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THE CORAL ENGINE: THE WAY FOR LOCAL COMMUNITIES TO SUSTAINABLY PRODUCE CORALS FOR REEF REHABILITATION AT A LARGE SCALE

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ABSTRACT

Traditionally, marine infrastructure development is regarded to have a negative impact on the ecosystem in or near which it occurs. As a consequence, a whole industry has been treated as a threat and the ingenuity of companies in this industry was forced to focus on minimizing potential negative impacts. Recent trends are to also consider potential positive spin-offs, by including nature-based components in the designs.

In this context, Dutch dredging and marine contractor, Van Oord, launched its Coral Rehabilitation Initiative in 2010. A mobile laboratory, named ReefGuard, was developed, to be operated anywhere in the world for sexual reproduction and rearing corals at a large scale (Van Koningsveld *et al.*, 2017). ReefGuard is used to initiate 'Coral Engines': large scale nurseries with corals obtained through sexual reproduction as well as from fragmentation. These Coral Engines guarantee the long term and large-scale supply of genetically diverse corals for reef creation and rehabilitation. Having coral 'in stock' furthermore allows reefs to be repaired quickly following harmful events such as hurricanes. The involvement of local stakeholders in its setup and operation foresees in sustainable opportunities for research, education and awareness, and local employment.

Since 2010 ReefGuard has been applied in five large scale field applications (Australia 2014, 2015, The Bahamas 2015, 2016, 2017) (Van Koningsveld *et al.*, 2017; Robijns *et al.*, 2018; Schutter *et al.*, 2018) producing thousands of sexual recruits consistently. In 2017 a first Coral Engine was delivered with several tens of thousands newly settled coral recruits, and hundreds of one year old recruits and fragments. This paper explains the concept of the Coral Engine in more detail and shares perspectives for future implementation along marine construction projects across the world.

Marine infrastructure projects thus become opportunities for coral reef rehabilitation with essential financial and logistical capacity on site, and often also a legislative requirement for compensation of harmful environmental impact.

Keywords: Coral, Stakeholder, Sustainability, Restoration.

INTRODUCTION

Coral reefs are globally threatened by anthropogenic stressors such as overfishing, pollution, and infrastructural developments for urbanization of coastal areas and growing global trade by shipping (Hoegh-Guldberg *et al*., 2007; Pandolfi *et al*., 2011; Hughes *et al*., 2018), resulting in the decline of reef-building coral populations and live coral cover. Passive conservation efforts, such as designating marine protected areas (MPAs), have largely yielded insufficient results in reef recovery (Rinkevich, 2008). To effectively cope with reef degradation, passive conservation measures should be complemented with unconventional, non-passive methods (Hoegh-Guldberg *et al*., 2007; Rau, McLeod, & Hoegh-Guldberg, 2012; van Oppen *et al*., 2017) such as active reef rehabilitation techniques (Rinkevich, 2005). Over the past two decades, the coral gardening concept by means of asexually propagated corals has been successfully applied with dozens coral species in all regions of the world (Rinkevich, 2014). A different approach to reef rehabilitation includes the production of sexual coral recruits from wild-caught gametes that are released during annual mass spawning events (Petersen & Tollrian, 2001; Pollock *et al*., 2017; Rinkevich, 1995). Similar to the coral

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gardening approach, sexually produced coral recruits may undergo an ex situ rearing or nurturing period before being outplaced onto the reef (Guest *et al.*, 2014). Sexual reproduction promotes genetic exchange between individuals and increases genetic variation within populations (Bengtsson, 2003). As an asexual approach does not directly achieve the desired increase in genetic diversity in these reefs that in turn increases species and reef resilience (Elmqvist *et al*., 2003; Hughes, 2003), the addition of sexual recruits has considerable value to asexual propagation techniques in reefs where sexual recruitment is impaired (Kojis & Quinn, 2001; Petersen & Tollrian, 2001).

For reef rehabilitation to have a significant impact, it is crucial to develop methods that enable implementation at a large scale. The implementation of large-scale initiatives requires a substantial amount of time and effort, and needs to be optimised to be able to significantly counteract reef degradation on a global scale. This paper provides insight in the main developments within the Van Oord Coral Rehabilitation Initiative, and what these can mean for future applications in hydraulic infrastructure development projects.

Van Oord's Coral Rehabilitation Initiative

New sustainable design philosophies, like the 'Building with Nature' approach, aim to be proactive, utilising natural processes and providing opportunities for nature as part of the infrastructure development process (De Vriend & Van Koningsveld, 2012; De Vriend *et al.*, 2015). Other similar philosophies have emerged, such as 'Working with Nature' promoted by PIANC (PIANC, 2011) and 'Engineering with Nature' promoted by the US Army Corps of Engineers (Bridges *et al.*, 2014). In line with this trend, Dutch dredging and marine contractor Van Oord, launched a Coral Rehabilitation Initiative in 2010 as part of its Marine Ingenuity and Corporate Social Responsibility program. The main idea of this initiative is to use already proven coral propagation techniques at a significantly large scale to promote true environmental gain around coastal and marine infrastructure projects. In order to achieve the Coral Rehabilitation Initiative's objectives, it was essential to enhance the understanding of the positive or and/or negative effects of in- and ex-situ culturing intervals, potentially in combination with various treatment regimes. In addition, it was crucial to learn about the most effective outplacement approaches.

The ReefGuard facility

The ReefGuard is a land-based coral breeding facility that has been developed by Van Oord, to enable the production of huge amounts of sexual coral recruits anywhere across the world (see Figure 1; van Koningsveld *et al*., 2017). The ReefGuard offers a controlled environment to facilitate fertilisation of gametes, settlement of coral larvae, and rearing of growing coral recruits (see Figure 2). The ReefGuard consists of a set of laboratory containers that can be operated at any desired location in the world. To advance the use of the ReefGuard for reef rehabilitation at a large scale, the methods for successful assisted fertilisation and rearing of corals was well-studied and optimized in experimental studies over de years 2014-2017. A critical step in this process was the enhancement of larval settlement rates. The complex settlement cues for many coral species are still largely unknown and can furthermore be affected by ongoing climate change (Webster *et al*., 2013). The ReefGuard facilities allow to enhance larval settlement rates by optimising factors such as substrate type, water quality, larval age at settlement (i.e. days after fertilisation), and settlement time (i.e. period of time the larvae are incubated to settle on substrates). Furthermore, transplanted corals that are cultured ex-situ for a period of time have a higher survival rate than corals transplanted to the reef earlier (Guest *et al*., 2014). Thus, the selection of an optimal aquaculture period is an important design parameter for rehabilitation efforts. However, costs of maintaining corals in nurseries are high (Edwards, 2010). As such, much of the ReefGuard experiments were designed to increase practical understanding of factors that enhance settlement rates as well as that determine optimal aquaculture lengths.

Figure 1. Left: ReefGuard facility (orange/blue containers and tent) operational in the Bahamas (August 2015); Middle-top: Filter container aimed at maintaining proper water quality; Middle-bottom: Wet laboratory designed to handle multiple smaller basins and to perform microscope inspections; Right-top: Aquarium laboratory designed to provide a high level of environmental control (container on the left in the top panel). Right-bottom: Patio area with a range of basins that can be used in various stages of the breeding process (from: Van Koningsveld *et al*., 2017).

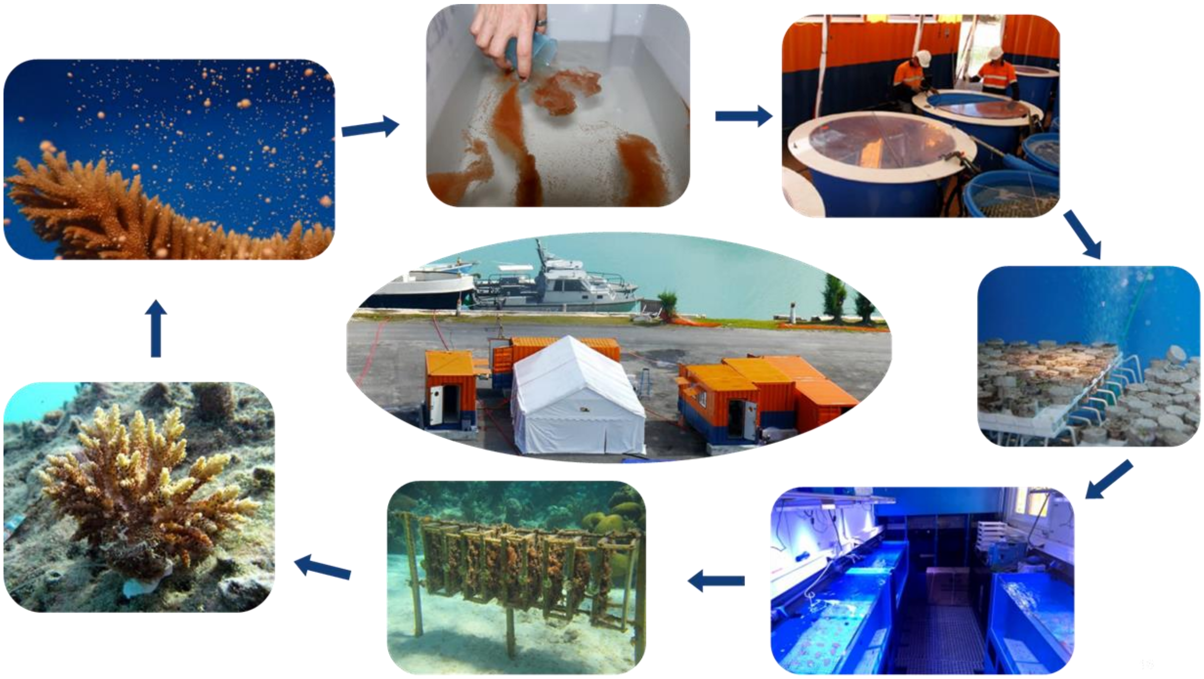

Figure 2. The coral reproductive cycle in the ReefGuard: Buoyant gamete bundles rise to the water surface after mass spawning where they are carefully collected. Gametes from different colonies are gently mixed for fertilisation after which the embryos go through several developmental stages to become coral larvae. These larvae are reared for a couple of days until they become settlement-competent and are offered suitable substrates to settle on. Once attached and metamorphosed into small coral recruits, they're placed in an in situ nursery where they continue growing into adult colonies until being permanently outplaced at a reef.

The Coral Engine

The ReefGuard system produces thousands of coral recruits obtained from natural mass spawning events. These coral recruits of various ages are placed in nurseries in the open sea. The nurseries can furthermore be filled with coral fragments obtained from existing reefs to accelerate the production of coral biomass, and thereby become so-called Coral Engines. Nurseries to asexually propagate corals from fragments are common practice (Rinkevich, 2014), but this combination of both asexually and sexually produced corals in a nursery is novel. A Coral Engine is an in situ coral nursery that contains both i) locally sourced coral fragments and ii) sexually produced coral recruits obtained from natural coral spawning events. It combines the advantages of quick biomass production using coral fragments, with ensuring genetic diversity from sexual reproduced corals to enhance resilience.

Opportunities for collection of fragments without purpose-specific damaging thriving reefs, arise from unforeseen natural impact on reefs, such as caused by hurricanes, or from anthropogenic impact, such as destruction required for infrastructural development of for example ports and waterways. These impacts foresee in ‘fragments of opportunities’ that can be recycled and used for mass coral production in the Coral Engines. Both the sexually produced recruits reared in the ReefGuard and the fragments of opportunity will grow into mature colonies which in time will provide a continuous supply of i) full-fledged colonies for transplantation to rehabilitate or create reefs, ii) fragments to establish new nurseries and iii) gametes for natural reproduction during coral spawning (see Figure 3).

As the corals grow, the Coral Engine provides a continuous source of full-grown outplantable coral colonies. Local stakeholders should preferably take ownership of the Coral Engine to guarantee the long-term operation and maintenance of it. Having coral 'in stock' allows the owners to create new reefs when desired, and to quickly restore or rehabilitate reefs following harmful events such as hurricanes.

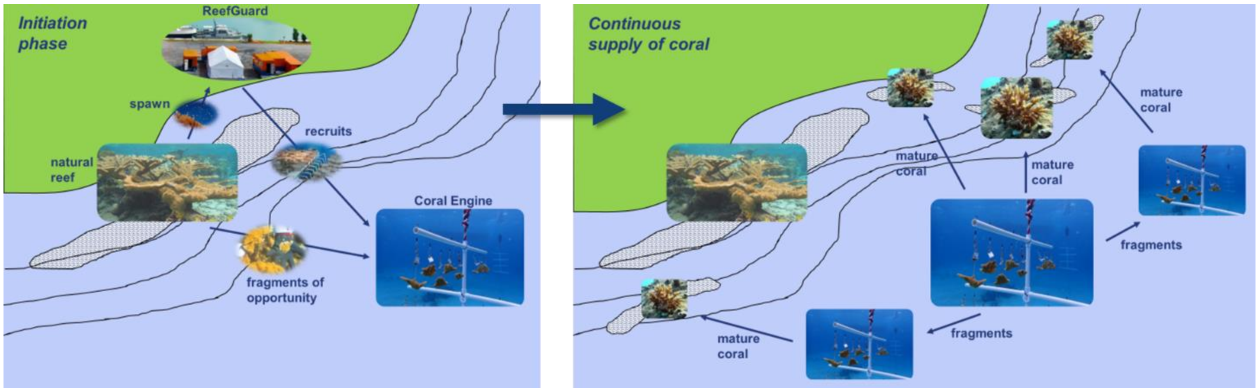

Figure 3. The initiation phase of the Coral Engine consists of setting up a coral nursery filled with both sexually reproduced recruits and fragments of opportunity (left). Over time, this nursery provides genetic diverse mature coral colonies that can be used for creating and/or rehabilitating coral reefs, and to expand the amount of ‘coral in stock’ by establishing more nurseries (right). The outplaced mature coral colonies produced by the Coral Engine will contribute to the continuous coral regeneration via natural spawn events.

ACHIEVEMENTS

After the design and construction of ReefGuard was completed in 2013, it was applied in five field experiments. The five pilot projects – two on Ningaloo reef in Australia (2014 & 2015), and three on in the Bahamas (2015, 2016 & 2017) were successfully executed (Van Koningveld *et al*., 2017; Robijns *et al*., 2018; Schutter *et al*., 2018).

The experiments provided the essential knowledge and practical know-how on how to perform controlled coral breeding experiments at quite remote locations as dictated by the presence of coral reefs, and of an ecologically significant scale (tens of thousands of surviving juveniles to work with). Overall it can be concluded that the initial objectives of the Coral Rehabilitation Initiative were successfully achieved (van Koningsveld *et al*., 2017): The ReefGuard proofed to be a mobile highly controlled environment for coral breeding activities which can be applied at basically any project site in the world, also under extreme environmental conditions (heat, dust, hurricane force winds). Gametes can be successfully collected both in-situ (with a diving team at night) and ex-situ (both on a jetty and inside the ReefGuard). The collected eggs can be successfully fertilised, yielding >1 million larvae consistently that can be nurtured up to the stage that they are ready to settle (Van Koningsveld *et al*. 2017, Robijns *et al.* 2018, Schutter *et al*., 2018). The coral larvae can be settled on substrates of choice (such as aragonite tiles and different types of ropes) by tens of thousands (Robijns *et al.* 2018). Treatments with additional feeding during the ex situ culturing phase for several months enhances the in situ survival and growth of the recruits after outplacement in nurseries (Schutter *et al*., 2018). Recruits reared in the ReefGuard that were outplaced in nurseries on the reef were found to have significant number of survivors after several months to years, and are ready to be used for active reef rehabilitation (Van Koningsveld *et al*. 2017, Schutter *et al*., 2018).

The first Coral Engine was established at Goulding Cay, a reef near the western tip of the island New Providence, Bahamas in August 2017. Different nursery structures were installed, i.e. 9 racks, 10 PVC trees, and 1 rope table (see Figure 4). These structures were filled with recruits of elkhorn coral *(Acropora palmata)* reared in the ReefGuard, 472 reared in 2016 and ~29,500 reared in 2017. Also, 200 fragments of elkhorn coral were added, collected from 10 different sites around the island.

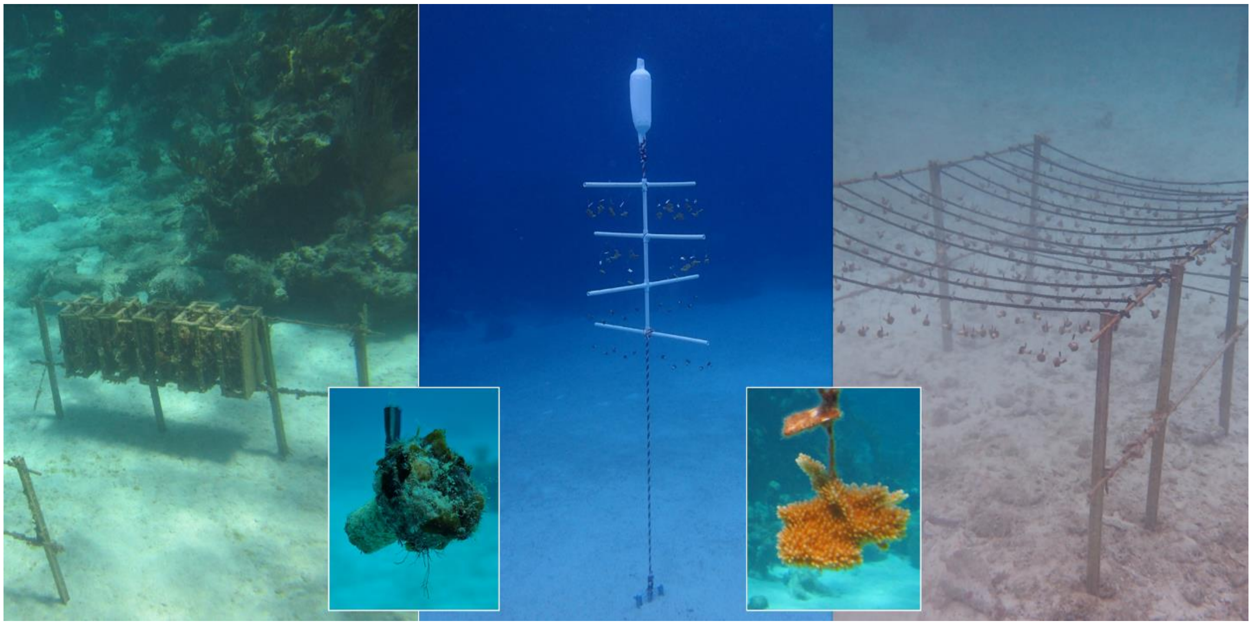

Figure 4. Coral Engine at New Providence, Bahamas, consisting of racks (left), PVC trees (middle) and a rope table (right), filled with coral recruits growing on aragonite plugs and with coral fragments.

Local parties were involved at an early stage of the coral propagation activities to achieve long-term operation of the Coral Engine: the diving centre Stuart Cove's Dive Bahamas, the NGOs Bahamas Reef Environment Education Foundation and the Reef Rescue Network of the Perry Institute for Marine Science, and the governmental authority Royal Bahamas Defence Force. To enhance the commitment to ownership by local partners an official event was organized to officially hand over the newly installed Coral Engine by Van Oord to the stakeholders. In the presence of 150 invitees including the Bahamian Minister of Works, the Coral Engine was assigned to the local stakeholders. By accepting ownership, these parties devoted themselves to the joint maintenance the Coral Engine and the encouragement of conservation groups, schools, members of the public and tourists to visit the site and become actively involved with its continued development and the subsequent outplacement activities.

Initially at the moment of installation, each of the 10 PVC trees contained 8 arms, of which 4 contained each 5 plugs with recruits of year class 2016 (200 plugs with recruits in total), and 4 contained 5 fragments per arm (200 fragments in total) (see Figure 4). A maintenance exercise was undertaken three months after deployment to clean the structures from a modest algae growth. Despite the passing by of hurricane Irma, all 10 structures looked in order. One year after deployment of the Coral Engine, a more extensive monitoring exercise was undertaken lead by the Reef Rescue Network to determine the survival and health status of the recruits and fragments outplanted in the 10 PVC trees. Some damage was observed, i.e. 1 structure was missing with only the anchor remaining, another structure was missing two arms, and several individual fragments and plugs with recruits were also missing. Damage to the structures were likely caused by small boat anchoring, as no major storms too place since the previous observation.

Out of the 200 plugs with recruits outplanted originally, 173 were still remaining in the PVC trees, with 30% of these plugs still having 1 or more coral recruits growing on them. These recruits all look very healthy and some had grown up to several centimeters (see Figure 5). Out of the 200 fragments outplanted originally, 163 were still remaining of which 96% were in excellent condition (>90% healthy tissue), 2% in good condition (>50-90% healthy tissue) and 2% in poor condition (1-50% healthy tissue). All fragments had grown, up to double their size (see Figure 5).

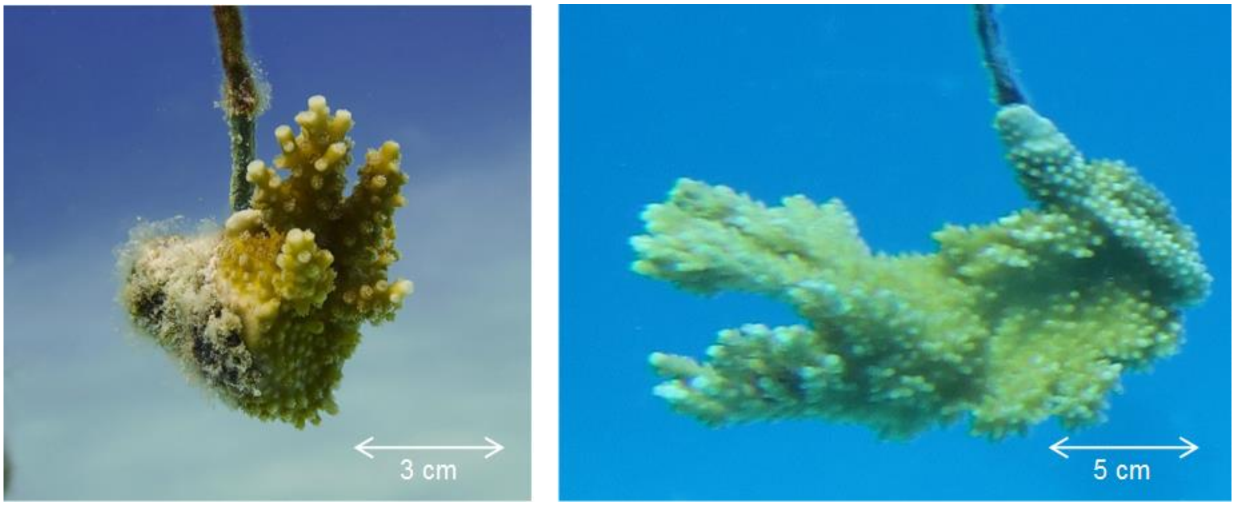

Figure 5: A two year old recruit (left) and a fragment (right) of *Acropora palmata*, one year after outplanting in the Coral Engine. The recruit has grown from pinhead into a multi-branched small colony during this year, the fragment has doubled in size.

CONCLUSIONS

The Coral Rehabilitation Initiative has demonstrated through field experiments in Australia and in the Bahamas that active reef rehabilitation by means of the ReefGuard and Coral Engine can become a viable part of marine and coastal infrastructure development. These successful campaigns required a substantial level of knowledge on coral ecology and aquaculture techniques, as well as the extensive involvement of expert scientists and local stakeholders.

The Coral Rehabilitation Initiative aims to adhere and contribute to the state-of-the-art in scientific understanding of early stage coral survival, and to strengthen the understanding of causal linkages between environmental parameters and coral recruitment. The ReefGuard enabled the production of tens of thousands of coral recruits. This facilitated the ability to conduct scientific experiments on the survival rates of coral recruits at a scale that was not previously possible (both in size and numbers), providing knowledge that is crucial for the design of effective active rehabilitation strategies. Corals cultured for a period of time in a laboratory under favourable conditions before placing them out on a reef were found to have higher rates of growth and survival than corals transplanted directly onto a reef.

The ReefGuard also allows the initiation of a series of self-sustaining coral nurseries, i.e. the Coral Engine. A Coral Engine contains sexually reproduced coral recruits as well as locally sourced coral fragments, obtained from naturally or anthropogenically destructed reefs. Within the Coral Engine, the recruits and fragments will grow into full-fledged colonies, continuously supplying coral mass for reef creation or restoration, and gametes for natural reproduction.

Coral Engines are sources of ecosystem services, both by providing the product coral, which is in high demand, as well as for educational purposes. The *produced corals* can be used for multiple purposes, such as restoration and construction of reef ecosystems to boost recreational activities (e.g 'house reefs' for tourist resorts), use in coastal protection measures, to enhance fisheries resources, or even for trade in the aquaria industry to prevent illegal destruction of natural coral reefs. The *production process of corals* also provides multiple opportunities for research, education and awareness purposes, and local employment arising from operating the Coral Engine. By providing a range of ecosystem services with long-term socio-economic merits for local stakeholders, the Coral Engine shows to be a sustainable mechanism with multiple benefits for both man and nature.

In conclusion, The Coral Rehabilitation Initiative with the ReefGuard and Coral Engine systems, in combination with the wider trends for sustainable solutions – such as 'Building with Nature', 'Working with Nature' and 'Engineering with Nature' - provides important management solutions for true environmental gain, thereby assisting to achieve goals of international legislative acts for the sustainable use of our marine environment. Close collaboration between academic researchers, non-profit conservation organisations, local stakeholders and marine contractors is crucial in achieving successful coral rehabilitation at a large scale and for the long-term.

REFERENCES

Bengtsson, B.O. (2003). Genetic variation in organisms with sexual and asexual reproduction. *Journal of Evolutionary Biology*, 16(2), 189-199.

Bridges, T.S., Lillicrop, J., Wilson, J.R., Fredette, T.J., Suedel, B., Banks, C.J., and Russo, E.J. (2014). 'Engineering with Nature' promotes tripple-win outcomes. *Terra et Aqua*, 135(2), 17-23.

De Vriend, H.J. and Van Koningsveld, M. (2012). Building with Nature: Thinking, acting and interacting differently. *EcoShape*, Building with Nature, Dordrecht, the Netherlands.

De Vriend, H.J., Van Koningsveld, M., Aarninkhof, S.G.J., De Vries, M.B., and Baptist, M.J. (2015). Sustainable hydraulic engineering through Building with Nature. *Journal of Hydro-environment Research*, 9(2), 159-171.

Edwards, A.J. (Ed.) (2010). Reef Rehabilitation Manual. Coral Reef Targeted Research & Capacity Building for Management Program: St Lucia, Australia.

Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J., Walker, B., and Norberg, J. (2003). Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment*, 1(9), 488.

Guest, J.R., Baria, M.V, Gomez, E.D., Heyward, A.J., and Edwards, A.J. (2014). Closing the circle: Is it feasible to rehabilitate reefs with sexually propagated corals? *Coral Reefs*, 33(1), 45-55.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., …, and Hatziolos, M.E. (2007). Coral reefs under rapid climate change and ocean acidification. *Science*, 318(5857), 1737-1742.

Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., …, and Wilson, S.K. (2018). Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, 359(6371), 80-83.

Kojis, B.L., and Quinn, N.J. (2001). The importance of regional differences in hard coral recruitment rates for determining the need for coral restoration. *Bulletin of Marine Science*, 69(2), 967-974.

Pandolfi, J.M., Connolly, S.R., Marshall, D.J., and Cohen, A.L. (2011). Projecting coral reef futures under global warming and ocean acidification. *Science*, 333(6041), 418-422.

Petersen, D., and Tollrian, R. (2001). Methods to enhance sexual recruitment for restoration of damaged reefs. *Bulletin of Marine Science*, 69(2), 989-1000.

PIANC (2011). PIANC Position Paper 'Working with Nature'. Permanent International Association of Navigation Congresses (PIANC).

Pollock, F.J., Katz, S.M., van de Water, J.A.J.M., Davies, S.W., Hein, M., Torda, G., …, and Willis, B.L. (2017). Coral larvae for restoration and research: A large-scale method for rearing Acropora millepora larvae, inducing settlement, and establishing symbiosis. *PeerJ*, 5, e3732.

Rau, G.H., McLeod, E.L., and Hoegh-Guldberg, O. (2012). The need for new ocean conservation strategies in a high-carbon dioxide world. *Nature Climate Change*, 2(10), 720-724.

Rinkevich, B. (1995). Restoration strategies for coral reefs damaged by recreational activities: the use of sexual and asexual recruits. *Restoration Ecology*, 3(4), 241-251.

Rinkevich, B. (2005). Conservation of coral reefs through active restoration measures: Recent approaches and last decade progress. *Environmental Science & Technology*, 39(12), 4333-4342.

Rinkevich, B. (2008). Management of coral reefs: We have gone wrong when neglecting active reef restoration. *Marine Pollution Bulletin*, 56(11), 1821-1824.

Rinkevich, B. (2014). Rebuilding coral reefs: Does active reef restoration lead to sustainable reefs? *Current Opinion in Environmental Sustainability*, 7, 28-36.

Robijns, N., Nuñez Lendo, C.I., Hoftijzer, M., Koningsveld, M. van, Schutter, M., Elzinga, J., Smolders, T., Osinga, R., and Hofstede, R. ter (2018). Large-scale ex situ settlement on artificial substrates using sexual recruits of endangered Elkhorn coral, Acropora palmata. *Under review.*

Schutter, M., Hofstede, R. ter, Bloemberg, J., Elzinga, J., Koningsveld, M. van, and Osinga, R. (2018). Enhancing survival of ex situ reared sexual recruits of *Acropora palmata* for reef rehabilitation. *Under review.*

van Koningsveld, M., ter Hofstede, R., Elzinga, J., Smolders, T., Schutter, M., Osinga, R. (2017). "ReefGuard: a scientific approach to active reef rehabilitation." *Terra et Aqua*, 147, 5-16.

van Oppen, M.J.H., Gates, R.D., Blackall, L.L., Cantin, N., Chakravarti, L.J., Chan, W.Y., …, and Putnam, H.M. (2017). Shifting paradigms in restoration of the world's coral reefs. *Global Change Biology*, 23(9), 3437-3448.

Webster, N.S., Uthicke, S., Botté, E.S., Flores, F., and Negri, A.P. (2013). Ocean acidification reduces induction of coral settlement by crustose coralline algae. *Global Change Biology*, 19(1), 303-315.

Young, T.P. (2000). Restoration ecology and conservation biology. *Biological Conservation*, 92, 73-83.

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