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Multi-dimensional approaches to scaling up coral reef restoration

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ABSTRACT

Local and global stressors have led to rapid declines in coral reef health around the world. A range of active restoration techniques have recently been introduced in attempts to stem and reverse this decline, but their efficacy is debated. In particular, restoration faces the challenge of scale; successful projects must be deployed quickly over large areas, without being prohibitively expensive.

Indonesia has more coral reefs – and more coral reef restoration programmes – than any other country on Earth. The past two decades have seen a rapid expansion in the scale of Indonesia's restoration efforts. Having started in the 1980s, there are now hundreds of individual programmes across the country, several of which have outplanted tens of thousands of corals. Here, we identify ten different social, economic and environmental approaches that have contributed to this scaling up of reef restoration in Indonesia. We discuss the theoretical basis for each approach and provide case studies of their implementation from sixteen different Indonesian programmes.

In combination, these diverse approaches have created opportunities to increase the operational efficiency, spatial scale, speed of deployment and social inclusivity of reef restoration in many different contexts. Their examples represent valuable learning experiences, highlighting a range of mechanisms through which management and policy interventions might aim to increase the scale of coral reef restoration. By combining ecological, social and economic strategies in a multi-dimensional approach to scale-up, reef restoration can deliver more beneficial and equitable outcomes locally, regionally and globally.

1. Introduction

Coral reef ecosystems around the tropics are threatened by a suite of global and local stressors [50,55]. Climate change, overharvesting, destructive fishing practices, water pollution, outbreaks of disease and coral predators, and increasingly frequent and severe storm events are all combining to cause great damage to reefs worldwide. The resulting dramatic changes to reef ecosystems threaten biodiversity and jeopardise ecosystem service provision for hundreds of millions of people [33,120].

Preventative management has traditionally been the dominant strategy used to protect coral reefs, through the implementation of marine protected areas (MPAs) and other restrictions on the use of reef ecosystems [26,46]. Whilst these strategies can be very effective in maintaining and improving reef health in many cases [69,73], it is becoming increasingly evident that preventative management alone will not be sufficient to protect reefs in the Anthropocene [3,4,61]. This is largely because the ecological benefits of marine reserves do not always persist in the presence of diverse threats such as climate-related disturbances [14,43], reduced water quality [66,68] and crown-of-thorns starfish outbreaks [89,116]. Further, while some damaged reefs do exhibit natural resilience [39,42], many fail to recover because of a lack of recruitment, the presence of unstable substrate, or phase shifts to macroalgal-dominated ecosystem states [32,41,62,65]. As such,

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successful reef management in the 21st century is likely to require a diversified 'toolkit' of conservation approaches, including both preventative management to reduce the impact of local stressors and active habitat restoration to rebuild reefs when irreversible damage occurs [81, 86].

Active coral reef restoration encompasses a broad range of techniques, including asexual propagation of transplanted coral colonies, the release of sexually-derived coral larvae and enhancement of natural substrate with artificial structures to increase habitat suitability [13,17]. A diverse range of restoration projects have been carried out across the tropics by academic, governmental, non-profit (NGO) and private sector organisations, over spatial scales ranging from square metres to hectares and temporal scales ranging from weeks to decades [24,52,93,97].

Perhaps the most pertinent challenge facing reef restoration today is the need to dramatically increase its operational scale. Coral reefs face threats that affect large areas in a short period of time, so effective interventions must have the capacity for large-scale implementation to match the scale of the problem [10]. Restoration programmes that regrow only small areas of reef are unlikely to be useful in responding to disturbance events that can cover thousands of square kilometres [23]. Similarly, restoration programmes that take decades to achieve progress are unlikely to be useful for responding to disturbance events that happen every few years [60]. As such, a key challenge for reef managers in the Anthropocene is to increase both the spatial scale and the speed of restoration programmes, by rapidly deploying successful techniques over large areas without compromising on quality or cost efficiency [110].

The challenge of large-scale restoration is especially pertinent in Indonesia – the global epicentre of coral reef diversity. Indonesia's 40,000 km^2 of coral reefs represent 16 % of the world's total – more than any other single country – and lie at the centre of the Coral Triangle, which contains 76 % of all coral species [15,111]. These diverse reefs are at high risk from local stressors such as overharvesting, destructive fishing practices, coastal development and water pollution [37]; indeed, a quarter of Indonesia's human population live within 10 km of a coral reef and 93 % of Indonesia's reefs are characterised as being threatened by local stressors [15]. This combination of high biodiversity and high prevalence of localised threats means that effective coral reef restoration is widely perceived as valuable and important in Indonesia, and recent decades have seen the establishment of hundreds of reef restoration projects across the country [93]; this is more restoration projects than have been documented in any other country in the world [13].

Whilst the majority of Indonesia's coral restoration projects currently remain small-scale, several of them have grown dramatically in recent decades, with some individual projects outplanting tens of thousands of coral fragments and running for nearly 20 years [93]. In this paper, we explore the multi-dimensional approaches that have contributed to the scaling up of some of Indonesia's restoration programmes. We identify ten approaches comprising ecological, social and economic processes (Table 1), discuss their theoretical underpinning and provide case study examples of their implementation in Indonesia (Fig. 1). These case studies are not intended to be an exhaustive list of restoration work in Indonesia (see Razak et al. [93] for a comprehensive review of Indonesian reef restoration programmes); rather, they represent a selection of projects that use a variety of different methods and span a wide range of geographies, organisation types and project sizes. By highlighting and learning from the achievements of successful Indonesian case studies, we hope to provide insight that can guide management and policy interventions concerning reef restoration worldwide. Although the unique circumstances of each of these individual projects mean that no single strategy can be replicated exactly in different contexts, many general lessons can be learned that may be applicable to other projects with similar goals.

Table 1
Summary of approaches taken by Indonesian coral reef restoration projects to increase their scale.

Approach	Spatial scale			Case study projects
	Local	Regional	Global	
Mixed approaches (socio-economic and ecological)				
1: Management of external threats	✓	✓		Yayasan Misool Baseftin (www.misoolfoundation.org); Yayasan Orang Laut Papua (www.theseapeople.org)
2: Strategic placement of projects	✓	✓	✓	Indonesia Coral Reef Garden [7]; Mars Assisted Reef Restoration System [101]
Socio-economic approaches				
3: Diversified participation	✓	✓	✓	Kelompok Sinar Bahari [88]; Karya Segara fishers group [105]
4: Local leadership	✓			Karya Segara fishers group [105]; Gili Trawangan community [8]
5: Supply chain management	✓	✓		Mars Assisted Reef Restoration System [101]
6: Centralised training hubs		✓		Coral Triangle Center (www.coraltrianglecenter.org); IPB School of Coral Reef Restoration (www.ipb.ac.id)
7: Business and industry involvement	✓	✓	✓	Sheba Hope Grows (www.shebahopegrows.com)
Ecological approaches				
8: Smart ecological design	✓			Bunaken EcoReef [72]; Sumbawa Reef Balls [6]; Jepara artificial patch reefs [75]; Mars Assisted Reef Restoration System [101]
9: Management of non-coral organisms	✓	✓		Yayasan Orang Laut Papua (www.theseapeople.org); Mars Assisted Reef Restoration System [101]
10: Evidence-based adaptive management	✓			Sumbawa Reef Balls [6]; Kuta coral transplants [80]; Karangasem artificial reefs [106]; Komodo rock piles [31]; Kapoposang coral transplants [108]; Mars Assisted Reef Restoration System [101]

1.1. Mixed approaches (socio-economic and ecological)

1.1.1. Approach 1: management of external threats

1.1.1.1. Theory. It is a central principle of restoration ecology that any attempts to rebuild ecosystems should be combined with measures to reduce further damage [35]. In this way, restorative and protective management strategies should be seen as complementary rather than mutually exclusive or redundant [86]. Restoration programmes that do not engage in efforts to reduce external threats are unlikely to see rapid ecosystem recovery and growth, because positive restoration progress will be hampered by ongoing degradation. As such, scaling up restoration efforts will not be possible without effective management of external threats.

On coral reefs, particular emphasis is placed on the need to reduce or mitigate water pollution, overharvesting and climate change impacts [24]. There are several examples where coral restoration success has been limited by recurring damage caused by these external stressors. Artificial reefs in the Maldives that initially reported the successful establishment and growth of hundreds of corals [20,21] later saw progress undone when 98 % of restored branching corals died in a bleaching event [27]. Additionally, the extreme variation in survival of outplanted *Acropora* corals in the Florida Keys has been linked to a range

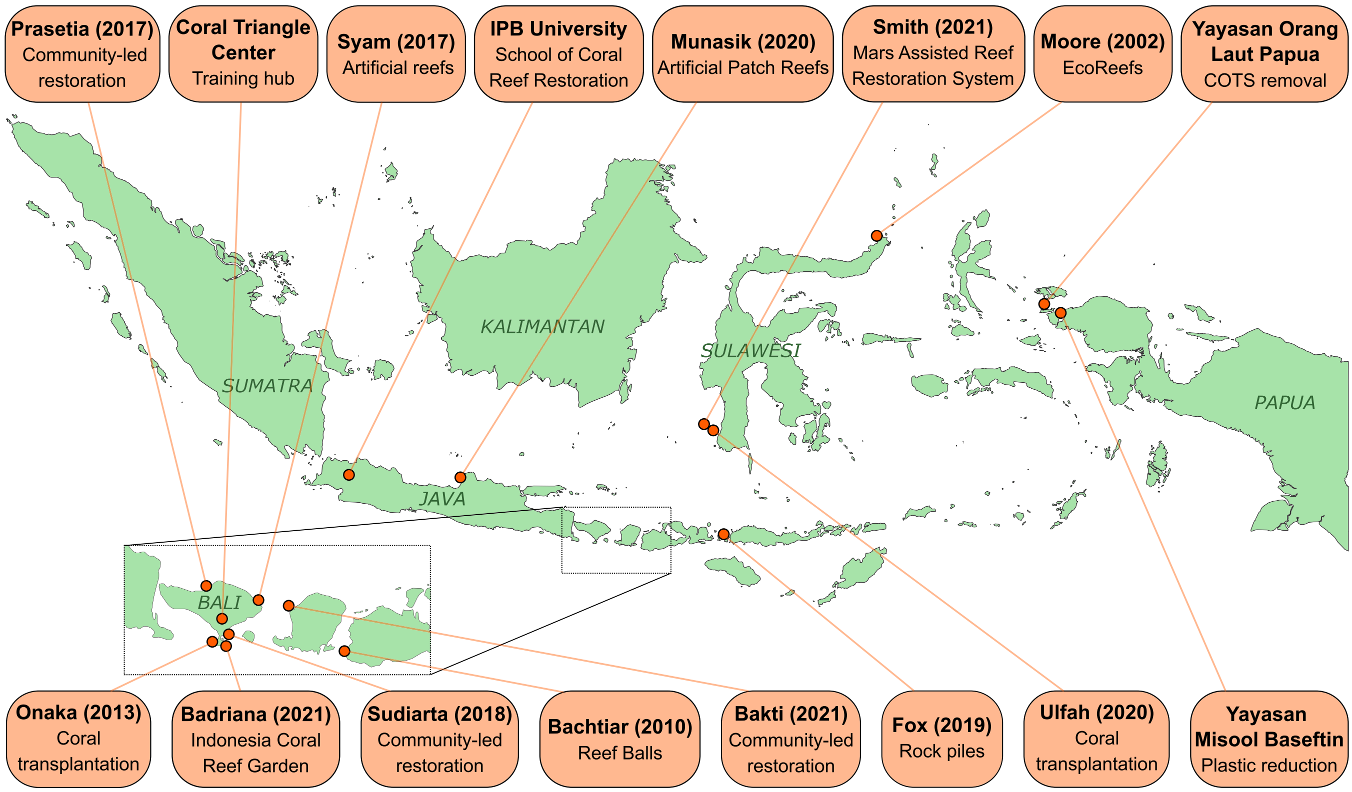

Fig. 1. Map of case studies of coral reef restoration in Indonesia. Each point refers to a case study that exemplifies one or more approaches to scaling up restoration (see Table 1). Abbreviated citations (or names of organisations, where no citations exist) are given in bold; the main restoration method used in each case is given in plain text. Case studies use a variety of different methods and span a wide range of geographies, organisation types and project sizes.

of external stressors [113,118], including the presence of *Dictyota* algae [119]. It is important that wherever possible, protective management strategies should be implemented and supported in tandem with restoration; sites where such management of local stressors is impossible are not likely to be well suited to restoration.

1.1.1.2. Indonesian example. There are many programmes across Indonesia that invest simultaneously in both habitat restoration and threat reduction. This approach is exemplified by two NGOs working in Raja Ampat. Yayasan Misool Baseftin (www.misoolfoundation.org) recognise that marine plastic can spread and exacerbate coral disease [67], so they organise a community recycling project called 'Bank Sampah Sorong Raya' that provides financial incentives for local communities to collect plastic rubbish to be sent to Java for recycling. Since 2014, the programme has collected over 2000 metric tons of recyclable plastic [30], reducing the potential for marine debris to cause harm to the reefs that they are working to restore. Similarly, Yayasan Orang Laut Papua recognise the threat posed by crown-of-thorns starfish (COTS) outbreaks [90]. In addition to carrying out coral restoration, they work with the Raja Ampat Marine Park Authority to organise a collaborative COTS reporting and culling programme (www.theseapeople.org/cots-in-raja-ampat). The NGO's website host a real-time interactive map of COTS outbreaks that can be populated by users in the field, and they provide training, equipment and capacity building to help local groups identify, report and remove starfish. It is important to note that external threat mitigation of this nature is supported by site selection to identify areas where threat reduction is possible (see Section 1.1.2), and regular ecological monitoring to help identify threats as they occur (see Section 1.3.3). Together, these approaches reduce the threats faced by both natural and restored reefs, allowing restoration to scale up faster and more effectively.

1.1.2. Approach 2: strategic placement of projects

1.1.2.1. Theory. Regional conservation initiatives are most effective if individual projects are placed strategically rather than at random [85]. For example, marine protected areas (MPAs) that are established as isolated units are less impactful than those established in an integrated approach that creates an ecologically connected network [100]. Simulations of the expansion of MPAs across Fiji revealed that a co-ordinated network of MPAs was more than twice as successful at meeting habitat representation objectives than an ad-hoc distribution [70]. Similar results were demonstrated in the Philippines, where coordinated networks were again more efficient than uncoordinated scenarios at representing different habitats [56]. The same premise is likely to be true for habitat restoration schemes – a connected network of restoration projects will likely have greater ecological benefit than a disparate set of randomly placed projects.

There are a diverse range of ecological and socioeconomic factors to consider when placing marine conservation projects within a regional strategy. One approach is to use known patterns of ecological connectivity, prioritising areas that have disproportionate potential to be important sources of larval dispersal. For example, marine reserves in the Bohol Sea were positioned to protect important sources of larvae so they might provide spill-over benefits to nearby areas [1], and similar approaches have also been used in several other reef systems around the world [45,54]. Alternatively, other approaches prioritise conservation efforts in places that have low vulnerability to external threats and therefore high likelihood of beneficial outcomes. For example, reefs that are less likely to face bleaching events under future climate change projections have been highlighted as wise investments in conservation [12]. In addition to these ecological considerations, some strategies also incorporate social context; patterns of local marine tenure have been incorporated into MPA plans in the Philippines, ensuring that costs and benefits of conservation are shared equitably between different fishing communities [115]. Across all of these examples, it is evident that site selection strategy can be guided by a complex range of biophysical, ecological and social parameters. By considering all of these factors together, a successful network of restoration projects can have beneficial impacts that exceed the sum of its parts [82].

1.1.2.2. Indonesian example. Several of Indonesia's restoration programmes have considered both ecological and socio-economic factors when choosing project locations. One recent example of this is the Indonesia Coral Reef Garden (ICRG) project in Bali. One of the primary objectives of this programme was to create up to 11,000 jobs, replacing lost employment associated with Covid-19 travel restrictions and the associated collapse of the tourism industry [83]. The locations chosen in Bali (one of Indonesia's busiest tourist destinations) reflect this objective, as this area was in particular need of job creation. Secondarily, ecological factors were then considered to locate the project within this wider area; standardised surveys were carried out to measure depth, water temperature, salinity, dissolved oxygen, pH, turbidity and benthic composition across the region, and these factors were combined using a simple addition weighting method to choose two locations that were suitable for coral growth [7].

The Mars Sustainable Solutions project in Sulawesi also considered multiple factors when choosing restoration sites [101]. An initial site in the Spermonde archipelago was chosen in part because this area is thought to be a climate refuge; regional patterns of wave-generated heat fluxes mean that reefs here are less likely to be impacted by bleaching than those in other areas of the world [5]. In recent years, further restoration sites have been established in collaboration with the Indonesian National Parks Authority (Balai Taman Nasional); in these additional sites, social context was often the primary driver determining site choice. Locations were chosen within existing MPAs where close collaboration between local communities and the Indonesian National Parks Authority had already been established. This ensured that restoration was being carried out in locations where existing community-linked marine conservation initiatives had already developed the necessary experience, relationships and trust to ensure success, dramatically increasing the speed at which new restoration projects could develop. As such, a mix of ecological and social factors combined to guide site selection in such a way that allowed projects to scale up efficiently in areas where future success was most likely.

1.2. Socio-economic approaches

1.2.1. Approach 3: diversified participation

1.2.1.1. Theory. Engaging and including a diverse range of stakeholders, particularly traditional owners, is a key concept in achieving successful conservation outcomes [92,96,104]. In marine and coastal ecosystems, the engagement of local communities has proven to be of pivotal importance in achieving effective management [19,114], and promoting local involvement is likely to lead to more equitable and impactful shared benefits [48]. By contrast, marine conservation projects that are characterised by low workforce diversity can be significantly limited in their effectiveness [103]. Importantly, diversified participation of a wide range of local stakeholders should happen across all phases of the planning, management and ongoing monitoring of programmes [35].

1.2.1.2. Indonesian example. Coral restoration is carried out by a wide range of participants across Indonesia, with projects organised by the government, private sector companies, universities, NGOs, local communities, student groups, tourist operators and dive clubs [93]. This approach is exemplified by the restoration group 'Kelompok Sinar Bahari' on the north coast of Bali; this project was set up by fishermen from Kaliasem village, with the aim of providing opportunities for the whole local community to learn about, engage with and participate in reef restoration and coastal resource management [88]. A similar community-driven approach taken by the Coastal Fishermen Group of Karya Segara (CFGKS) was similarly instrumental in transforming local environmental practice. Here, a group of 42 young fishers who had previously used destructive cyanide fishing and coral mining techniques decided to abandon these practices in favour of pro-environmental management, organise environmental education events amongst the local community and carry out coral reef restoration in collaboration with the tourism industry [105]. CFGKS mobilised support from the Environment Agency of Bali, the Ministry of Marine Affairs and Fisheries, the Government of Denpasar Municipality and several NGOs, in an inclusive programme that sought to engage multiple groups and become a community-wide motivating force for environmental sustainability. The fact that this project engaged a diverse range of participants from across the local community and was led by youths was felt to be particularly impactful in its achieving societal change, and the programme was awarded the "Kalpataru", Indonesia's national award for environmental management. By involving the whole community, rather than just a small subset of people, projects like this can substantially improve attitudes towards restoration – ultimately leading to greater levels of participation, faster scale-up and increased chances of long-term success.

1.2.2. Approach 4: local leadership

1.2.2.1. Theory. Whilst regional-scale strategy is demonstrably important in restoration planning (see Section 1.1.2), this must be balanced with the parallel need to consider the local context of each individual project. A common failure of conservation planning is that regional strategy and local projects do not inform each other [71], and it is widely recognised that restoration initiatives that fail to empower local communities and stakeholders are often unequitable and unsuccessful [11, 64,82]. Further, local support and leadership are recognised as key determinants of longevity in conservation programmes, which in turn facilitates effective scaling up [77]. It is important that local communities are empowered to decide and guide the priorities and targets of restoration initiatives in their area, accepting that these may not always align with the priorities of regional or national strategy [38]. Achieving this balance between the parallel needs for regional strategy and local leadership will require a level of inherent flexibility, allowing for dynamic adjustments that reflect both ecological and socio-economic context [91].

1.2.2.2. Indonesian example. The prioritisation of local leadership is an important challenge, faced especially by restoration projects that seek to involve multiple sites, partners and stakeholders. In some cases in Indonesia, restoration projects involving external partners have invoked concerns regarding dispossession and a loss of ownership of local resources [109]. In this instance, the project involved were able to make operational changes to their community engagement programme to alleviate the concerns of the individual families involved. Other multilateral Indonesian projects have also developed important approaches to ensuring that regional or international involvement does not come at the expense of local ownership and leadership. For example, restoration work at Gili Trawangan Island is carried out by a collaboration involving foreign businesses, academics, NGOs and the local government. Here, local leadership is maintained through the institutionalisation of traditional customary laws that regulate marine activities, which all stakeholders work together to uphold and implement [8]. This example highlights the importance of prioritising within-community leadership as a key principle to ensure scalable restoration success. Other relevant approaches to integrating multiple stakeholders and partnerships whilst maintaining local sovereignty are explored in Sections 1.2.1, 1.2.3 and

1.2.5.

1.2.3. Approach 5: supply chain management

1.2.3.1. Theory. Restoration processes are often complex and demand many different skills, including those that are interpersonal (liaising with stakeholders and communities), institutional (engaging with authorities), practical (sourcing materials, constructing and deploying restoration structures), logistical (managing budgets and workforces) and scientific (ecological monitoring of restored ecosystems). Any one of these requirements can limit the scale of restoration projects, even if other skillsets are present in abundance. A useful parallel for this challenge is the manufacturing industry, where making and selling products is also a complex process involving a diverse array of processes, any of which can become a limiting factor to success. For many years, manufacturing businesses have employed supply chain management as a tool to increase efficiency [57,107]. Complex tasks are broken down into discrete processes that relate to separate aspects of supply, manufacture or distribution, helping teams to increase their efficiency through specialisation. Supply chain management can address weak points in a process in several ways. First, rate-limiting steps can be identified and overcome with the addition of resources, expertise or altered strategy (termed 'debottlenecking'). Additionally, unsustainable processes such as overexploitation of raw materials or inefficient use of resources can be recognised and eliminated (termed 'life cycle analysis') [51]. Just like manufacturing processes, ecosystem restoration programmes can benefit from supply chain management, debottlenecking and life cycle analysis, because these management techniques create opportunities to identify and correct 'weak points' in the system. Programmes that address these weak points will ultimately be better equipped to rebuild ecosystems at large scales.

1.2.3.2. Indonesian example. As a company with a background of industrial manufacturing, Mars Sustainable Solutions have experience in supply chain management which they apply to their reef restoration project in Sulawesi [101]. The process of restoration using Reef Stars has been broken down into eleven discrete steps that each require different skills (Fig. 2). Within each step, local experts identify and improve areas where efficiency and/or sustainability might be increased, based on site-specific knowledge of process and its local context. This debottlenecking process has helped achieve high efficiency and increased scale in several areas. For example, raw material sourcing has been made more efficient by choosing materials that are readily available from local markets and communities. As a result of this 'localising' of the supply chain, restoration progress was not impeded by a lack of materials despite the global Covid-19 travel shutdown. Coral collection has also been made more sustainable through the creation of standardised operating procedures that ensure there is no damage to 'donor' reefs from which coral is harvested. Methodological refinements such as these are easier to identify and implement in a discretised supply chain than they would be if the restoration method was evaluated as a single process.

This supply chain management has also led to notably diversified engagement, as men, women and children from a range of different

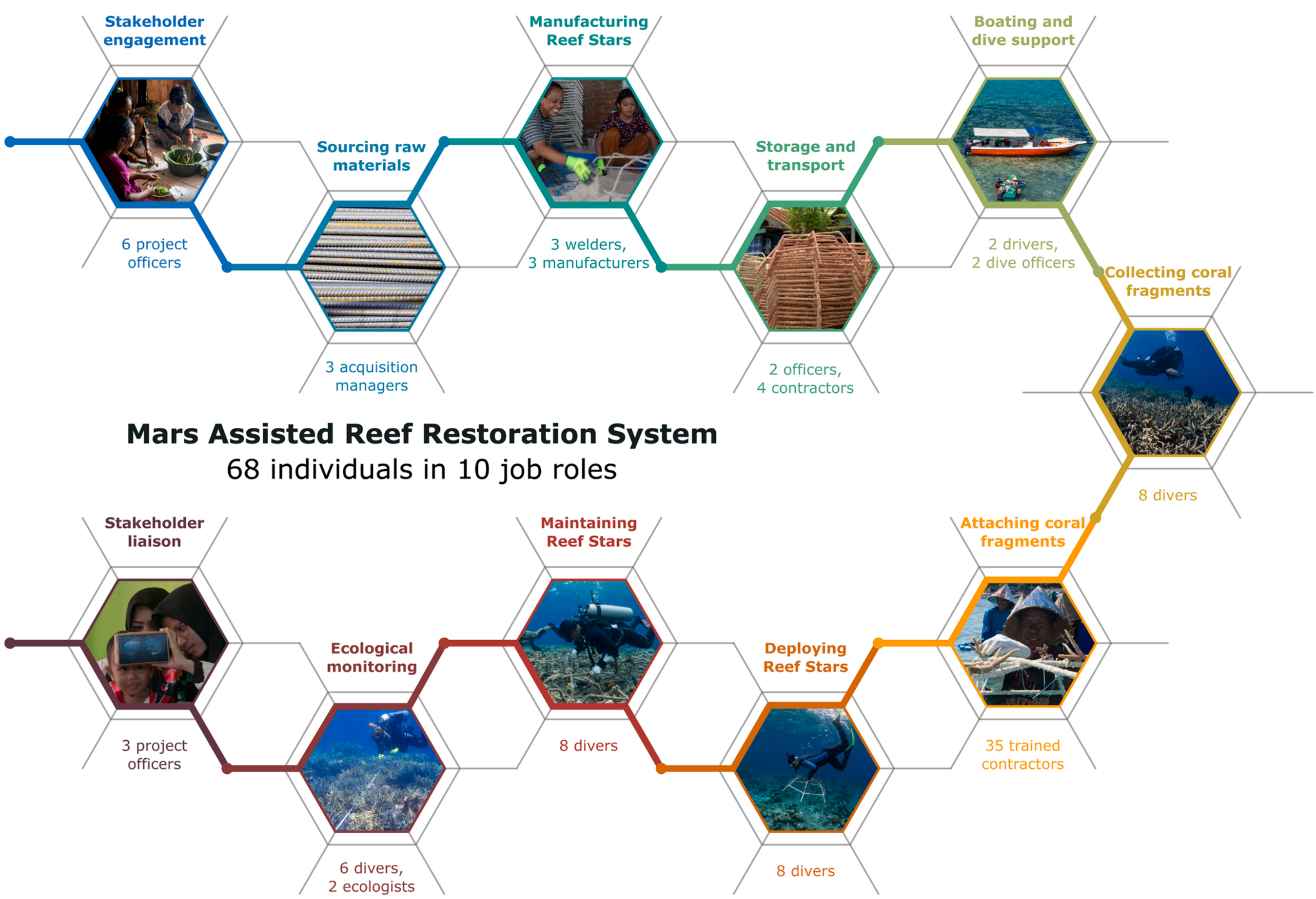

Fig. 2. The Mars Assisted Reef Restoration System (MARRS) as an example of supply chain management applied to coral reef restoration. The restoration process is broken down into a series of small steps, each of which is carried out by distinct groups of people with specialised skillsets. This maximises stakeholder engagement, expertise of participants and restoration efficiency. The stages shown in this schematic are illustrative of some aspects of the MARRS, rather than being an exhaustive list of all processes involved.

sections of the local community are now involved in the restoration process (see Section 1.2.1). For example, raw material sourcing is commonly done by working professionals from a nearby city; manufacturing of Reef Stars is often carried out by women living on rural islands; coral attachment is usually completed by local fishermen; and ecological monitoring often involves postgraduate students from a nearby regional university. Each of these different groups are skilled and experienced in their own individual tasks and therefore achieve high throughput, and the overall team network is noteworthy in its social diversity. As such, by dividing up the whole restoration process into smaller individual steps, Mars have been able to increase operational efficiency whilst simultaneously fostering multilateral ownership and decision-making.

1.2.4. *Approach 6: centralised training hubs*

1.2.4.1. Theory. Large-scale impacts of marine conservation are more likely to be seen through the combined effect of multiple projects across a region, rather than the isolated impacts of any single project ([44, 112]; see also Section 1.1.2). As such, restoration projects will have greater impact if they inspire, facilitate and support the establishment of other projects nearby, rather than remaining as isolated examples of success. Indeed, the effectiveness of learning and information sharing within networks has been identified as a key factor defining the success of marine conservation initiatives in the Coral Triangle [114]. Importantly, each individual project in a region will have different opportunities and challenges, meaning that information-sharing networks work best when they build capacity for local decision making and action using a range of different techniques, rather than attempting to roll out a single 'silver bullet' technique across all locations [110,114].

A 'hub and spoke' model represents an efficient mechanism for providing centralised training across a region. This model, whereby central 'hubs' connect a network of smaller 'spokes' (Fig. 3A) is widely used to increase the efficiency of transportation, logistics, communication and healthcare systems [2,29,58,59], and might usefully be applied to ecosystem restoration as well. Hub and spoke networks are particularly effective at maximising the two-way flow of information or resources between multiple nodes in a network. New restoration projects are likely to have greater success in a hub-and-spoke system than if they were isolated, because practitioners are equipped with the necessary skills, materials and support from the outset rather than having to 'start from scratch' and learn through their own experience.

1.2.4.2. Indonesian example. Several Indonesian initiatives are creating 'hubs' of restoration experience through which individual projects ('spokes') can connect and learn from other, similar initiatives. For example, the Coral Triangle Center (CTC) (www.coraltrianglecenter.org) acts as a regional coordinating body to facilitate information sharing, training, raw material sourcing and quality checking of individual restoration projects around Indonesia. The CTC is effective in this role because they have strong pre-existing connections to both national agencies and local communities, and experience of organising similar networks such as the Coral Triangle MPA Learning Network [112] and the Bali Reef Rehabilitation Network [18,22]. These networks bring together practitioners from across the region through in-person meetings and online platforms (e.g. www.facebook.com/groups/444534066278084/) to share lessons learned, discuss challenges and opportunities, standardise operational guidelines and work together to achieve better practice. Crucially, these networks allow for two-way sharing of information, meaning that practitioners learn throughout the lifetime of their projects rather than having 'one-off' training episodes with no ongoing capacity development. In early 2021, the CTC collaborated with the Indonesian National Parks Authority, Bloomberg Philanthropies and Mars Incorporated to establish the 'Coral Reef Restoration Task Force'. This group uses a hub and spoke model to build capacity for reef restoration and resilience-based management in MPAs across Indonesia (Fig. 3B). This partnership coordinates events where restoration practitioners from MPAs across the region come to Sulawesi to receive bespoke training in a range of restoration techniques. Training is customised for each location and target group, by applying scientific guiding principles into site-specific socioeconomic, cultural and historical contexts.

Another example of a central coordinating body facilitating knowledge exchange between restoration projects is the recently formed 'SCORES' (School of Coral Reef Restoration) at IPB University (www.ipb.ac.id/news/index/2021/12/departemen-ilmu-dan-teknologi-kelautan-ipb-university-launching-school-of-coral-reef-restoration/d0d8c1eb2eeb620d2cbdbbd210cdb143). This online community of scientists and restoration practitioners organise weekly webinars to share different approaches to reef restoration and learn from the experience of others. By facilitating two-way knowledge exchange within members of regional restoration networks, the CTC and SCORES are both streamlining communication between restoration projects, dramatically increasing the speed at which successful initiatives can be established and scaled up. These centralised training and knowledge exchange bodies are therefore important in enabling the acceleration of restoration success throughout Indonesia.

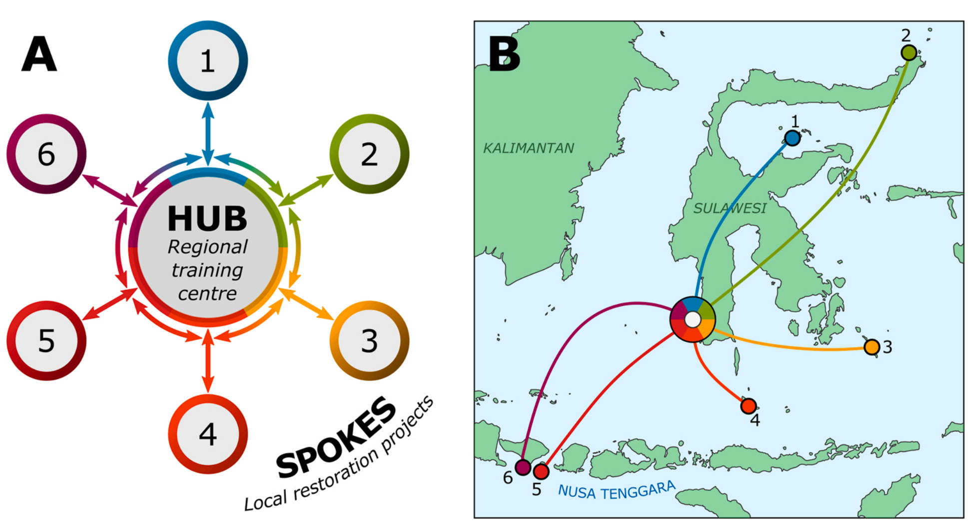

Fig. 3. The 'hub and spoke model' of centralised training applied to regional capacity building in coral reef restoration. A) A schematic depicting two-way information flow and knowledge exchange between a centralised hub (regional training centre) and peripheral spokes (local restoration projects). B) The Coral Triangle Center led the creation of a 'Coral Reef Restoration Task Force', which uses a hub and spoke model to build capacity for reef restoration in MPAs across Indonesia. Practitioners from six different MPAs are trained in reef restoration and resilience-based management through visits to the Mars Sustainable Solutions site in south west Sulawesi.

1.2.5. Approach 7: business and industry involvement

1.2.5.1. Theory. A major challenge for upscaling reef restoration around the world is to translate success in individual regions into positive restoration outcomes globally. Intersectional collaboration with large-scale businesses and industry is likely to be a valuable approach for supporting, financing and launching restoration on a global scale, for several reasons.

First, large businesses and industries may be well positioned to provide long-term financial support for restoration [9]. The continuity of multi-year funding is a key predictor of conservation success [48], but the world's coral restoration efforts are currently dominated by short-term projects; over 60 % of programmes report fewer than 18 months of monitoring data [13]. Businesses and industries with stable finances may be able to provide financial backing over time periods that will allow the restoration of mature, self-sustaining reefs [63].

Further, whilst the globalisation of restoration might be facilitated through centralised training (see Section 1.2.4), language barriers and long-distance travel often makes cross-continental collaboration difficult for small projects. By contrast, large-scale businesses are well equipped to bring together people and organisations across different geographies, disciplines and sectors. Partners across a range of industries are important because they will provide a diverse range of unique perspectives and opportunities for mobilising and financing restoration in different contexts [53,63]. For example, in some contexts tourist operators may be well placed to play a dominant role in leading restoration efforts; in other contexts, community-driven projects may be the best option; and in some settings governmental projects may be most effective. Large organisations will be able to span multiple industries to achieve a blended strategic model of this nature, involving a range of different restoration practitioners in multiple different socioeconomic contexts.

Finally, large businesses are well placed to mobilise a large number of people and generate widespread public engagement with restoration and conservation. This is essential both for participation in restoration activities themselves, and to generate the public awareness and community goodwill required to support restoration projects. Many businesses create valuable opportunities for public engagement with conservation, although care must be taken to avoid the inherent risks of 'greenwashing' associated with business' spurious claims to environmental sustainability [34]. If business involvement can be achieved in a genuine and equitable manner, it has the potential to drive global restoration scale-up by bringing together financial stability, international partnerships and effective community engagement.

1.2.5.2. Indonesian example. A diverse range of organisation types are currently involved in restoration across Indonesia, including corporate, governmental, NGO and tourist operators [93]. One current example of a large organisation unifying these multilateral partners to facilitate global scale-up is the SHEBA® brand's 'Hope Grows' campaign; a recent commitment to support reef restoration in every continent around the tropics over the next ten years (www.shebahopegrows.com). The involvement of this brand facilitates opportunities for global scale-up by combining large-scale business operations with local community-driven action. The initiative's first step is to establish collaborations with local partner organisations to create a network of regional centres around the world, which might act as restoration training hubs (Fig. 3C). This network of restoration projects involves a range of different partners; for example with the NGO Oceanus, A. C. in Mexico (www.oceanus.org.mx/en/marrs-en); with the governmental department GBRMPA (Great Barrier Reef Marine Park Authority) in Australia [36]; and with the hotel resort Hurawalhi (www.hurawalhi.com) and the Maldives Coral Institute (www.maldivescoral.org) in the Maldives. This diverse range of local partners are all well-equipped to deliver community-centred restoration projects, and by bringing them together with long-term funding and a global vision, the Hope Grows campaign is able to establish a network of restoration projects that is both internationally supported and locally led. This large-scale campaign was also able to generate far greater public interest than individual restoration projects usually do, with its launch reported by several of the world's largest international media platforms to an estimated audience of tens of millions of people. Coverage of this nature may have further beneficial outcomes for restoration worldwide by leveraging further funding and interest from other organisations. This synergistic collaboration between local communities, NGOs, private sector organisations, government authorities and large-scale corporations is an encouraging model for facilitating the large-scale implementation of coral reef restoration around the world.

1.3. Ecological approaches

1.3.1. Approach 8: smart ecological design

1.3.1.1. Theory. At a local scale, carefully considering the design of restoration systems can have significant positive impacts on the speed at which outcomes are achieved. For example, in some terrestrial plant systems, increasing spacing between propagules can increase survival and growth rates due to reduced competition for light and water [25,87]. In other cases, the opposite is true; planting or deploying propagules closer together can increase success through positive facilitative interactions [94]. For example, planting marsh grass seedlings closer together can increase growth rates and survival by augmenting sediment stabilisation and oxygen sharing [99]. These examples all demonstrate that across a range of biomes, small adjustments to the positioning and context in which restoration propagules are planted can make a disproportionate difference to their survival and growth. Employing 'smart ecological design' – planting restoration propagules and units in configurations that maximise individual survival, growth and performance – is therefore a key decision-making strategy that increases the efficiency and scale of restoration projects. In many cases, this can be facilitated through the use of modular restoration systems that allow outplanting in a range of different designs and densities.

1.3.1.2. Indonesian example. Many of the most commonly used restoration techniques in Indonesia today involve the deployment of repeated modular units, such as Reef Balls [6], EcoReef [72] and Reef Stars [117]. These modular structures all allow for flexibility in outplanting configurations, to achieve smart ecological design. For example, in the Mars Assisted Reef Restoration System, coral fragments are attached to modular hexagonal steel structures called Reef Stars, which are connected together in interlocking networks on degraded reef flats [101,117]. Each of these Reef Stars can have a variable number of coral fragments attached to them, in differing orientations and positions; this gives the opportunity to carry out simple experiments to determine the optimum spacing and species configurations to achieve different goals. For example, in a modular outplanting system used in Central Java, coral fragments can be deployed in both horizontal and vertical positions, allowing flexible approaches depending on environmental context [75]. In some cases, horizontally-planted fragments exhibit higher survival due to increased stability and reduced susceptibility to wave damage [75], but in other contexts vertically-planted fragments survive better because they are less at risk of sedimentation [79]. As such, the ability to plant corals in different configurations facilitates strategic variation that might lead to increases in restoration success.

As well as fixing corals to restoration modules in different arrangements, the modules themselves can also be arranged in different configurations to meet different goals (Fig. 4). For example, where projects aim to achieve high levels of continuous coral cover and a physical structure that can withstand a high degree of wave energy, Reef Stars can be arranged in a compact design. This configuration facilitates rapid

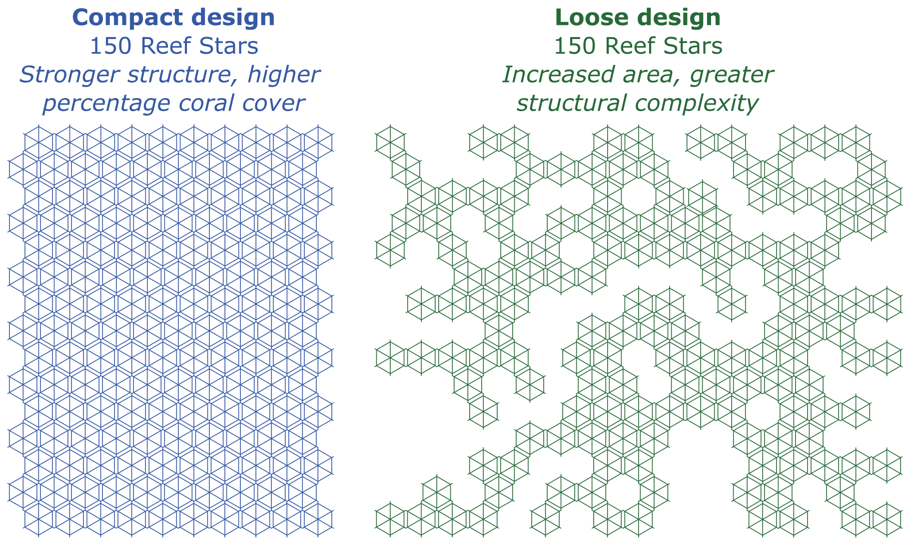

Fig. 4. Mars Assisted Reef Restoration System 'Reef Stars' deployed in different configurations. Altering the build configuration has the potential to create different functional outcomes. Compact designs (left) are likely to achieve higher percentage coral cover and withstand a greater amount of wave energy; loose designs (right) potentially cover a wider spatial area, lead to greater multi-dimensional habitat diversity and allow for building around other natural or artificial structures.

increases in percentage coral cover [117] and ensures that all Reef Stars are supported by a tight lattice that can withstand strong waves without sustaining major damage. Alternatively, where projects aim to achieve a more heterogenous reef environment with greater multi-dimensional structural complexity, a loose design can be employed that includes spaces between Reef Stars. This loose configuration covers a greater spatial area with the same number of Reef Stars, and potentially creates greater structural complexity and a wider diversity of habitat niches for fishes and other reef-associated animals, because there are more spaces between Reef Stars for larger animals to shelter. The loose configuration also allows Reef Stars to be arranged around existing natural structures (such as coral bommies) or other restoration techniques. As such, the modularity of the restoration system creates opportunities for smart ecological design that leads to flexible deployment strategy and the opportunity to prioritise different ecosystem functions and outcomes in different scenarios.

Whilst modular systems create many opportunities for strategic restoration outplanting, it is important to note that this is not the only way of achieving smart ecological design. Where resources are not available to create modular systems, some of the same design principles may be valuably applied to other outplanting methods. Indeed, further understanding of the impacts of different design strategies on functional performance and growth will be key to achieving increases in scale across a wide range of methods in different ecological contexts.

1.3.2. Approach 9: management of non-coral organisms

1.3.2.1. Theory. In many cases, 'non-target' organisms and connected ecosystems can have significant impacts on the likelihood of restoration success [110]. For example, mangrove forests and seagrass meadows often form important cross-habitat ecological networks with coral reefs, contributing to ecosystem function and service provision [47,74,76,95]. Simultaneous co-restoration of these complementary habitat types is likely to be a beneficial strategy for increasing the scale and success of coral restoration. Additionally, co-restoration of particularly beneficial individual species can improve the survival and growth rate of coral. For example, programmes in the Caribbean are experimenting with co-restoration of *Diadema* sea urchins and coral, because sea urchins can elevate grazing function on restored ecosystems and enhance survival and growth rates of outplanted corals [16,84]. Conversely, other species can be detrimental to coral growth, and efforts should be made to reduce their impact [116]. As such, considering the impacts of non-coral species and ecosystems can be an important aspect of increasing the efficiency and scale of coral restoration.

1.3.2.2. Indonesian example. Several Indonesian restoration programmes make efforts to manage the impacts of non-coral species and ecosystems on coral restoration success. In the Mars Assisted Reef Restoration System (MARRS), careful consideration is given to avoiding the negative impacts of macroalgal overgrowth on juvenile coral settlement and survival [102,119]. First, macroalgae is manually removed from restoration sites by SCUBA divers for the first three months after coral outplanting. Second, farming damselfish are removed from sites, to prevent their cultivating of large patches of fleshy macroalgae which inhibits juvenile coral growth and survival [40,98]. These approaches both reduce the prevalence of macroalgae in the early stages of restoration, helping to increase the survival and growth of outplanted corals [101,117]. The Yayasan Orang Laut Papua programme also manages non-coral organisms, through its collaborative programme to monitor and remove crown-of-thorns starfish from its restoration sites and the surrounding reefs (see Section 1.1.1). In both of these programmes, considering the management of non-coral species creates opportunities to increase the growth and survival rates of coral, scaling up restoration success.

1.3.3. Approach 10: evidence-based adaptive management

1.3.3.1. Theory. Ecological, social and economic monitoring are all essential for the successful management of coral reefs, because together they provide an evidence base for carrying out adaptive management [78]. This is especially relevant in the case of restoration, where monitoring is necessary for understanding the impacts of interventions, enabling practitioners to identify techniques that work well and scale them up to achieve maximal impact [28,35]. Importantly, successful monitoring also allows programmes to modify or stop approaches that are not having desired outcomes. However, the necessity for monitoring is often overlooked by restoration programmes; in a recent global review, fewer than half of projects with ecological objectives were carrying out ecological monitoring [13]. Across more than 500 records of restoration projects in Indonesia, 16 % mentioned having a post-installation monitoring framework in place [93].

A lack of effective monitoring makes scaling up restoration difficult because it reduces the available information about which methods are most effective in different contexts, precluding evidence-based decision making on restoration strategy [28]. Conversely, projects that do engage in regular monitoring are likely to be able to identify successes and failures early, learn from these experiences and move to rapidly scale up successful restoration initiatives [121]. This concept applies to both ecological and socio-economic metrics; monitoring ecological impacts on reef ecosystems alongside records of restoration costs, and economic and social impacts in local communities and stakeholder groups, will allow for meaningful evaluation of the cost efficiency and wider impact of restoration interventions [49].

1.3.3.2. Indonesian example. Several Indonesian projects that have implemented monitoring programmes have gained valuable insights into the relative effectiveness of different aspects of their projects, allowing them to scale up the success of subsequent restoration work. For example, a project using rockpiles in Komodo National Park has collected a time series of nearly 20 years of monitoring data [31]; this is one of the longest time series of its kind in the world [97]. This dataset was pivotal in allowing comparative analysis of the factors affecting restoration success, meaning that future projects can increase the efficiency and scale of their efforts [31]. For example, the data revealed that hard coral growth was markedly lower in areas with high tidal currents, suggesting future restoration efforts might consider this aspect of the environmental conditions when defining their restoration goals [31]. Additionally, simultaneous collection of economic data facilitated a comparative analysis of different management strategies for the Komodo National Park, comparing the cost-effectiveness of this coral restoration with that of marine patrols to enforce blast fishing bans [49]. As such, monitoring of both ecological and socio-economic metrics can underpin evidence-based decision making, allowing restoration interventions to be carried out with greater efficiency.

There are several other examples from around Indonesia where similarly valuable lessons have been learned from regular monitoring of restoration projects. For example, monitoring programmes in Bali [80] and Sulawesi [108] have provided useful reference measures of coral growth rates on restored reefs, and a 15-year monitoring dataset provided evidence of recovering fish diversity on artificial reefs in Bali [106]. Monitoring of coral recruitment to Reef Balls at Sumbawa Island demonstrated that three years after deployment, coral colony abundance was ten times lower on Reef Balls installed in 10–12 m depth than those in shallower water, probably due to increased sedimentation on these deeper structures [6]. This suggests that future restoration in this site might valuably be focussed at shallower depths. Regular monitoring at the Mars Sustainable Solutions site in Sulawesi has allowed responsive changes in both ecological and social strategy. Ecological monitoring data demonstrated that a minor bleaching event in 2021 affected only corals occurring at 3 m or shallower, leading to subsequent builds having a minimum depth of 4 m. Results from social surveys demonstrated that top-down approaches to community engagement were not reaching the whole community, leading to subsequent approaches having a more integrated structure. In all of these examples, regular monitoring provides important evidence of the effectiveness (or otherwise) of different restoration techniques, allowing for responsive modifications of strategy and effective scaling up of successful approaches. This adaptive management framework can help restoration projects to optimise their delivery of certain functions; projects that regularly evaluate their performance can more effectively target specific goals such as fisheries benefit, coastal protection or biodiversity increases.

2. Concluding remarks

Active restoration is a promising new tool for managing the Anthropocene's rapidly changing coral reef ecosystems, but in order to be effective it must be scalable. Indonesia has more coral, and more coral restoration programmes, than any other country in the world, and the operational capacity of these programmes has been increased through a diverse range of ecological and socio-economic processes (Table 1).

Regional, national and international policy surrounding coral restoration could now use these ten principles to facilitate further scaling up of reef restoration worldwide. Whilst there is no single 'silver bullet' solution for effective restoration, the implementation of these ten approaches could help restoration programmes to achieve more meaningful and lasting impact. For example, environmental legislature could demand that restoration programmes support local marine tenure and leadership (Section 1.2.2). Permit awarding bodies could insist on the collection and sharing of ecological monitoring data (Section 1.3.3), and the implementation of measures to mitigate local stressors that might undermine restoration success (Section 1.1.1). Central governing bodies could create or support regional training centres to accelerate the uptake of successful restoration methods (Section 1.2.4). No single approach is more or less important than others; rather, practitioners should seek to employ as many as possible of these principles, within the bounds of resource availability and local context.

By learning from these multi-dimensional examples of Indonesian success, decision makers and restoration practitioners across the tropics may be able to substantially increase their operational capacity. This upscaling of restoration progress could provide greater benefit to the reefs and people that restoration programmes aim to serve.

CRediT authorship contribution statement

Timothy AC Lamont: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Tries B Razak:** Conceptualization, Investigation, Data curation, Writing – review & editing. **Rili Djohani:** Conceptualization, Writing – original draft, Writing – review & editing. **Noel Janetski:** Conceptualization, Investigation, Writing – review & editing. **Saipul Rapi:** Conceptualization. **Frank Mars:** Conceptualization. **David J Smith:** Conceptualization, Investigation, Writing – review & editing, Visualization, Project administration.

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