reef Restoration organised by AIMS in Townsville in February 2017 which resulted in the following publication:

- Ken Anthony, Line K. Bay, Robert Costanza, Jennifer Firn, John Gunn, Peter Harrison, Andrew Heyward, Petra Lundgren, David Mead, Tom Moore, Peter J. Mumby, Madeleine J. H. van Oppen, John Robertson, Michael C. Runge, David J. Suggett, Britta Schaffelke, David Wachenfeld and Terry Walshe (2017). New interventions are needed to save coral reefs. ***Nature Ecology and Evolution***: DOI: 10.1038/s41559-017-0313-5.

Outcomes from this project have also been presented to staff from the Great Barrier Reef Marine Park Authority and the Great Barrier Reef Foundation and during GBRF webinars in 2019 and 2020, which contributed to Harrison obtaining funding and permission from GBRMPA to trial larval restoration projects in the southern GBR in 2016 (GBRF funding) and 2017 (GBRMPA funding).

ACIAR Commission and PAC meeting 2019

Outcomes from this project were presented and then discussed in detail with Commissioners and PAC experts at a joint meeting of the ACIAR Commission and the Policy Advisory Council in Townsville during September 2019.

Australian Embassy presentation

In April 2019, Harrison, Cabaitan and Dunbabin (QUT) presented the key outcomes from the ACIAR projects in a talk attended by Ambassador Steven Robinson, and Darran Rooper, Consul General, and many other people including:

Philippine Government Guests

1. National Economic and Development Authority
- Ms Jane Desiree Andal, Supervising Economic Development Specialist – Natural Resources Division, National Economic and Development Authority
2. Bureau of Fisheries and Aquatic Resources
- November A. Romena, Senior Aquaculturist, National Fisheries Research and Development Institute
- Ms Ludivina Labe, Chief, Bureau of Fisheries and Aquatic Resources
3. Biodiversity Management Bureau - Department of Environment and Natural Resources
- Ms Desiree Maaño and Ms Nilda Baling

International Development Partners

4. Philippines Green Climate Fund Readiness Programme (with UNDP)
- Ms Maria Theresa V. Espino-Yap, EnP, National Coordinator for Philippines Green Climate Fund Readiness Programme UN Development Programme
- Mr Kevin Benico, Philippines Green Climate Fund Readiness Programme, UN Development Programme
5. Food and Agriculture Organisation
- Mr Paulo Caparas, Specialist on Fisheries Food and Agriculture Organisation

SMARTSeas PH Project (with UNDP)

- Dr Vincent Hilomen, Project Manager, SMARTSeas PH Project

DFAT/Embassy Guests

- Anne Orquiza, Portfolio Manager for DRR and Climate Change
- Ave Mejia,  Senior Program Officer for Education Program
- Doris Avila, Program Officer – Development Assistance Program
- French Perdon – Program Officer for Education
- Elaine Valte – Program Officer for Political
- Jaime Cooper – First Secretary for Political
- Joy Valenzuela – Program Officer - Governance
- Rollie Dela Cruz – Portfolio Manager for Scholarships and Innovation
- Mai Alagcan, ACIAR
- Mara Faylon, ACIAR

ACIAR Feature articles and campaigns

The outcomes from this project were featured in two articles in the *ACIAR Partners magazine*

*The Philippines* in Issue Three 2017: “To the aid of coral reef habitats” pages 20-22.

*“Boomerang research”* in Issue four 2020 pages 3-4.

2017 ACIAR Media Campaign

The results from this Project were featured in the highly successful ACIAR multimedia campaign in September 2017: Australian Centre for International Agricultural Research.

- Filming for a news feature report at SCU and video sequences from the project sites by Harrison was broadcast nationally on Channel 10 *The Sunday Project* on 10 September 2017 (estimated audience ~340,000)

The ACIAR Media Release and campaign stimulated 179 story uptakes (84 online and 95 broadcasts), with an estimated online and print reach of 53.7 million people (actual audience reach not known). Interviews included:

- feature stories with AAP http://www.sbs.com.au/news/article/2017/09/11/ivf-coral-could-be-game-changer-reef-health
- various radio stations, The University Network TUN: https://www.tun.com/blog/southern-cross-university-restore-damaged-coral-reefs-using-sexuality/
- and the ABC News website http://www.abc.net.au/news/2017-09-12/coral-research-breakthrough/8895512.

2018 ABC Media ACIAR campaign

In May 2018, ACIAR supported two ABC journalists to travel to the Philippines to interview project team members and staff, and local community representatives about the outcomes from this project. The interviews highlighted the project's successes with larval restoration and were featured in high profile ABC broadcasts plus online stories:

- *ABC TV 'Landline'* http://www.abc.net.au/news/2018-06-02/coral-future:-bringing-coral-reefs-back-to-life/9828180
- *ABC 'Science Show'* http://www.abc.net.au/radionational/programs/scienceshow/coral-shows-encouraging-response-to-relocation-trial/10018690
- *ABC World Today*

An initial Southern Cross University press release announcing this ACIAR project funding and associated media reports are available at the Scimex site https://www.scimex.org/newsfeed/more-coral-sex-helps-restore-damaged-reefs.

Project outcomes have also been featured in a wide range of online stories about reef restoration including:

- an Australia Unlimited Austrade media story promoting selected Australian expertise and success internationally http://www.australiaunlimited.com/environment/international-coral-sexpert-peter-harrison
- Feature article in *Science News* in October 2016: https://www.sciencenews.org/article/reef-rehab-could-help-threatened-corals-make-comeback
- NBC News story in February 2017: http://www.nbcnews.com/mach/environment/how-we-re-teaching-endangered-coral-reefs-help-themselves-n715581
- Deutsche Welle in Berlin in 2017 http://www.dw.com/en/sexual-healing-for-dying-coral-reefs/a-39052694

GBR Media related to ACIAR Project

In March 2019, Harrison was interviewed live from Heron Island in the southern GBR for episodes of the *BBC Blue Planet Live* international broadcasts, and in the final episode broadcast to the UK on 31 March, key outcomes and video sequences from the ACIAR Philippines larval restoration sites were included in the broadcast. A global version was released by BBC so the ACIAR project outcomes will have been potentially seen by more than 10 million viewers (the first *Blue Planet Live* episode was viewed live by ~6.8 million people).

Many other news reports, online stories and documentary interviews about the coral larval restoration projects on the GBR have also included details of the research in the Philippines supported by the ACIAR projects.

Social media

An ACIAR Coral Larval Restoration and Fish Habitat Program Facebook account (Figure 8.6) and an Instagram account have been established for this project and for the SRA FIS/2018/128 project. These social media accounts are coordinated by Rickdane Gomez, with regular updates posted to highlight key project outcomes. Additional social media posts about the project are managed by other team members on their personal accounts, to raise the project profile.

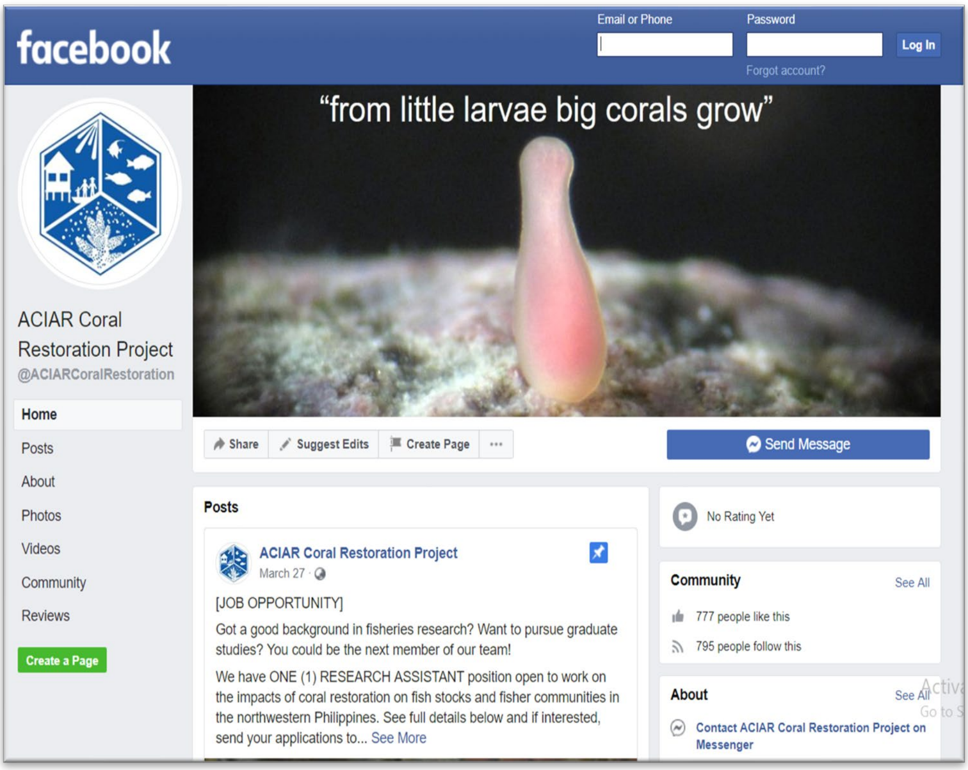



Figure 8.6. Facebook page for the ACIAR Coral Restoration and ACIAR Fish Projects

# 9 Conclusions and recommendations

## 9.1 Conclusions

This transdisciplinary research project has achieved its aim to actively restore damaged reef coral communities in the Northern Luzon region of the Philippines using mass coral larval restoration and to evaluate the socio-economic impacts of alternative reef restoration strategies. Significant outcomes were achieved for all four objectives of this project including some globally significant results that provide a strong foundation for future larger-scale reef restoration work in the Philippines, Australia and internationally.

Substantial research on coral spawning periods on Bolinao-Anda reefs confirmed that large multispecific coral spawning events occur after full moon periods in March and April each year, with additional corals spawning from February to July. This new information allows predictable access to many millions of spawned gametes and embryos for mass larval rearing on reefs and in the laboratory. This research also enabled the development of innovative techniques for collecting coral spawn slicks at the sea surface in floating spawn catchers, and mass culture of millions of larvae in floating reef pools for larger scale larval restoration experiments. Experiments also examined fertilization responses of gametes from three coral species, with optimal fertilization outcomes resulting from high sperm densities and combining gametes within two hours after spawning.

Seven new coral larval restoration reef trials were successfully initiated on degraded reef sites in the municipality of Anda and on reefs in the Hundred Islands National Park. Multiple new breeding populations have been established from this project and the previous ACIAR SRA project, proving that coral larval restoration can be successful even on badly degraded reef areas. These breeding populations include successful reproduction of fast-growing two year old *Acropora tenuis* colonies, which represents a new world record for rapid coral growth to reproductive size among broadcast spawning corals. Continued monitoring of restored corals has shown persistent survivorship and growth, with significantly increased coral cover and fish abundance in larval restoration plots compared with control plots without enhanced larval supply. Higher abundance of damselfish that shelter in branching corals and coral-eating butterflyfish coincided with increased coral colonies and cover recorded in larval restoration plots compared with control plots. Innovative controlled larval release methods were successfully trialled in 2019 using concentrated larvae squirted directly onto degraded reef plots, and a larger-scale multihectare larval release trial was completed using an autonomous underwater vehicle LarvalBot developed by a colleague from QUT. Additional experiments examined the optimal timing for release of competent coral larvae to enable more efficient delivery of larvae onto target reefs.

Evaluations of the social, environmental and financial impacts of alternative reef restoration strategies showed that coral reef restoration in the Philippines would generate net social welfare gains. That conclusion holds for both coral gardening and mass larval restoration techniques at both local and national scales, but the results indicate that the benefit-cost ratios for the larval enhancement projects are greater than those of the coral gardening projects. In addition, the higher net values of the national projects compared to local projects suggest that the returns to the community from reef restoration investments warrant a nationwide approach in the Philippines.

## 9.2 Recommendations

The following actions are recommended to increase the impacts of this project and to build on the achievements so far. Based on the successful outcomes of the project it is recommended that the coral restoration process be scaled up across multiple regions in the Philippines by establishing and training local coral restoration networks to sustain the outcomes after future projects. These local networks should involve a broad range of key stakeholder groups including representatives from local coastal communities, local government units, other government agencies, researchers and the private sector. The coral larval restoration methods should be optimised and scaled-up by including a range of innovative techniques to restore more resilient heat-tolerant coral communities capable of withstanding predicted increases in sea temperatures resulting from climate change, to enable the recovery of reef fish assemblages and restore essential reef ecosystem services on larger areas of degraded reefs.

This would be best achieved using an innovative multidisciplinary research strategy involving biophysical and social sciences. The larger-scale programme should aim to establish community-based reef restoration and protection networks in each region in partnership with key municipal, regional and national agencies that are responsible for marine conservation and fisheries management. This approach would expand and sustain the impacts from this project, further build research training and capacity, and support local communities who depend on these essential reef resources for their food and livelihoods.

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