CORDAP 2023 Coral Accelerator Program

Aquaculture/Automation Priority Area – Additional Topic Guidance

This document is a preview summary of the soon to be published 'CORDAP R&D Technology Roadmap for Coral aquaculture, Monitoring and Outplanting.'

Climate change and other anthropogenic impacts have driven coral reef degradation on a global scale to unprecedented levels of decline, with further dramatic deterioration predicted by the end of this century. Along with a drastic reduction in global carbon emissions, we face an imperative to restore, rehabilitate and maintain marine habitats to secure the ecosystem services they provide. While terrestrial restoration projects have benefited from the agricultural revolution that has provided industrial-scale tools for effective habitat restoration and rehabilitation, slower technological transformation in the marine sector has resulted in a lack of cost-effective and scalable solutions for reef restoration.

To address the fundamental challenges in advancing the upscale and effectiveness of reef restoration, as part of a scoping study on exploring the frontier of coral aquaculture, an in-person workshop was held from the 29th to 31st of January 2023 at the King Abdullah University of Science and Technology (KAUST), Saudi Arabia, bringing together international academic, industry-based and technology experts from various fields, including scientists in coral reef biology and ecology alongside experts in marine (including coral) restoration, engineering and aquaculture. The workshop aimed to promote interdisciplinary dialogue among participants to identify areas where investments in research and development (R&D) are needed to enable economical coral aquaculture (both in situ and ex situ) and outplanting at scale.

Workshop participants were specifically tasked with exploring the technological advancements required for upscaling coral restoration efforts to achieve ecologically significant impacts. Participants were requested to name and evaluate (score) (a) solutions perceived to innovate industrial land- and ocean-based coral nurseries, (b) solutions to integrate and implement assisted evolution strategies, as well as (c) technological solutions for outplanting and monitoring. Our scoring system integrated technology-readiness levels, scalability, associated cost for development and application, as well as potential impact. The experts' evaluations were then analyzed and rated according to four critical components: 1) Lead-time, 2) Quality, 3) Cost, and 4) Flexibility. These ratings (defined further below) aim to describe the potential of each solution to enable efficient and effective reef restoration at scale, across different ecological regimes and resource capabilities. In doing so, critical and priority areas that could benefit from strategic investment to most rapidly advance reef restoration solutions at scale were identified.

Aquaculture/Automation Priority Areas

Workshop participants identified that substantial investment is needed globally to support Research & Development (R&D) for the following main topics in order to effectively up-scale reef restoration.

1. **Infrastructure for Coral Production**

To effectively upscale coral restoration efforts, particularly in developing nations, will require optimized infrastructure that will enable low-cost unit economics associated with high throughput coral production. Priority areas to address these include:

a) *Standardization and modularization of infrastructure, from coral substrate materials to nursery and outplanting components (e.g., modular Life Support Systems, standardized in-situ nursery systems and final outplant products).*
b) *Reduction of maintenance for infrastructure (e.g., incorporating mechanical, biological, and/or chemical antifouling technologies).*
c) *Solutions for the enhancement of coral growth, performance, and survival (e.g., improved light, temperature, and flow regime systems, material science for coral substrates, tank space optimization).*

2. Management and Workflows

Coral restoration technologies remain limited to custom-made tools with few standardized off-the-shelf or modular operational designs available. Another major bottleneck to upscaling restoration efforts is the massive time (and labor) investment required throughout the production pipeline, mostly related to stock and inventory maintenance. To overcome these bottlenecks, efficient coral production and management workflows were highlighted as priorities with an emphasis on:

a) *(Semi- or, eventually, fully-) automated inventory systems for livestock management.*
b) *Efficiency of asexual and sexual propagation.*
c) *Standardized software/hardware to optimize data collection and production efficiencies.*
d) *Development of production and deployment modeling tools that incorporate costs and coral mortality rates through the whole workflow process to enable production/deployment simulations, and improving decisions, designs and R&D investments.*

3. Integrating Resilience

For coral restoration efforts to be successful in the face of climate change, resilience based strategies, in particular those that can integrate assisted evolution-based approaches at scale, with high throughput, need to be developed. The following areas were identified as key priorities for implementing assisted evolution-based approaches at a large scale:

a) *Phenotyping/genotyping pathways to assess stress resilience (e.g., thermal resilience).*
b) *Pathways for selective breeding.*

c) *Coral symbiont/microbiome manipulation and enhancement (e.g., application of probiotics).*
d) *Environmental hardening (e.g., thermal stress hardening).*

For more information on this topic, which was the focus of another 2023 CORDAP Scoping Study, please refer to the 'CORDAP R&D Technology Roadmap for Understanding Natural Adaptation & Assisted Evolution of Corals to Climate Change.' This document can be accessed here .

4. Efficient Outplanting

Arguably the key steps that limit cost-effective reef restoration in water is the process of outplanting, and the yields that can be generated from re-planting reef areas over time. Major needs remain to develop new tools and operations that can advance outplanting, with emphasis on:

a) *Attachment processes; reducing or eliminating manual diving efforts that restrict in water time (e.g., automation).*
b) *Strategies/techniques to increase survival of outplants (e.g., environmental priming of receiving sites).*

5. Monitoring

Capacity to demonstrate effective restoration is critical and involves effective monitoring of activities over space and time. Not only does this extend to the restoration (and reference) sites of concern but also to the underlying propagation activities and operational processes. Major needs remain to develop more effective monitoring strategies, with emphasis on:

a) *Cost-effective and long-term monitoring approaches (e.g., sensors, sensor array design, data access).*
b) *Cloud storage and advanced (automated) data processing.*
c) *Database design and curation, and data integration with computer vision, image classification and other fields of Artificial Intelligence (AI) .*

Rationales for the identified priority areas

1. There is a need to provide efficient and low maintenance solutions to coral aquaculture and nursery efforts. Current approaches mostly lack standardization and off-the-shelf and/or modular solutions, which inflate the cost and constrain scalability of restoration interventions.
2. Current median coral production costs impede landscape or global scale restoration efforts, hence we need to identify strategies that enable a substantial reduction in costs.

3. Due to the dramatic increase in synergistic stressors on corals - and notably ocean warming that drives acute heating anomalies - that continues to threaten coral populations globally, efforts should integrate methods to maximize genetic diversity and facilitate assisted evolution and, ultimately, increase resilience in the restored community.
4. As coral outplanting efforts are currently a main cost-factor, innovative strategies are needed to improve attachment methods (and materials), early survival efficacy, and optimize deployment times (including via automation). Systems of production, transport, logistics, and technological development need to be integrated such that the whole workflow is designed as an integrated system. As an example, if we consider the objective to produce new surviving corals on a reef at the lowest unit surviving coral cost, where for any particular method of coral production and deployment there will be a point where investing more in production/deployment to reduce post-deployment coral mortality is no longer worthwhile. Thus, tools are needed to enable different methods (from production to deployment) to be compared against goals, and to help identify where improvements in any specific method would provide the greatest benefit.
5. Long-term monitoring of environments and operations is vital to inform on success and/or failure, and therefore guide whether and where activities should scale, continue as is or stop. Integrated systems are required that permit monitoring environmental parameters, operations (including *Life Support Systems*), outplant performances etc., while generating processable datasets to optimize workflows and allow scaling-up. Moving systems to AI requires suitable data curation to be established.

Applicants should use the following criteria to assess their proposed applications potential to be disruptive technologies/solutions:

1. Lead Time - Time to be market ready for widespread adoption and supply.
2. Flexibility - Potential to scale up under a variety of environmental conditions and economic contexts.
3. Quality - Potential of the technology/strategy to restore/enhance reproductive activity/output of coral populations and to promote genetic diversity and resilience.
4. Cost - The amount of estimated R&D funding that would be needed to develop solutions in each topic so that they can be widely adopted.

While the lower technical requirements generally make ocean-based coral propagation cheaper, coral aquaculture in land-based nurseries offers a controlled environment for coral growth, enables easier pathways for sexual propagation, potentially offering greater biosecurity, and has greater potential to benefit from standardization and automatization in the near future. Overall solutions discussed indicated that while many technologies to advance coral aquaculture to industrial scales are often used in other industries (such as fish aquaculture and aquarium trade) and can be readily available, these are often not applied in synergy to increase efficiencies and scalability of coral aquaculture facilities. A major deficit identified is the lack of standardization.

In general, multiple obstacles hinder the scale and effectiveness of current restoration endeavors. One significant factor is the insufficient exchange of technical knowledge among operators and other related industries. Although there are numerous ways to improve aquaculture efficiency, either through existing solutions or by adapting techniques from related fields, there is still a lack of strategic deployment and integration of these approaches. For example, leveraging technologies and methods from the fish aquaculture and aquarium trade could significantly advance the coral restoration aquaculture sector. Another important outcome is the adoption of reef restoration technologies that are already at Technology Readiness Level 9 (i.e. TRL 9) but lack widespread implementation. These ready-to-scale technologies require attention and promotion to achieve their full potential. A lack of technology application and knowledge transfer could be attributed to a lack of coordinated efforts (such as the one described here), the limited funding and restricted scale of previous (and most current) restoration projects. Such projects often operate in isolation, however, this current limitation is expected to improve with the emergence of larger government-funded initiatives for example DARPA Reefense Program (the United States Defense Advanced Research Projects Agency).