Exploring methods to enable mass active reef restoration

Executive summary

Coral reefs are globally under threat as repeated bleaching events caused by climate change and other human factors create a volatile environment which is devastating ecosystems. Large portions of coral reefs are dying out and projected increases in temperature will the majority of corals gone within decades. While climate change mitigation is essential, natural recovery of reefs takes centuries indicating the need mass reef restoration now and in the future to rehabilitate these ecosystems. Various methods of Restoration exist with varying costs and scalability. Current practices are constrained by costs and labour intensiveness as well as lack of funding, particularly among smaller community organisations. Innovation and integration of novel technologies present new opportunities for mass restoration yet remain inaccessible to smaller groups due to technical complexity and cost. This study combines a review of literature, benchmarking of the current market of reef restoration solutions and qualitative research involving practitioners to assess the field. Findings reveal a fragmented landscape comprised of a lack of standardisation in tools or practice and limited collaboration between organisations. Opportunities are still present to enact change however, including a greater focus on citizen science, collaboration and knowledge sharing and standardised toolsets.

Contents

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Name: Stephen Terry
Student number: n10779493
Date: 07/09/2025

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Student number: n10779493
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Introduction

Coral reefs around the world are facing unprecedented threats as warming waters, coastal developments and agricultural runoff all serve to make environmental conditions for delicate marine ecosystems more volatile. This is especially true in Australia where our Great Barrier Reef, the largest coral reef system in the world is being decimated by repeated coral bleaching events. The UN (2025) states that with a 1.5°C increase in temperature 70-90% of coral will die off, and a 2°C increase will see no corals remaining in our oceans, showing the dire situation we are faced with. Driving solutions to mitigate and reverse climate change are vital to making waters habitable for coral reefs, but these ecosystems grow and develop over the course of hundreds or thousands of years making it likely that natural recovery from these conditions won't be seen in our lifetimes (Jaap, 2000).

Coral reef restoration is a broad term that covers many methodologies but they are united under the goal of restoring degraded reefs to a state where they can form a self-sustaining ecosystem of corals and other incidental marine life. (GBRF, 2023). Reef restoration as a field has been growing as conditions on reefs have become more and more bleak, with there now being hundreds of companies across the world operating a different scales developing solutions to problem of reef restoration. The Coral Research & Development Program (2025) identified 200 companies working on methods and products targeted at reef restoration from Autodesk, developing AI-powered robots to assist with coral seeding, to McLaren, who have partnered with the Great Barrier Reef Foundation to assist in development of large-scale reef restoration. This style of mass reef restoration aims to counteract the effects of climate change and other threats to the reef, and in a future where climate change has been mitigated or reversed it could in time restore reefs to their former extent far more quickly than they would have recoverd naturally.

Aim

This report will explore the background of reef restoration as a whole and investigate methods used by organisations of varying sizes to better understand the reef restoration landscape and how mass reef restoration can be performed and how it will benefit coral reefs in Australia and around the world.

Background

There is extensive literature on the topic of reef restoration covering both current methods and exploring innovations to improve the effectiveness of the practice.

Reef restoration

Reef restoration can be defined as the process of assisting recovery of an ecosystem that has been degraded and an attempt to return it to its historic trajectory (SER, 2004). It can be separated into active and passive restoration, where passive restoration focuses on eliminating factors that lead to degradation to allow natural regeneration, while active restoration focuses on the seeding and augmentation of the ecosystem (Boström-Einarsson et al., 2019). Methods of reef restoration can be broadly grouped into three categories:

Coral gardening
Collection of coral fragments or larvae in to reared in field based or land based nurseries. Once sufficiently developed the corals are outplanted to a restoration site where they will continue to grow.

Direct transplantation
Coral fragments are taken from rubble or donor colonies and directly planted at the restoration site.

Substrate addition/stabilisation
Artificial reefs are added or rubble is stabilised to provide a more suitable habitat for coral and other marine life.

Economic factors

Reef restoration is an expensive and labour-intensive endeavour as evidenced by Bayraktarov (2019) and Boström-Einarsson et al. (2019) who conducted independent literatures reviews and found the median cost to be 404,174 and 474,621 US$/hectare respectively. They both independently found the nursery phase of coral gardening to be the least expensive and substrate addition to be the most expensive. Naturally there is great variability even between the same approach conducted by different groups as processes are non-standard. Furthermore, restoration organisations are often community organisations that struggle to scale due to a lack of economic incentives and research and development being reliant on grants, charity and other irregular sources of funding (cordap, 2024).

Innovation in the field

Various technologies are being researched in the interest of improving the effectiveness of reef restoration as well as making the process more scalable. Automation is being pursued as a means to scale the monitoring of reefs and management of nurseries, including spawning and rearing of corals to increase output and data availability (Severati et al, 2024, AIMS, unknown). Such automated systems would reduce personnel and training requirements and speed up operations (Lyndon & Bainbridge, 2015). Other areas of innovation include novel material usage such as in 3D printed reef structures and selective breeding of corals to survive warmer temperatures (Reef Design Lab, unknown, Humanes, et al., 2024).

Discourse

Within the literature there is some discussion on the benefits and purpose of reef restoration. Some critics of the field argue that if the causes of reef degradation aren't addressed, such as climate change, then the undertaking is a waste of funding that could have been directed towards other conservation efforts (Frias-Torres et al., 2018).

This overview of the subject shows the need to investigate the relationship between organisations and the emerging technologies that are changing the face of marine conservation as a whole.

Benchmarking

Benchmarking is an essential tool in assessing the current market of any industry and allows strengths, weaknesses and potential market gaps to be identified. To gain a clear understanding of the market, products displaying a variety of technologies were selected to represent the different processes and methods involved in reef restoration, including outplanting, addition of artificial substrate, maintaining coral nurseries both in-situ and ex-situ and monitoring reef health and water conditions.

Current market

Aquaculture systems and marine robotics favour the cutting-edge technologies and integrate systems such as artificial intelligence for autonomous operation. Lower-tech tools and techniques are seen where more traditional restoration techniques are targeted, or for static, long-lasting solutions like artificial reefs.

- Simple tools to assist with attachment of corals during outplanting
- Artificial reefs with varying niches
- Various systems to support aquaculture operations
- Autonomous marine robots

Product details

Product	Description	technology	Pricing model	Pros	Cons
Coralclip	A simple stainless-steel spring with an integrated masonry nail, designed to be hammered into solid substrate to allow quick and easy out planting of coral fragments	Mounting hardware	purchase	inexpensive, simple to use	Unsuitable for fixing larger coral fragments
Generic caulk gun	Caulk gun used to deploy marine concrete for use in fixing corals to substrate	Mounting hardware	purchase	simple to use, can fix larger corals	Caulk gun prone to getting jammed Short working window due to cement Unsuitable for vertical substrates
MARS	Artificial reef designed as a permanent substrate and to replace jury-rigged in-situ nurseries, with its lattice structure it also acts as a habitat for other marine life. It is able to be deployed from small boats and can be constructed by divers like a Lego set.	Artificial substrate	Purchase/build to order	simple to assemble, modular can be adpated to different environments	Expensive
Hyperboloid reef	Modular artificial reefs made from sustainable materials with a focus on coastal protection and marine habitat creation. Steel reefs can be augmented with electrolysis to promote mineral growth on the structure, making it a better coral substrate.	Artificial substrate	Purchase and installation	modular, electrolysis provides enhanced coral growth	Requires supporting power infrastructure for electrolysis Expensive
oPod Aqua	Ocean powered pump designed to support aquaculture operations such as reef restoration by cooling water. Wave motion pumps cold nutrient rich water to corals and onboard sensors monitor data such as temperature, pH and currents.	Autonomous monitoring/ Aquaculture	Purchase and installation	Provides cooling and moniitoring in one package	Labout intensive installation Expensive
C.H.A.R.M.	Autonomous coral farming robot that feeds, cleans and monitors corals to keep them healthy as they grow, automating the most repetitive tasks of coral aquaculture. Uses a unique business model that allows the public to 'adopt' corals and monitor their growth.	Coral aquaculture	Purchase/service	vastly reduces labour, highyl scalable coral output	Expensive Technical knowledge required
Coral AUV	Autonomous underwater robot capable of navigating coral reeds and conducting repeatable surveys of corals with an advanced sensor suite.	Autonomous monitoring	unknown	vastly reduces labour, scalable and repeatable monitoring	Expensive Technical knowledge required

Criteria	Ranking			
	1	2	3	4

Cost	very expensive	expensive	medium	affordable
Development	research stage	trial stage	early adoption	mature
Expertise required	in-depth technical knowledge required	extensive training required	some training required	minimal/none
Scalability	not scalable	limited scalability	moderate scalability	highly scalable
labour	highly labour intensive	moderately labour intensive	Somewhat labour intensive	minimal labour required

Table 1: Ranked scheme of benchmarked criteria.

Criteria	Product ranking						
	Coralclip	Caulk gun	MARS	Hyperboloid reef	oPod Aqua	CHARM	Coral AUV
Cost	4	4	1	1	1	2	2
Development	4	4	4	4	3	2	2
Expertise required	3	3	3	3	2	2	2
Scalability	3	1	3	3	3	4	3
Labour	2	1	3	3	4	4	4
Total score/20	16	13	14	14	13	14	13

Table 2: Products with ranking criteria applied.

As seen in the ranked decision matrix, the Coralclip scored the highest out of the products analysed. This is indicative of its simplicity and scalability. Provide with simple training, a restoration practitioner can outplant 100 corals an hour, with each clip deployed in around 15 seconds (Coral Nurture Program, 2025). Despite this it can be seen that the various other solutions scored similarly and it should be noted that autonomous technologies like the Coral AUV and CHARM had their scores impacted by the fact that they are emerging technologies. With further development they could rank higher due to their best-in-class scalability and labour criteria, meaning despite a large upfront cost, they are capable of scaling reef restoration with minimal resources required for upkeep.

Gaps and insights

While reviewing the breadth of products and solutions available for reef restoration activities it was noted there was a lack of purpose-built tools for current widespread manual restoration methods like coral outplanting. This is exemplified in the selection of a generic caulk gun as a product to review as there are no purpose-built examples or other alternatives for applying the marine concrete used in that particular method. As these manual methods are widespread among smaller organisations and community-driven efforts with limited funds there is an opportunity to provide a greater variety of standardised, cost-effective and robust tools designed for marine environments. On the opposite end of the spectrum, high-cost autonomous solutions are still very much in their infancy and employed only by research organisations with access to funding. This presents an opportunity to create open-source projects or otherwise connect smaller organisations with larger ones so more people have access to these cutting-edge technologies.

Research

Methodology

Gathering research from primary sources is important to gain first hand qualitative data from stakeholders and end users. This qualitative data can be analysed to gain insights on the users needs that may not be readily available in literature, and can be cross referenced with said literature to identify areas of potential discourse or correlation. To ensure suitable qualitative rigour, a triangulation approach was taken, which data being gathered from two qualitative methods.

Surveys

23 questions – approx. 10 minutes
15 participants

Surveys were chosen as a method of qualitative research as they are a time efficient means of research for both the researcher and the participant. A survey once set up can be easily shared or emailed to many people, and for those that participate, the survey doesn't take much of their time. Although response rates are typically low for surveys, the number of people they can reach typically counteracts this and sufficient participants can be found. Surveys also provide a structured series of questions that all participants answer, allowing trends to be observed.

The survey was sent to a wide variety of organisations and individuals known to be involved in coral reef restoration. Some of these contacts were leveraged through personal networks, which improved the chance of getting a response. The rest were found from searching online using resources such as CORDAP's (2024) report on the global reef restoration landscape, which listed 200 organisations in the industry. An email template was created including details on the study, consent information, and where possible a personalised comment on the work done by the organisation to make their input feel more valued, and thus hopefully increasing the chance of their participation. The survey was eventually sent out to 40 individuals and organisations, of which 15 participated achieving a satisfactory response rate of 37.5%.

Some limitations of surveys include the lack of detail of responses, especially if all questions are multiple choice with preset options. The survey was set up based off preliminary research to provide as many relevant options as possible, however each question was left with an 'other' option to allow the participant to fill in extra details where required, as well as some short answer questions which would allow them to provide greater insight. These short answer responses could then be analysed using coding techniques similarly to those used for the interviews. As this sample size of 15 is still quite small the quality of the data provided could be improved by collecting more responses.

Interviews

4 participants
3 x 30 minutes | 1 x 10 minutes

Interviews were chosen as the second qualitative research method in this study due to the greater depth of detail they allow compared to surveys. They were conducted in a semi structured manner with a general focus on how the interviewee had conducted reef restoration, their thoughts on mass restoration and where they believed the field was headed in the future.

Interviews were sourced from the same personal contact of mine within the industry, as having a reference made it far easier to obtain willing participants. The interviewees were all practitioners of reef restoration involved with organisations or varying sizes, including small private companies, universities and government organisations, and all with over 20 years' experience in the field. Three of the interviewees were conducted as a long form zoom call, that was recorded for the purpose of creating a transcript. The fourth interviewee was impromptu and this conducted over the phone with notes being taken by hand.

Limitations of interviews include time intensiveness both on the interviewer's and interviewee's part. The potential for bias exists as well, as the quality of the information gathered is dependent on the interviewee's ability to recall it in the moment, which could be skewed by their perspective, or the perspective and framing of the question by the interviewer. The rapport between the interviewer and interviewee can act as a limitation as well, however was not an issue in the interviews conducted in this study, with each subject being quite friendly and forthcoming about their experiences.

Conclusion

The triangulation of qualitative research in this study was conducted via interviewees and surveys. Efforts were made in the research design to overcome the inherent limitations of each method and thus gather comprehensive and useful qualitative data that was as free from bias as possible. 15 survey participants were recorded and 4 participants were interviewed with the data being collated and analysed to gather further insights on reef restoration.

Analysis and Findings

Analysis of the results of the surveys and interview were conducted with multiple methods depending on the kind of data being dealth with. This section of the report covers the findings of this analysis including key quotes, statistics, bivariate analysis and thematic coding. The interpration of these findings and further implication will follow in the discussion.

Surveys

Survey resulted where transferred from google forms to google sheets where they could be more easily processed and compared with one another. The qualitative short answer questions were set aside for thematic coding analysis along with the interviews and the remaining questions were analysed to find key statistics, with bivariate analysis being conducted on demographic data in relation to key questions regarding automation and citizen science among others.

Demographics

Practitioners from many organisation around the world were surveyed an thus a wide variety or organisations and levels of experience were observed. The majority, 40%, were non-profit organisations, followed by equal proportions of government organisations and for profit companies with a single respondent being from a university. Experience varied but the majority of respondents had between 1-10 years in the industry.

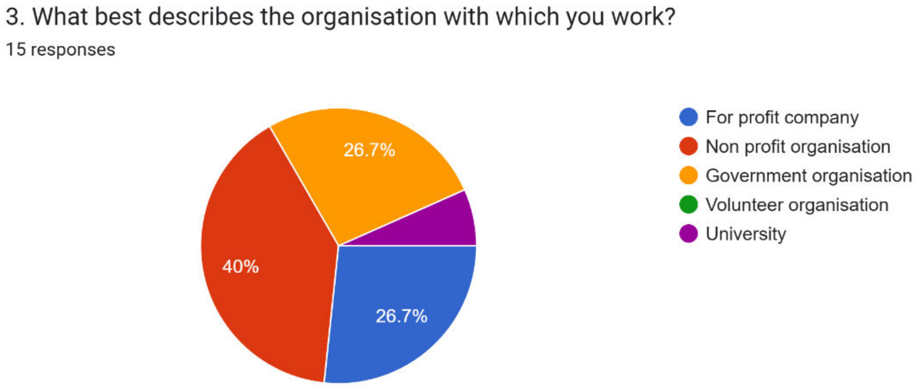

Figure 1: Pie chart of distribution or organisation type among survey participants.

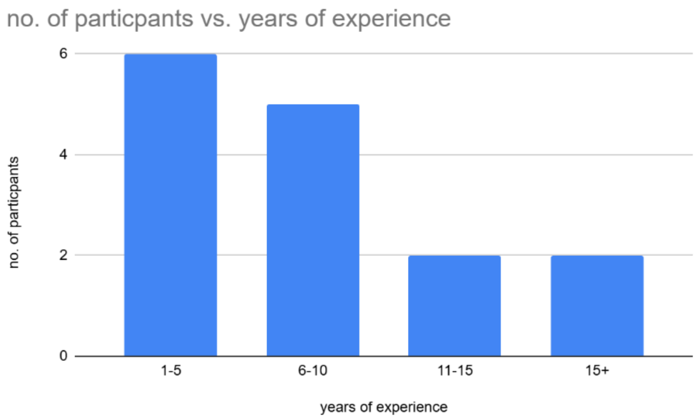

Figure 2: Age distribution of survey participants.

Restoration practice

Practitioners were asked what methods of restoration they used, the majority of which were reef monitoring and coral gardening. 80% of practitioners also responded that they used two or more restoration practices in conjunction with each other.

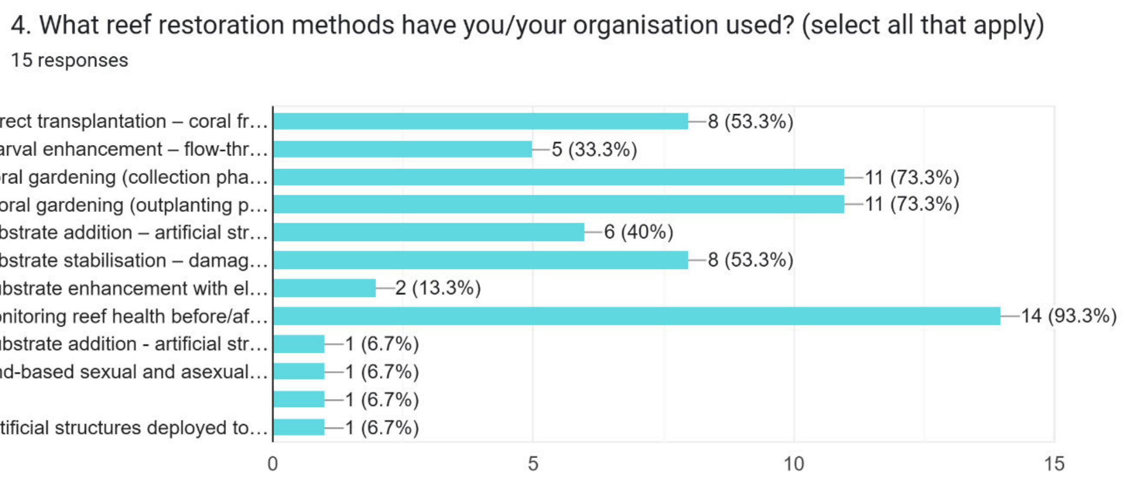

Figure 3: Distribution of reef restoration methods used.

Challenges faced

Likert scale questions were used to determine how much of a challenge different factors of the reef restoration process caused to practitioners. Results found that manpower, funding and legislation caused a majority of practitioners problems, while the time span over which projects were done equipment procurement were mixed, and may only cause issues on a case by case basis.

Interviews

After conducting the interviews, recordings taken during the interviews were converted to a transcript using AI tools, and then thoroughly analysed using thematic coding techniques. Codes were initially identified during the course of secondary research and these were used a base, added to and refined into the final set of codes which can be seen in the appendix. Key themes from the interviews are identified and explored below.

Citizen Science

Citizen science came up very often as a topic to explore for scaling up reef restoration as volunteer work currently makes up a not insignificant portion of restoration work. It was mentioned several times the tourists, fishers, scuba divers and other people passionate about the reef would continue to be a valuable resource for restoration. Comparisons were drawn to existing citizen science schemes for picking up marine debris, claimed to have involved 300,000 people to date. It seems the caveat for involving them in more technical work such as monitoring or outplanting would be training to ensure they are doing to work to a required standard.

"a lot of scaling up is going to come from you know human resources and participation by uh whether it's professionals or people who are actually paid or whether it's um a pool of volunteers who are just keen to be involved"

Automation

Automation seemed to be a divisive subject between different interviewees. A common belief was that while automation was potentially useful for some use cases, investment in people would be what would allow reef restoration to scale up. Another theme that appeared alongside automation was the cost, a survey respondent wrote that for community based restoration efforts automated systems would be unaffordable and too technical. While

"even though there's a lot of talk about automation of processes a lot of scaling up is going to come from you know human resources and participation by uh whether it's professionals or people who are actually paid or whether it's um a pool of volunteers who are just keen to be involved"

Collaboration

Collaboration between organisations was another key topic identified as an area that could be improved. One interviewee expressed frustration that restoration organisations would compete with one another, stating his product he's bringing to market will be available for anyone to utilise or build off of. This was also presented as an issue, as governmental regulations which are also regarded as a challenge by many served to prevent collaboration and impede progress in some instances.

"The worst thing we can do in this game is compete with one another. You do see it. I see it often. People from the marine aquarium supply industry that I work in, they want to get into this, but they won't leave their competitive nature at the door. Yeah. Great Barrier is a bloody big place, and no one's going to be the Kate Crusader in this. You've just got to go and make a contribution to it."

Standards

Due to the number of organisations in reef restoration and the number of approaches that can be used, the aren't any set standards in the industry. One interviewee is working on a project with the goal of being an end-to-end system with standardised elements for land-based nurseries, ships and in-situ nurseries to allow better efficiency, but there doesn't appear to be a drive to replicate this in a larger scale across the industry. Not only standardisation of practice is mentioned, but standardised reporting and success criteria were mentioned as challenges.

*"So one of the things that we're doing here is basically through the consultation process is trying to develop end-to-end solutions with both in-situ and ex-situ operations […] where all of the land-based systems integrate with the sea-based activities. So trays are the same size, nurseries are the same sort of shape and consistency***"**

Conclusion

The surveys and interviews resulted in a great deal of qualitative and quantitative data the analysis of which has revealed key insights into the challenges faced by restoration practitioners as well as their thoughts on emerging technologies. The issue of manpower could be a driver for increased levels of citizen science activity and regulation and legislation remain as barriers to restoration and potential collaboration. Additionally, automation holds both promise but a lack of interest for some due to the level of investment required. Further discussion of these factors how will break down how they could relate to potential solutions.

Discussion

In the initial literature review and benchmarking, gaps were identified regarding the availability of emerging technologies for the majority of restoration practitioners, as well as the lack of standardised or purpose-built toolsets for them to make use of in their current practices. As a result of this the landscape of reef restoration is highly fragmented, with the many organisations around the world pursuing reef restoration separated both in practice and toolsets, making the scaling up of restoration solely the interest of larger organisations or governments both of which have more funding. By delving more deeply into these topics through qualitative research these gaps have been substantiated and further topics of interest discovered.

In the survey, equipment procurement was seen as a mixed topic, not as a unanimous challenge among respondents. However, alongside the discussion regarding standards in equipment and approach in the interviews, it’s clear that equipment usage is still a topic of contention, even if not unanimous. This supports what was explored in the benchmarking where a disproportionate focus in the market is on high tech solutions outside of the budget of many groups. Furthermore, the challenge of manpower seen in the survey correlates with the enthusiasm the interviewees had for increased levels of citizen science. If relatively unskilled citizen scientists become a more common resource for these organisations, standardised equipment will make it far easier to train them and thus give these smaller organisations a method of scaling their operations.

Collaboration between organisations was not identified as a challenge in the literature but was described as a major stumbling block in the interviews. This aligns with the landscape, there are hundreds of organisations, many working independently using patented technology. With that in mind its clear how scaling up of reef restoration will require rethinking of how smaller restoration organisations work with each other and can be linked back to the idea of standards; making working with one another more streamlined.

Automation is presented as being the future of restoration in the literature, but some discourse was already presented there and is reflected in this study too. Naturally with smaller scale organisations these technologies will be out of reach due to the large upfront cost, even though they may reduce labour and increase efficiency. A path forward for accessing these technologies may relate back to collaboration, and partnering with larger companies or using their technology as a service.

The findings of this study have added detail to the gap originally identified in the literature review, namely the topic of collaborations of collaboration and manpower. These findings still relate broadly to the gap and can be linked back to standardised tools and accessibility of automation in the industry. With the more narrowly defined needs of the industry, implications on design can be identified and areas for potential solutions proposed.

Design Implications

The findings of this study have several implications for design of a successful solution to the problems outlined. The goal of mass reef restoration is achievable but difficult in the current fragmented landscape. Individual organisations may go perform their own restoration actions as needed, but it is the divided toolsets and methods rather than the divided discrete restoration actions that are hindering mass reef restoration.

Successful designs should focus on robust purpose-built tools enabling restoration organisations around the world, especially smaller or community driven ones, to be equipped with standardised toolsets thus improving efficiency, and allowing easier knowledge sharing and collaboration.

Successful designs should also facilitate a greater presence of lesser-skilled community members and citizen scientists a means to bolster reef restoration.

Opportunities

Standardised equipment
Iterating on traditional method of reef restoration to create a streamlined but familiar toolset purpose built for marine use, rather than jury-rigged, would take a lot of guesswork

Affordability & Versatility
Funding is a consistent issue among many reef restoration organisations. If a solution is cheap, can be used to fulfil multiple functions, or both, it will be ideal for their use.

Semi-automated solutions
Fully autonomous solutions tend to be expensive and overly technical – semi automated solutions to amplify the work done by a single operator could be a satisfactory compromise that requires less technical ability and less monetary investment.

Collaboration
Tools to enable knowledge sharing and collaboration between organisations will be key to enabling scaling up of restoration among smaller organisations.

Conclusion

The findings of this report indicate the shortcomings of the existing reef restoration landscape and the need to scale up operations to meet the still growing threats of climate change. Major gaps in current research were identified and expanded upon with further qualitative research include a greater need for standardisation in the field to allow greater focus to be placed on the restoration activities themselves rather than the means of doing so. Increased standardisation leads into the next finding being that of collaboration, and the difficulty that is faced in doing so currently. Lastly the topics of manpower and citizen science were covered and how a simpler restoration process and toolset will favour integration of more citizen science into the field, thus alleviating some of the problems experienced with the lack available labour. Interventions were suggested addressing theses concerns, primarily cost effective emerging and traditional restoration tools to limit technical expertise needed, and development of a solution of framework to increase collaboration in the field.

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