IFRECOR

INITIATIVE FRANÇAISE
POUR LES RÉCIFS CORALLIENS

GUIDE TO ECOLOGICAL ENGINEERING:

THE RESTORATION OF CORAL REEFS AND ASSOCIATED ECOSYSTEMS

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UN environment programme

Centre d'Écologie Fonctionnelle & Évolutive

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Université Paul Valéry Montpellier 3

ACKNOWLEDGEMENTS

This guide is brought to you by IFRECOR, the French Coral Reef Initiative. Published in January 2020, it is the result of extensive data collection by French field officers. Now, thanks to UNEP, it is being translated into English. We would like to thank UNEP for bringing an international dimension to this project.
We wish to thank all those who helped to proofread and improve this guide, in particular:

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Thanks are also due to the entire "Anthropized Systems Ecology" team at the Centre for Functional and Evolutionary Ecology, and to Adrien Gallinaro, Julien Richard, Marie Zion, Laura Massinelli and Mathieu de Langlard. Thanks as well to the long list of people who helped proofread this work.

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PUBLISHER

N°ISBN 978-2-11-162285-2

FORMATTING AND GRAPHIC DESIGN

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ENGLISH TRANSLATION

Edward Ashley and Peter Castellani

CITATION STYLE

LÉOCADIE, A., PIOCH, S., PINAULT, M. (2020). Guide to Ecological Engineering: The restoration of coral reefs and associated ecosystems. Published by IFRECOR. 114 pages

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1 OBJECTIVES OF THE GUIDE

This work provides an inventory of ecological engineering techniques employed mainly in France, but also worldwide. It is devoted to the restoration of coral reefs and their associated ecosystems: seagrasses and mangroves.

It builds on two existing IFRECOR publications: "Reef restoration: Practical guide for management and decision-making",[1] by Michel Porcher, Sandrine Job and Muriel Schrimm, published in 2003, and "Reef restoration: Concepts and guidelines",[2] by Alasdair Edwards and Edgardo Gomez, published in 2007. The aim of this update is to help contracting authorities, environmental managers, project owners and research units to familiarize themselves with the techniques and to use synthetic data to propose solutions adapted for habitat restoration and selected ecological functions.

DEFINITIONS OF ECOLOGICAL ENGINEERING AND ECOLOGICAL RESTORATION

IFRECOR[3] (the French Coral Reef Initiative), **launched in 1999, is geared towards the sustainable management and protection of coral reefs and their associated ecosystems (seagrasses and mangroves).** Over the years, with the support of the Ministries of Ecology and Overseas territories of France, IFRECOR has been able to develop a genuine network within local authorities. To this end, several partnerships were created, which today bring together research units, consulting agencies and managers of marine protected areas, in addition to academics and project owners, among others. **IFRECOR has become the leading network for exchanges among environmental stakeholders in the French Overseas Territories that have coral reefs.**

IFRECOR working groups have developed several approaches to achieve their objectives of preserving and managing these ecosystems. In particular, they wish to make elected officials, administrations, companies and the general public aware of the socioeconomic and ecological issues pertaining to these ecosystems. They also want to establish a network to monitor the state of French coral reefs. Lastly, they wish to contribute to reducing threats linked to anthropization.

To accomplish this, they developed the MERCI-Cor[4] **tool, an experimental method for evaluating ARM measures.** The goal of the method is to gauge the expected ecological losses and gains for coral reefs following the implementation of development projects and related mitigation measures. **To complement this method, an ad hoc guide to ecological engineering techniques was needed.**

This guide is the result of the collaborative work of a very active community of stakeholders whose objective is to share common, updated tools for ecological engineering in reef environments in order to benefit from feedback (through the website: *www.ifrecor.fr*).

Ecological engineering encompasses all techniques and processes for solving socioeconomic and/or environmental problems through the use of living organisms or other materials of biological or non-biological origin (Moreno-Mateos *et al.*, 2015; Pioch *et al.*, 2018). Four technical approaches may be adopted: ecological restoration, ecological improvement or rehabilitation, creation and protection (figure 1).

[1] Online guide: http://ifrecor-doc.fr/items/show/1367

[2] Online guide: http://ccres.net/images/uploads/publications/5/reef_restoration_concepts__guidelines_french.pdf

[3] For more information: ifrecor.fr

[4] Online guide: http://www.ifrecor-doc.fr/items/show/17435

[5] Note: In this example of creation, the natural host environment is not degraded but is of limited interest in terms of originality, sensitivity, heritage and ecology.

Figure 1 The various ecological engineering techniques

RESTORATION

Promoting the recovery of damaged ecosystems and restoring them to a baseline condition through natural, ecological and self-regenerating means. (SER, 2004).

E.g.: by transplanting species recognized as founders of a reference ecosystem (keystone and engineer species, etc.)

ENHANCEMENT

REHABILITATION

Assisting in restoring certain functions of a damaged ecosystem. As with restoration, rehabilitation is carried out according to a baseline condition. With rehabilitation, the emphasis is on restoring and recovering processes, and thus on the ecosystem's productivity and services (SER, 2004).

E.g.: by transplanting species recognized as being at the root of a production process (biomass, seeding juveniles of species of fishing interest, etc.)

PROTECTION

Protecting a given site simply by prohibiting certain activities (fishing, recreation) or by managing and controlling them. Little to no direct intervention in the natural environment.

E.g.: a measure to manage the fishing of herbivorous species helpful to the recovery of coral ecosystems.

CREATION

REALLOCATION

Redirecting the ecological pathway of an environment that may have been damaged by human activity to enable the development of local ecological processes that are lacking and that differ from baseline processes. This involves introducing new biophysical processes to an ecosystem that is degraded or not naturally inclined to produce the targeted processes (SER, 2004).

E.g.: Installing artificial concrete reefs on sand (the original ecosystem) in order to promote the development of species.[5]

WHY RESTORE?

Taking upstream action to tackle the direct and indirect sources of the pressures that lead to environmental degradation is a priority in integrating these ecological engineering techniques into a more holistic approach to ecosystem restoration. Without this, the effectiveness of the measures implemented cannot be maintained in the long term. According to Elliott et al. (2007), this approach, defined as "passive", must be carried out upstream of ecological engineering actions, which are "active". The "active" approach will be the main focus of this guide. It should be noted that, in the context of mitigation measures, regulations require a restorative approach aimed at achieving an environment equivalent to the one that was destroyed ("like for like"). In practice, although this "strict" equivalence is very rarely achieved (with all species, habitats and functions restored), ecological similitude remains the objective of the "new ecosystem" (figure 2). **In general, only partial restoration of degraded ecosystems is possible** (Aronson and Morenos-Mateos, 2015).

Thus, users of this guide should be aware that these actions lead to a new ecosystem that is more or less similar to the reference ecosystem, and not to a return to the reference ecosystem under conditions of strict equivalence (figure 2). **In some cases, "beneficial" ecological engineering actions can be used as a reason to justify future degradation.**

For example, if a coral transplant is carried out under poor conditions while marine works are underway, the expected results will not be achieved. Indeed, the ecological importance of area reefs would be diminished, which could become a reason for authorizing future destruction (or poor ecological restoration) during new work. These actions should therefore take place within a controlled framework, where there is monitoring, compliance with regulations, performance evaluations before and after and action taken or sanctions imposed in case of failure (Boudouresque, 2001).

Ecosystems contribute to human well-being by providing ecosystem services (The Economics of Ecosystems and Biodiversity, 2010). Although anthropocentric, such services are an excellent vehicle for communication with policymakers and citizens. They can be divided into various categories: provisioning services (fishing), regulating services (mangroves and seagrass beds contribute to the sequestration of atmospheric CO_2) and cultural and social services (ecotourism) (The Economics of Ecosystems and Biodiversity, 2010; Pascal *et al.*, 2016).

The cost-benefit ratio of "restoring" nature is most favourable in coastal and marine natural environments (figure 3). Indeed, in coastal ecosystems, the net benefits during the 40 years after restoration are five times higher than the initial cost (The Economics of Ecosystems and Biodiversity, 2009).

HOW TO RESTORE?

Ecosystem restoration is complex and risky and may be difficult to predict in the long term (Chipeaux *et al.*, 2016). According to Clewell and Aronson (2013), it requires patience and even a kind of dedication in operators and managers. When planning a restoration project, several factors must be considered.

First, the objectives of the restoration project must be precisely stated. Their technical feasibility and the human and budgetary resources required to achieve them must then be assessed. In order to ensure effective long-term management of the restored site, the various strategies must be discussed with and communicated to all stakeholders in the territories concerned (SER, 2004). **In this sector, as in many others related to environmental management, although dialogue and empathy are the keys to success, they are often neglected.**

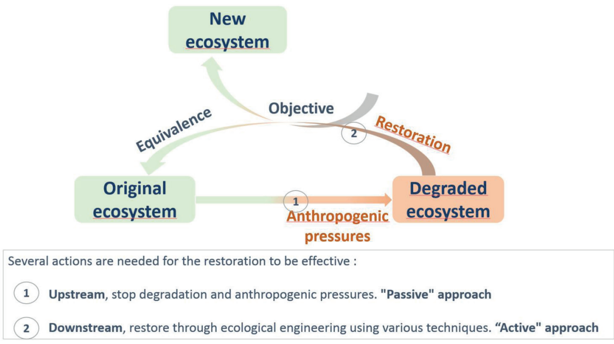


Figure 2 From a passive fight against pressures on ecosystems to active ecosystem restoration: the two approaches to restoring ecosystems, in chronological order. Note: The diagram is from an anthropocentric point of view, which does not consider natural pressures that may be exerted on the environment (Léocadie and Pioch, 2017).

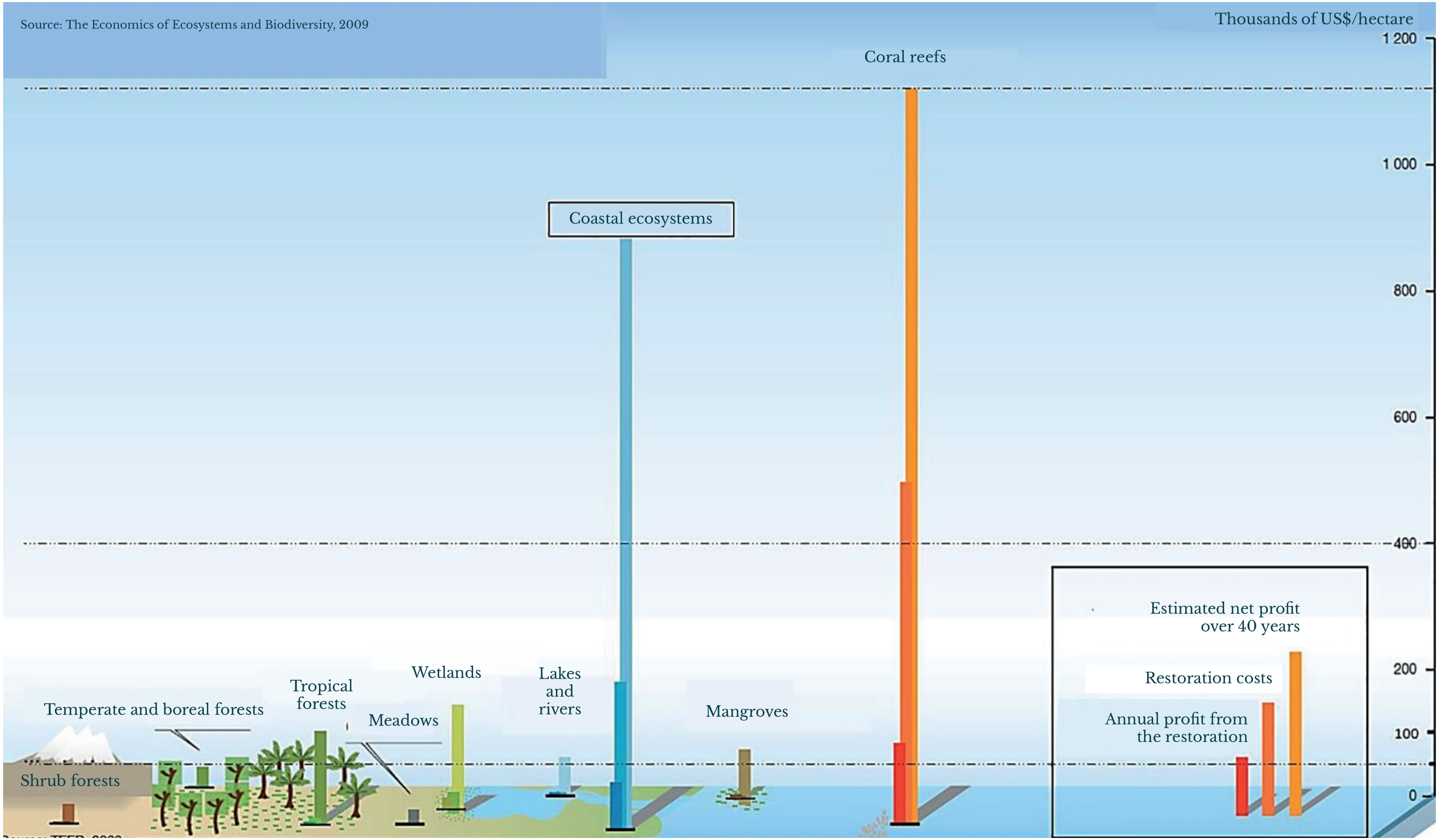


Figure 3 Monetized cost/benefit analysis of the ecological restoration of terrestrial and coastal ecosystems (Pioch - adapted from The Economics of Ecosystems and Biodiversity, 2009)

2

REGULATORY FRAMEWORK FOR MITIGATION IN THE MARINE ENVIRONMENT

Since the 2010s, the State has shown that it has the political will to mandate the mitigation of the environmental impacts of human activity. The Act on reclaiming biodiversity, nature and landscapes (No. 2016-1087 of 8 August 2016) and Decree No. 2016-1110 (11 August 2016) amending environmental impact assessments reaffirm this will. Achieving the goal of no biodiversity loss in species, habitats and ecological functions translates into a search for equivalence in the losses and gains of development projects. The concept of ecological mitigation is also attracting interest in the scientific community. According to Dupont and Lucas (2017), it poses "legal, scientific and practical challenges".

REGULATORY FRAMEWORK FOR MITIGATION IN THE MARINE ENVIRONMENT

Ecological engineering has grown rapidly over the past 20 years with the increasing demands of so-called mitigation measures. The notion of mitigation was introduced in France through Act No. 76-629 of 10 July 1976 on nature conservation, which formalizes three steps – "Avoid, Reduce, Mitigate" (ARM) – to be taken for any project that may have a negative impact on the environment (Morandeau and Villaysack, 2012; Pioch, 2013). However, it was not until 2005 that marine ecological engineering became truly popular, with the strengthening of regulations on environmental assessments: Natura 2000 sites were extended to marine settings in 2005, and reviews were conducted respectively on the declaration and authorization procedures relating to Act No. 2006-1772 on water in 2006 and on the procedures related to protected species in 2007. The Grenelle I and II Acts in 2009 and 2010, and the 2016 Act on reclaiming biodiversity, nature and landscapes have strengthened the obligation to apply the ARM sequence and to offset any significant residual impacts.[6] The 2016 Act sets the objective of "no net loss" of biodiversity (figure 4). Added to this are the European directives (the Water Framework Directive and the Marine Strategy Framework Directive)[7] on "good ecological status" and "sea restoration" and the establishment of significant public funding.[8] **According to article R. 122-13.-I of the French Environment Code, "the purpose of mitigation measures is to counteract the significant direct or indirect negative environmental impacts of the project that could not be avoided or sufficiently reduced. They are implemented as a priority at or near the affected site to ensure that it will continue to function sustainably. They must enable preservation in general and, if possible, improve the environmental quality of sites".** These measures are taken during the implementation of plans, programmes and projects with potentially harmful effects on nature (Borderon, 2014). **These measures are part of a sustainable development approach with environmental, social and ecological benefits** (Ministry of Ecology, Sustainable Development, Transport and Housing, 2012). It is a preventive approach that assesses the impact of a project on the environment. Obviously, the level of mitigation required is proportional to the residual impacts (after the implementation of avoidance and reduction measures).

[6] According to Act No. 2016-1087 on reclaiming biodiversity, nature and landscapes: "This principle implies avoiding damage to biodiversity and to the services that it provides; failing this, reducing the scope of such damage; and, lastly, offsetting damage that could not be avoided or reduced, taking into account the species, natural habitats and ecological functions affected."

[7] The water agencies have included restoration in their operational and financial objectives as a priority of the Water Development and Management Master Plan/water development and management plans.

[8] The water agencies have included restoration in their operational and financial objectives as a priority of the Water Development and Management Master Plan/water development and management plans.

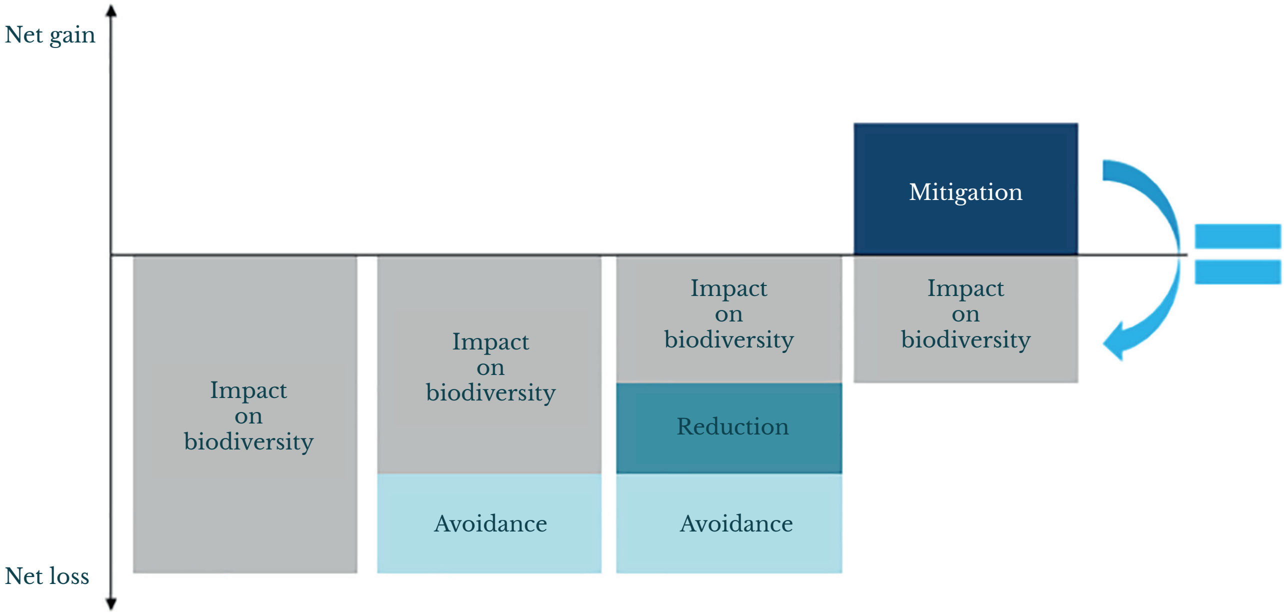


Figure 4 Diagram of the “avoid, reduce, mitigate” sequence applied to impacts on biodiversity (per A. Buffard, 2015)

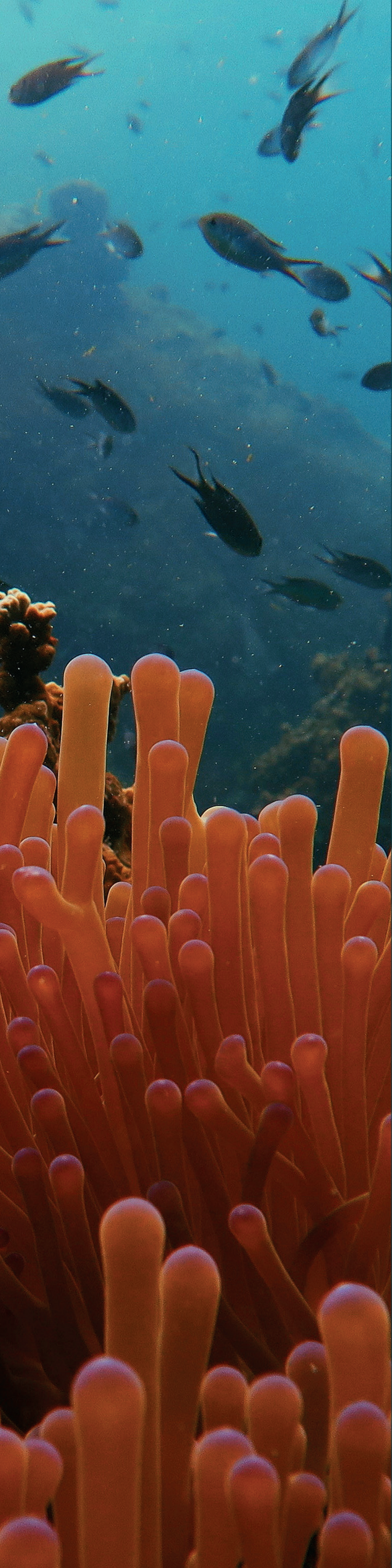
There are three categories of degradation that may require action to restore the marine environment:
❶ Authorized degradation, which is assessed ex ante, or before the fact
❷ Unauthorized degradation with an identifiable “culprit”
❸ Unauthorized degradation with no identifiable “culprit”

The assessment of the last two categories is carried out ex post, or after the fact. There are thus two types of restoration:
❶ Ex ante restoration, in the case of authorized degradation (subject to authorization under the Environment Code), as part of the mitigation measures taken within the framework of the ARM sequence (Acts No. 76-629 of 10 July 1976 and No. 2016-1087 of 8 August 2016 and articles L. 110-1 and L. 163-1 of the Environment Code).
❷ Ex post restoration under the Environmental Liability Act (Act No. LRE 2008-757).

The aim is to offset the biophysical losses caused by respecting the principle of ecological equivalence (qualitative and quantitative). The mitigation site must therefore be functionally analogous to the degraded site, i.e. must have the same ecological characteristics (the same functions, structures, compositions, etc.) (Jacob *et al.*, 2015).

3

CORAL REEFS



Coral reefs are home to a great variety of species: as many as 600 species of corals (in the Coral Triangle) and more than 2,000 species of fish, 3,000 species of molluscs, etc. Covering a mere 0.2% of the world's sea surface, coral reefs harbour one third of the world's marine fauna and flora. These complex ecosystems are highly vulnerable, and many pressures can alter their ecological state in a more or less irreversible way: backfilling, overexploitation of their resources, degradation of water quality, ocean acidification, temperature increase and extreme climatic events of varying intensity.

THE MAJOR CHALLENGES OF CORAL REEF CONSERVATION

Coral reefs are **rigid limestone structures composed of a multitude of small, primitive animals: polyps. The latter, arranged in colonies, live in symbiosis with microalgae: zooxanthellae** (figure 5). This symbiosis is essential for coral life. Indeed, the zooxanthellae produce organic molecules that account for around 80% of the coral's food, with the remainder being drawn directly by the polyp from the environment. The microalgae produce oxygen, thus supporting the polyp's breathing. At the same time, the removal of CO_2 by the zooxanthellae promotes the precipitation of calcium carbonate and thus the development of the coral skeleton. The zooxanthellae, meanwhile, find a stable environment within the polyp, where they are protected from variations in environmental conditions, sedimentation and predators. They also use the nitrogen and phosphate waste output of the polyp as a source of mineral elements, which are locally more concentrated than in the external environment. **It is this relationship between polyps and zooxanthellae that underpins the formation of coral reefs.**

Nevertheless, this symbiotic balance is extremely fragile, and the relationship is not sufficient for the proper development and survival of coral reefs. Other parameters are equally important: temperature, salinity, depth, pH and substrate. If one of these factors changes, the whole colony will be destabilized and coral construction will be disrupted.

Worldwide, coral reefs are distributed over 280,000 km² (Burke *et al.*, 2011), or **less than 0.2% of ocean area** (figure 6), **yet they are home to one third of marine biodiversity, or about 100,000 known species.**

France has coral reefs in all three oceans (figure 7). With a total reef area spanning 60,000 km², including built and unbuilt reef surfaces (lagoons and sedimentary terraces), France ranks fourth in the world in terms of reef surface area. The Millennium Coral Reef Mapping Project[9] made it possible to calculate the **French reef surface area at 8,778 km²**, all oceans combined, including **4,570 km² in New Caledonia, 3,000 km² in French Polynesia, 546 km² in the Indian Ocean area and 230 km² in the Caribbean area** (Andréfouët *et al.*, 2008). The state of overseas coral reefs varies greatly: they are doing rather well in New Caledonia, Polynesia and Wallis, but not in Réunion, the West Indies, Mayotte and Futuna. The diagram on page 18 summarizes the state of the health of French marine reefs in 2015.

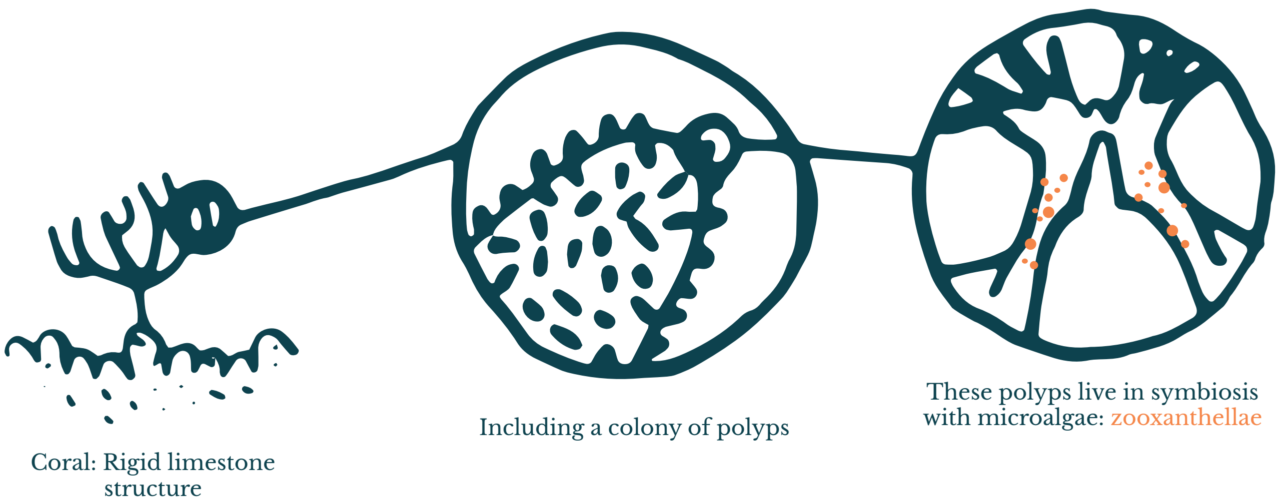


Figure 5 Diagram of the relationship between polyps and zooxanthellae

[9] For more information: http://imars.marine.usf.edu/MC/

SOME FIGURES

Figure 7 Distribution of French coral reefs (IFRECOR Programme of Action 2016–2020)

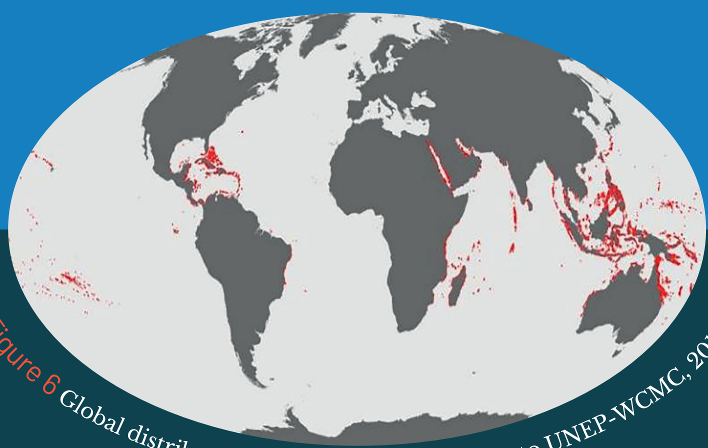
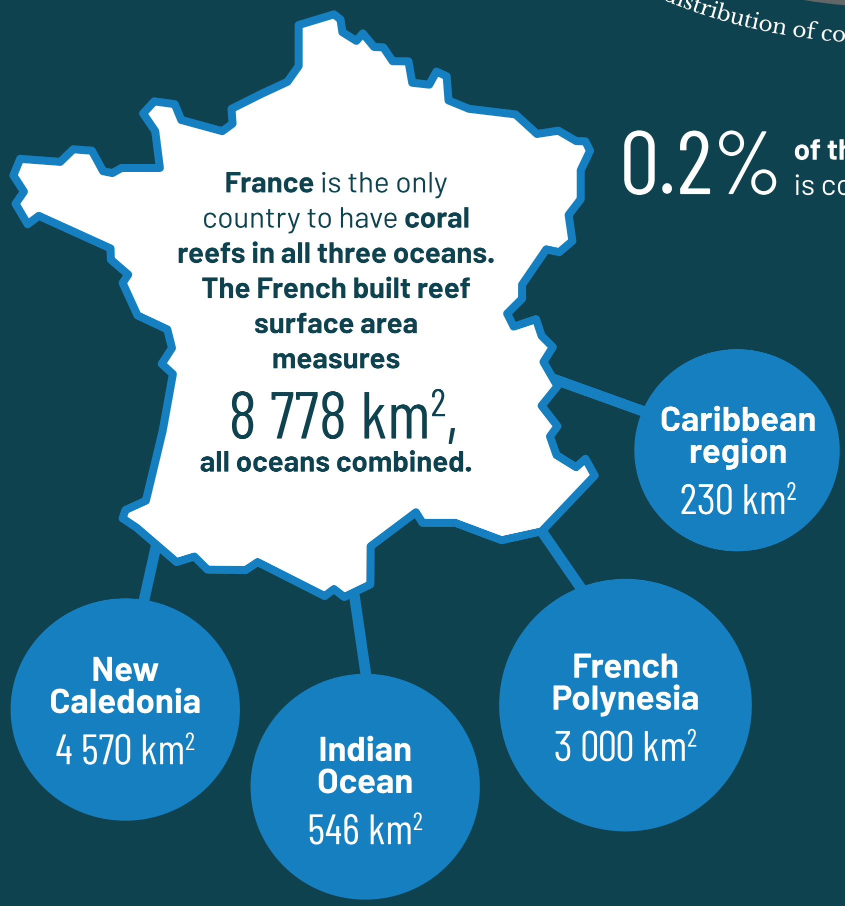


Figure 6 Global distribution of coral reefs (according to UNEP-WCMC, 2010)



0.2% **of the world's ocean area** is covered by coral reefs.

275 millions **people live in the immediate vicinity of coral reefs** (Burke *et al.*, 2011).

Ecosystem services associated with coral reefs provide US$ 375 billion per year* in benefits.

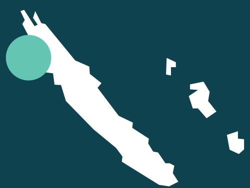
*Note: The methods for calculating French and American data may differ.

1/3 of **marine biodiversity**

Summary of the health of French coral reefs in 2015[10]
(Quod J.P. and Malfait G., 2016)

Guadeloupe
Since 2002, a decrease in coral cover has been observed, exacerbated by a major bleaching episode in 2005.

Saint Barthélémy and Saint Martin
In 2005, a rise in ocean temperature led to massive coral bleaching, bearing in mind that coral cover on these islands has never exceeded 26%.
Note: In 2017, Hurricane Irma caused significant damage to the coral reefs of these islands.



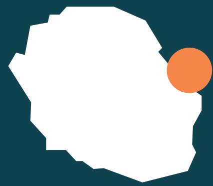
New Caledonia
80% of the reefs studied are in a "good to satisfactory" state of health, whereas only 7% are in a poor state of conservation.

Martinique
A general decrease in coral cover has been observed, along with an increase in macroalgal cover. However, it has been observed that the level of cover has stabilized at 20% on some sites. On one site, the level of cover even stands at 60%.

Scattered Islands (Indian Ocean)
The Islands have high biodiversity and healthy coral reefs.

French Polynesia
Good health at the national level, although the coral cover varies greatly depending on location.

Mayotte
The evolution of the reefs is characterized by fluctuating trends, with a strong decrease in the rate of coral cover between 1989 and 2004, then an increase since 2004.



Réunion
Since 2003, a clear decrease in coral cover has been observed, with opportunistic algae taking its place.

Wallis
Good reef health despite a significant bleaching episode observed in 2015.

Futuna
Poor health because, in the absence of a lagoon, the island is subject to natural and anthropogenic pressures.

Health index good — Health index poor — Health index very poor

THE ROLES OF CORAL REEFS

Reefs perform a multitude of functions. As habitat builders, they act as shelters, house a high level of biodiversity and serve as nurseries for juveniles and as food for many species. They bring numerous benefits to a billion people. They provide a range of ecosystem services:

Fishing

Coral reefs provide a source of income from the biomass production associated with them. Thus, fishing activity, whether commercial or recreational, is very strongly linked to the presence of these reefs. Coral reefs play a key role in the subsistence economy of the regions where they are found.

Tourism

The lush beauty of these reefs and the diversity of reef organisms attract **more than one million people to the French overseas territories per year** (Quod and Malfait, 2016).

Protection

The presence of reefs close to the shore helps to reduce damage to coastal facilities from repeated wave action or cyclonic events. It is estimated that **reefs absorb up to 97% of wave energy** (Ferrario *et al.*, 2014). Reefs also counteract coastal erosion (Wells and Ravilious, 2006).

Culture and traditional beliefs

Corals are an integral part of many cultures. In southern Kenya, for example, coral reefs are used in religious rites to appease spirits (Moberg and Folke, 1999).

Pharmacology

Chemical compounds from corals and other reef organisms have pharmacological potential in the treatment of cancers[11] and cardiovascular diseases, for example. The calcareous skeleton of corals can also be used as material for bone grafts[12] because of its similarity in composition to the human skeleton.

Coral reefs are therefore of unquestionable value in maintaining marine ecological equilibrium and, by extension, for the well-being of mankind.

[10] Based on expert opinion in the article: Jean-Pascal QUOD, Guillaume MALFAIT and the IFRECOR secretariat, 2015, "Etat des récifs coralliens et des écosystèmes associés des outre-mer français en 2015" ["State of coral reefs and associated ecosystems in French overseas territories in 2015"], IFRECOR document: http://www.ifrecor-doc.fr/items/show/1670

[11] http://www.coralbiome.com/fr/

[12] https://www.inserm.fr/thematiques/technologies-pour-la-sante/dossiers-d-information/biomateriaux/reparer-l-os

WHAT ARE THE THREATS?

Although coral reefs remain extensive, their survival depends on a delicate balance. They are now among the most threatened ecosystems. In 2008, a review of the health of the world's coral reefs (Wilkinson, 2011) showed that:

20% **of coral reefs are already irrevocably destroyed or have little chance of recovery**
25% **are in critical condition**
25% **are threatened**
30% **remain in satisfactory condition**

According to recent studies (Burke *et al.*, 2011), 90% of all coral reefs worldwide will be threatened with extinction by 2030. There is a direct or indirect connection between humans and the health of reef ecosystems. Threats to coral can have different origins: a direct anthropogenic origin, but also a natural origin (including extreme climatic events, temperature rise and ocean acidification). The impact of human activities affects the intensity of threats of natural origin, notably by accelerating and exacerbating climate change.

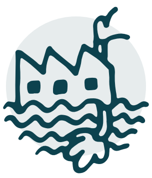
EXAMPLES OF DEGRADATION OF ANTHROPOGENIC ORIGIN

Land-use planning

Dredging	destruction, landscape degradation, modification of current patterns
Urbanization	hypersedimentation, landscape degradation, soil sealing
Backfilling	destruction, hypersedimentation, landscape degradation, mechanical habitat alteration

Wastewater discharges

Nutrient supply	algal bloom, eutrophication
Chemicals	poisoning, bioaccumulation, biomagnification
Sediment supply	asphyxia and reduction in photosynthesis



Agricultural, industrial and port activities

Emissions	degradation of various kinds depending on the type of emission
Oil exploitation	poisoning, bioaccumulation, biomagnification
Exotic species	decline and disappearance of species, epizootics

Sea-related activities

Overexploitation of resources	depletion of stocks
Anchoring of boats, trampling	mechanical habitat alteration
Beach overcrowding	wildlife disturbance, sunscreens
Coral mining	mechanical habitat alteration

Household waste

Microplastics	intoxication, bioaccumulation
Chemicals	poisoning, bioaccumulation, biomagnification
Nutrient supply	algal bloom, eutrophication

WHAT ARE THE CONSEQUENCES?

The causes of coral reef degradation are legion. Generally, they are cumulative and their impact is multiplied within the same ecosystem by synergistic effect, with often irreversible consequences for the reefs and the biodiversity that depends on them.

Bleaching

The accumulation of anthropogenic and natural impacts weakens and destabilizes these ecosystems. The stress caused by temperature rises results in an increase in the photosynthetic activity of the zooxanthellae. This stress leads the polyps to reject their microalgae, causing a halt in growth and reproductive activity. If conditions return to normal, polyp-zooxanthellae symbiosis becomes possible once more. On the other hand, if the stress persists, the partial or total death of the colony will be guaranteed. The development of algal turf reflects the irreversible nature of the situation. The increase in temperature and dissolved carbon dioxide induced by the increase in human activity modifies the living conditions of the coral reefs (Hughes *et al.*, 2003). In 2016, according to Hughes et al. (2017), **only 8.9% of the 1,156 reefs of the Great Barrier Reef escaped without bleaching** (figure 8). Veron et al. (2009) **estimate that, by 2030–2040, the amount of CO_2 in the oceans will be 450 ppm, leading to high global coral mortality** (figures 9 and 10). Other factors may be responsible for coral bleaching, such as decreasing salinity or excessively high pollution levels.

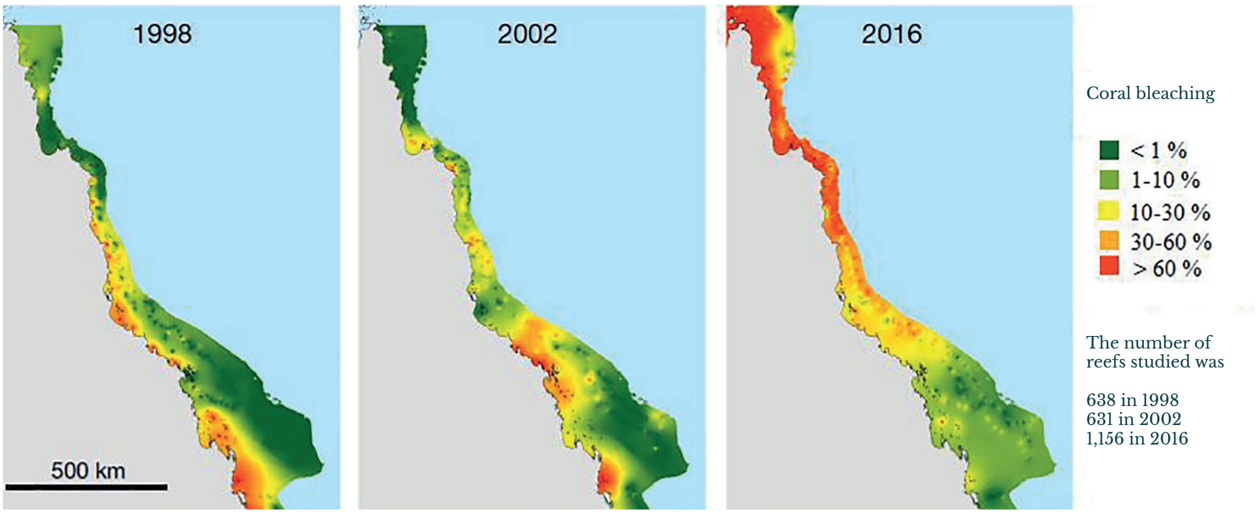


Figure 8 Extent of coral bleaching in the Great Barrier Reef (Australia) (Hughes *et al.*, 2017)

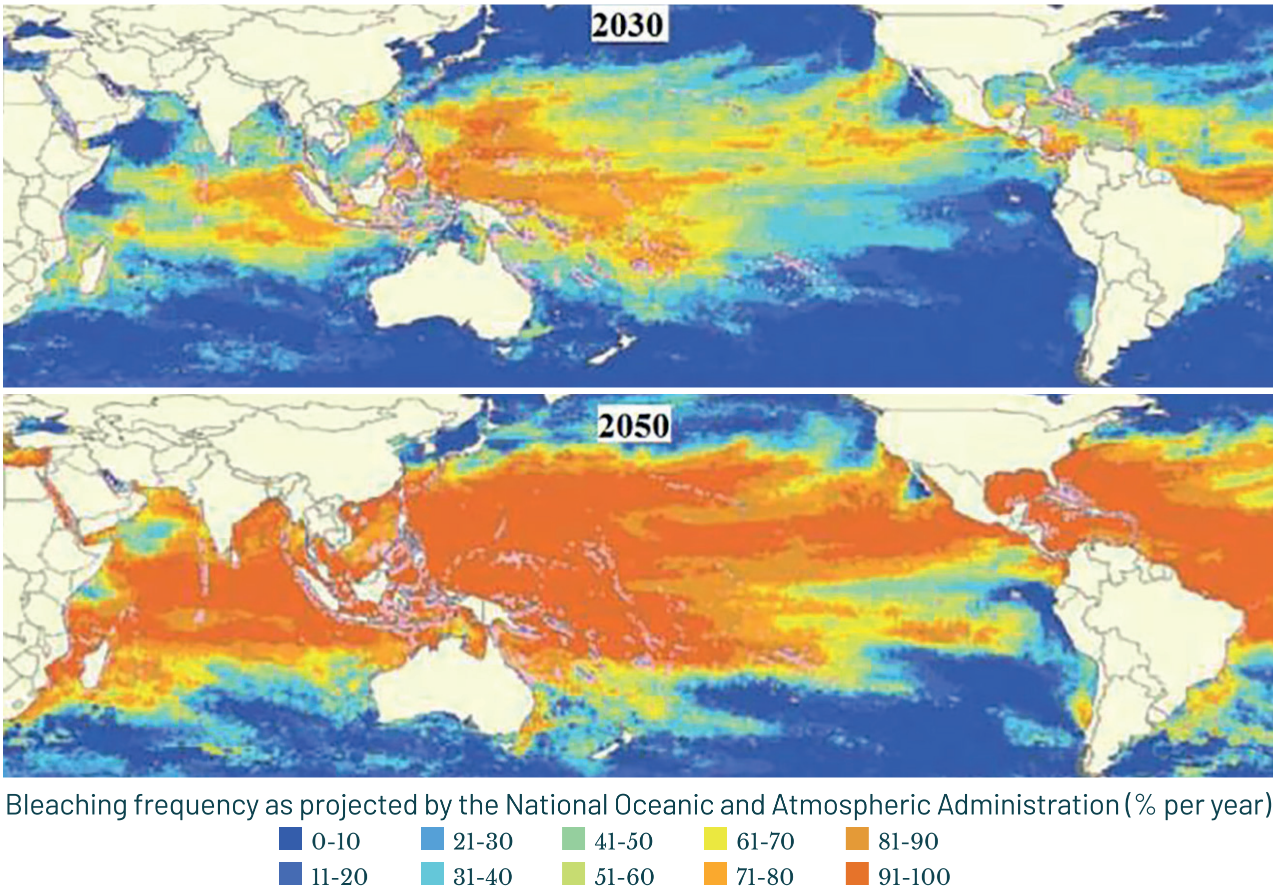


Figure 9 Predictions of the frequency of future coral bleaching events for 2030 and 2050 (Burke *et al.*, 2011)

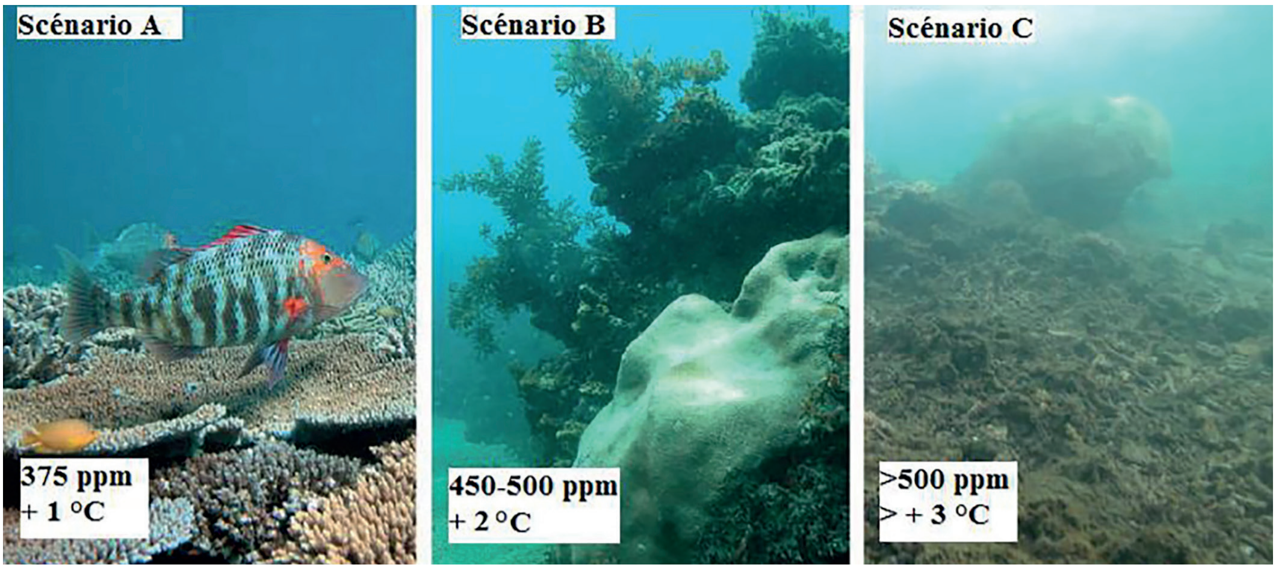


Figure 10 Three scenarios depending on increases in atmospheric CO_2 and temperature (Hoegh-Guldberg *et al.*, 2007)

Loss of biodiversity and resilience

The death of coral reefs is accompanied by a net loss of biodiversity. The organisms associated with them will either disappear or migrate to areas more suitable for their development.
The return to a normal dynamic balance is compromised.

Socioeconomic consequences

Many coastal populations depend on these reefs socioeconomically (figure 11), whether for tourism, fisheries or coastal protection. **The number of countries and territories that depend significantly on coral reefs is estimated at 108** (Burke *et al.*, 2011). **If the reefs disappear, a billion people will be directly affected** (Salvat and Rives, 2003). According to Edwards and Gomez (2007), **this would equate to a total economic loss of US$ 375 billion per year.**

The loss of coral diversity and, more broadly, the resultant global loss of biodiversity, could lead to catastrophic economic and societal consequences for the areas concerned.

low moderate high very high no reefs uninhabited area with reefs

Figure 11 Economic and social dependence of coastal populations on coral reefs: fisheries, food, tourism and coastal protection (Burke *et al.*, 2011).

Figure 12 Coral bleaching ©JBfotoblog|Getty images

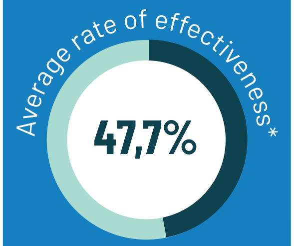
ECOLOGICAL ENGINEERING TECHNIQUES FOR CORAL REEFS

Over the past 20 years, several ecological engineering techniques have emerged for coral reefs. The most commonly used techniques are defined in the section that follows. The descriptions are illustrated with some examples of projects from around the world.

page 25 **Transplantation**
page 26 **Electrodeposition**
page 27 **Coral gardening**

TRANSPLANTATION

Technique used when the degraded site fails to recover naturally (Abelson, 2006). The method involves removing colony fragments from a donor site (or coral gardening) and replanting them in a receptor site.



Average cost**

6 618 058,63 $
international dollars/ha/year
(± 28 517 285,9 standard deviation)

Coral cuttings transported by boat ©Quod Jean-Pascal, "Bouturage coraux 2004 - La Réunion 1," ("Coral cutting 2004 - Réunion 1") IFRECOR document

Advantages

❶ Increase in **biological diversity** (Abelson, 2006).
❷ Immediate increase in **coral cover** (Abelson, 2006).
❸ Immediate improvement in **the aesthetics of the receptor site** (Abelson, 2006).

Disadvantages

❶ **Degradation of the donor site** (Abelson, 2006).
❷ **Fragility of the fragments** during wave action (Abelson, 2006).
❸ **Decrease in the fertility of individuals** due to the stress of transplantation (Abelson, 2006).
❹ **Fairly labour-intensive and the associated costs may be high** (Gleason *et al.*, 2001).

*Average calculated from the data available for follow-up periods of three years or more.
These values should be treated with the utmost caution. The reader is invited to refer to page 101 of the guide.
** Figures provided for information purposes only.

ELECTRODEPOSITION

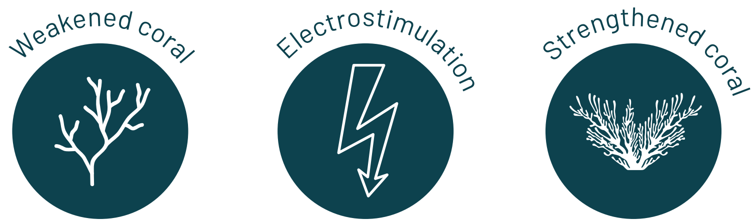
Electrodeposition is a mineral accretion technique by seawater electrolysis. The minerals present in the water precipitate onto a metal support under the action of an electric current. The growth of the calcareous skeleton is thus promoted, reinforcing the bonding of the coral to the substrate (Sabater and Yap, 2002).

Average rate of effectiveness*

75,5%

Average cost

N/A



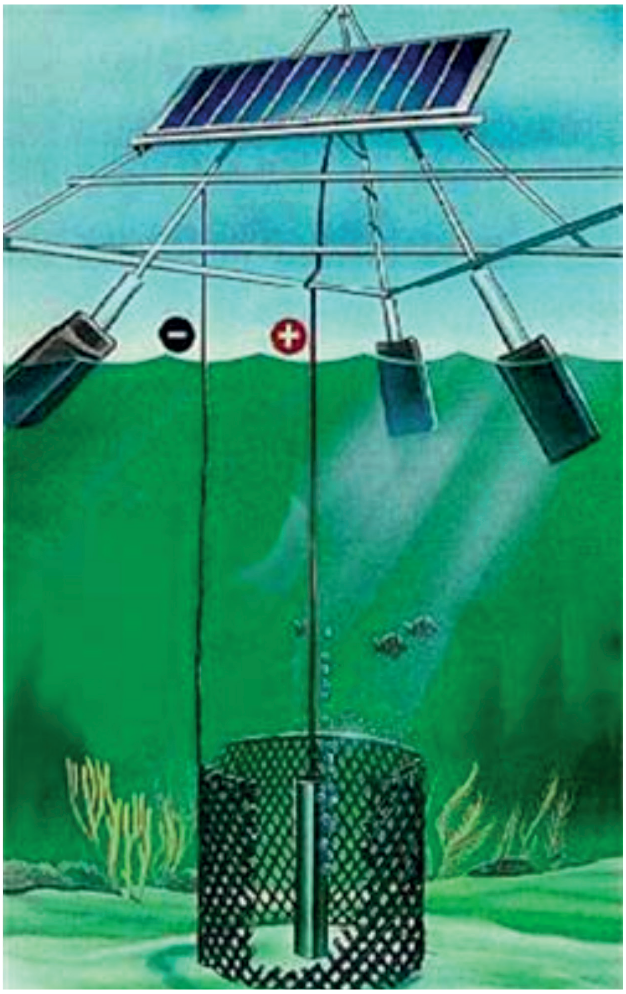
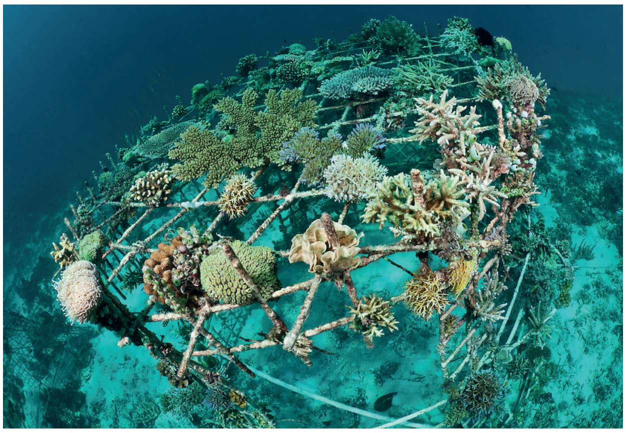


Illustration of electrodeposition (© Biorock.net)



Example of a successful electrodeposition experiment in Gili Trawangan, Lombok, Indonesia (© Matthew Oldfield Photography)

Advantages

❶ Firmly attached coral allocates more energy to **lesion recovery and growth** (Sabater and Yap, 2002).

❷ This technique **increases survival rates and resistance to stress** (Sabater and Yap, 2002; Goreau, 2014).

Disadvantages

❶ The effectiveness of electrodeposition **depends on the species that is being stimulated.** For example, it does not work with *Pocillopora damicornis* (Schuhmacher *et al.*, 2000).

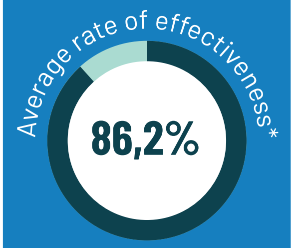
❷ The installation must be checked frequently to avoid **voltage issues,** among others (Goreau, 2014).

❸ Electrical stimulation can favour one species but **inhibit another** at the same time (Goreau, 2014).

* Average calculated from the data available for follow-up periods of up to two years.
These values should be treated with the utmost caution. The reader is invited to refer to page 101 of the guide.

CORAL GARDENING

A coral gardening is used to grow coral larvae or fragments before transplanting them to a receptor site.



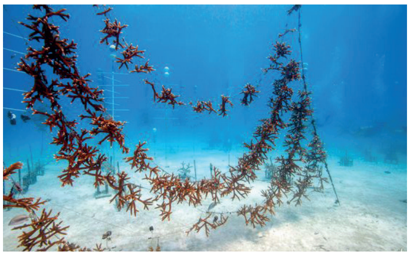
Average cost

51 665,96 $

international dollars/ha/year

(± 74 315,19 standard deviation)

Rope nursery
System of ropes anchored to the substrate and suspended by floats, on which the coral fragments are placed (Levy *et al.*, 2010; Johnson *et al.*, 2011).



Rope nursery ©Coralrestoration.org

Table nursery
Coral fragments are placed on ropes stretched to attach to crossbars, which form a "table" (Levy *et al.*, 2010; Mbije *et al.*, 2010).

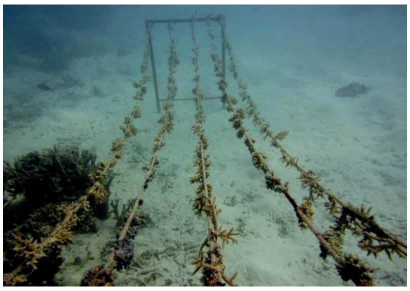


Table nursery ©coralreefcpr.org

Block nursery
Coral fragments are secured to a cement slab anchored to the sea floor (Johnson *et al.*, 2011)

Block nursery ©University of Miami, Rosenstiel School of Marine and Atmospheric Science

Frame nursery
Coral fragments are placed on metal, plastic or PVC mesh frames anchored to the sea floor.

Frame nursery ©University of Miami, Rosenstiel School of Marine and Atmospheric Science

Advantages

❶ Allows for coral fragments to be grown in **large numbers** (Levy *et al.*, 2010).
❷ **Controlled cultivation maximizes the survival rate and productivity** of the fragments (Amar and Rinkevich, 2007; Johnson *et al.*, 2011).
❸ **Easy to build and inexpensive:** possibility of using salvaged materials (Levy *et al.*, 2010; Mbije *et al.*, 2010).
❹ Using multiple types of nursery on a site **reduces the risk of losses** (Johnson *et al.*, 2011).

Disadvantages

❶ **Regular monitoring is necessary:** if the colonies grow too much, there is a **risk of platform collapse and of algal blooms** (Johnson *et al.*, 2011).
❷ In some nurseries with a high density of cuttings with little genetic diversity, **there is a greater risk of epizootic disease and mass mortality** (Ladd *et al.*, 2016).

* Average calculated from the data available for follow-up periods of three years or more.
These values should be treated with the utmost caution. The reader is invited to refer to page 101 of the guide.


©GabyBarathieu

CORAL REEF CASE STUDIES

P. 30 - 31 **Coral transplantation in Prony Bay**

P. 32 - 33 **Coral transplantation in Faa'a Lagoon**

P. 34 - 35 **Coral transplantation on Mbudya Island**

P. 36 - 37 **Coral transplantation in Balhaf (southern Yemen)**

P. 38 - 39 **Coral transplantation in Pointe-à-Pitre Bay**

P. 40 - 41 **Coral transplantation on artificial reefs ("Sulu-Reef Prostheses") in Shark Fin Bay**

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P. 44 - 45 **Coral gardening in Zanzibar and on Mafia Island**

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P. 48 - 49 **Coral gardening in Caye à Dupont**

P. 50 - 51 **Coral cutting in southern Yemen for replanting on virgin substrate**

COR n° 1

CORAL TRANSPLANTATION IN PRONY BAY

New Caledonia

Project carried out in Prony Bay, New Caledonia. Ordered by the Goro Nickel mining company and managed by Sopróner-Ginger.

Project	Port mitigation project in Prony Bay
Site	Prony Bay
Species	>13 species of coral
Surface area	2,000 m^2
Success rate	>80%
Cost	€24.94/m^2
Year	From December 2005 to January 2006
Field officer	sandrinejob@yahoo.fr

Objective

This coral biotope restoration project was carried out on three different sites:

❶ site 1: Montravel, sheltered
❷ site 2: Montravel, exposed
❸ site 3: Casy

The aim was to offset the impact of a port construction project on the coral reefs. An area of 2,000 m^2 was used to house the transplants.

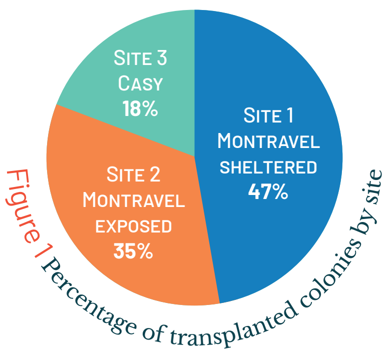


Figure 1 Percentage of transplanted colonies by site

Technique

The corals were removed by scuba divers using hammers and chisels. Colonies were arranged by genus in crates (to avoid negative interactions between organisms). The corals were transported in the open air, by boat, as the distance to the receptor sites was considered short enough (20-30 mins). The corals were watered continuously with seawater. The colonies were attached with a quick-setting cement (12 hours). A total of 1,762 colonies were moved during the project.

The choice of receptor sites was based on their having different parameters: physico-chemical, substrate, etc., so as to enable a comparison of the survival and adaptation of the transplants under different environmental conditions.

Collecting the coral © Sandrine Job

Watering the coral © Sandrine Job

Cost

Le coût total était estimé à 49 873,42 €

Materials and equipment	**€13,674.97**
Salaries	**€36,198.45**
Total	**€49,873.42**
Total per m^2	**€24.94/m^2**

Environmental monitoring

There were several days of follow-up: an initial day of follow-up, another day one month after transplantation, and then one day every six months for five years for a total of 10 follow-up days over five years.

There were two different types of follow-up:
❶ **Simple follow-ups, once a year in July/August**. To measure the survival rate, mortality, growth, site maintenance (cleaning, predator control). ❷ **Comprehensive follow-ups, once a year in January/February.** To assess the adaptation of the transplants to their new environment, their attachment, colonization, *etc.*

The causes of mortality in transplanted corals can be many: natural predation, transplantation stress, competition, diseases, environmental conditions, etc. Regarding the transplantation in Prony Bay, a low mortality rate was observed. In fact, the transplant survival rate was in excess of 80% for the three sites considered (figure 2). For the recovery rate, see figure 3: an average 30% increase in surface area was observed, depending on the site.

Note: The recovery rate includes the growth of the transplants and the natural coverage at the site.

The results four and a half years later:

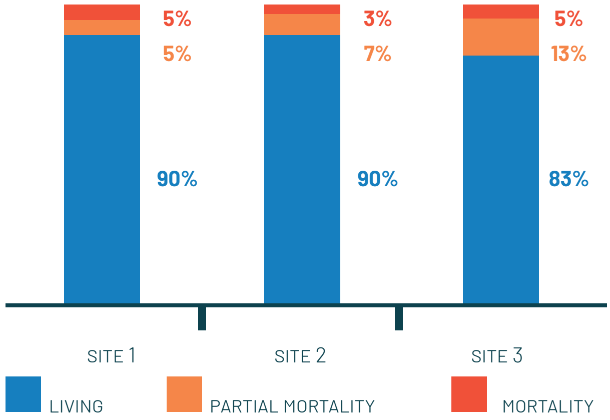


Figure 2 Survival rate, partial mortality and mortality (t+4.5 years)

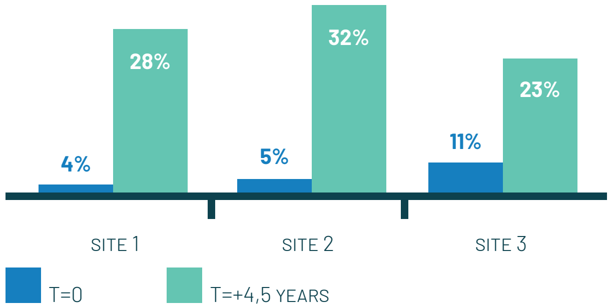


Figure 3 Live coral recovery rate (t=year 0 and t+ 4.5 years)

Assessment

During almost five years of follow-up, the transplantation operation was objectively observed to have been an overall success, demonstrating this choice of transplantation technique to be effective and suitable.

Success rate (%): >80%	**Duration of experiment (including follow-up): 6 years**		
Sequence phase	A	R	**M**
Type of measure	Restoration	Rehabilitation	**Creation**
C1: Creation/restoration of the environment Project aimed at creating a habitat on a site where there was not one initially			
Technical factors affecting risk:			
Species transferred	>13		
Removal technique	removal of coral fragments		
Attachment technique	bonding with quick-setting cement		
Means of transportation	by ship, stowed in crates		
Transportation time	20-30 mins		

Références

❶ Étude d'impact : Projet de Goro Nickel, Occupation du domaine public maritime- Baie de Kwé [Impact assessment: Goro Nickel project, Occupancy of public marine areas - Kwé Bay], 2013 New Caledonia.
❷ Rapport final : programme de reconstitution du biotope corallien en baie de Prony [Final report: coral biotope restoration project in Prony Bay], Ginger-Soproner, 2011.
❸ Rapport de mission : programme de reconstitution du biotope corallien en baie de Prony [Mission report: coral biotope restoration project in Prony Bay], Ginger-Soproner, 2006.

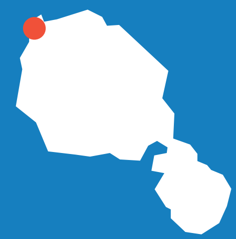
COR n° 2

CORAL TRANSPLANTATION IN FAA'A LAGOON

French Polynesia

Transplantation performed in the lagoonarium of the InterContinental Hotel in French Polynesia. The project was carried out by the association Te mana o te moana, BoraEcoFish and the InterContinental Tahiti Resort.

Faa'a Lagoon



Project .... Restoration of a hotel lagoonarium
Site .... Faa'a Lagoon
Species .... 10 species of coral
Surface area .... 2,080 m^2
Success rate .... N/A
Cost .... €4.92/m^2
Year .... From June to August 2011
Field officer.......... alicecarpentier.temana@gmail.com

Objective

The aim of the project was to recreate a coral area in the lagoonarium. The reserve had experienced a mass mortality event owing to a malfunction of the water supply pumps, leading to a decrease in the oxygenation of the site.

Through the project, the InterContinental Hotel hoped to:
❶ Create a living area consisting of coral nurseries and a nursery area
❷ Improve the appearance of the hotel's lagoonarium
❸ Raise awareness among hotel guests

Cost

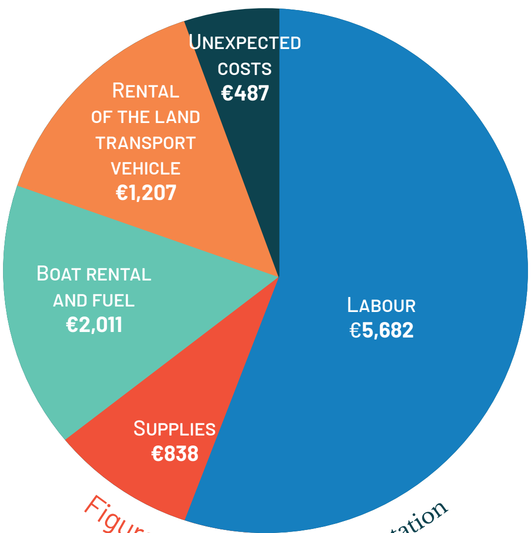


Figure 1 Cost of the transplantation

Total expenditure **€10,225** or **€4.92/m^2**

Technique

The coral transplantation technique was applied to 10 types of coral, namely: *Acropora sp.*, *Cyphastrea sp.*, *Fungia sp.*, *Herpolitha sp.* (free-living coral), *Montipora sp.*, *Pavona sp.*, *Pocillopora sp.*, *Porites sp.*, *Psammocora sp.* and *Synarea sp.* These species of coral were chosen on the basis of their appearance (colour, shape and structure).

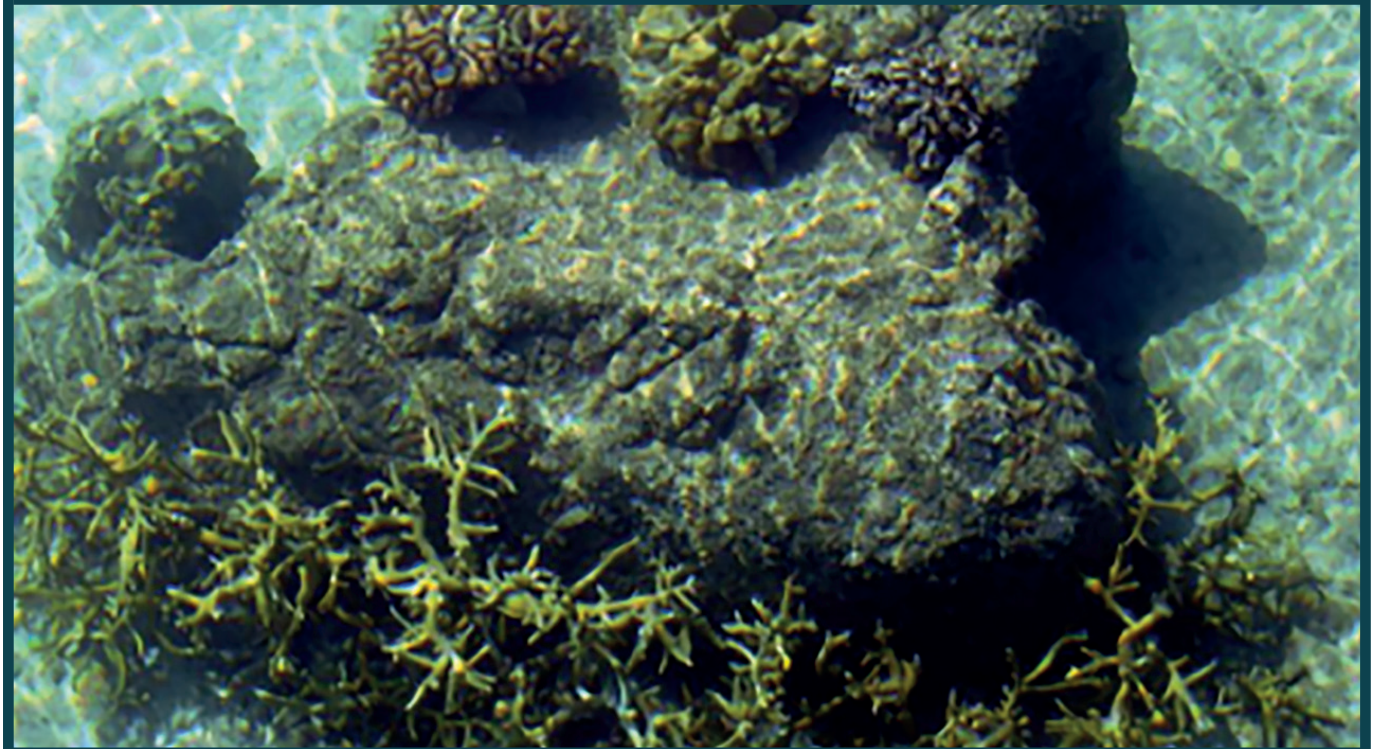
The process of recreation was carried out in two phases:

❶ Physical recreation
The coral garden on the site was redeveloped. The artificial reef blocks (Reef Balls) were moved and prepared for use as supports during the transplantation.

❷ Biological recreation
To minimize the impact on the donor site, the collection area for coral fragments was extensive. Removal from the natural environment was done in such a way as to cause as little harm as possible to the donor site, with preference being given to corals that were already broken, displaced or destined to be destroyed. All the fragments were transported by boat (underwater for the massive corals and in the open air for the branching, encrusting and foliaceous corals). The maximum distance travelled between the donor site and the receptor site was one kilometer in order to reduce transportation stress. The fragments were then attached to the Reef Balls.

Environmental monitoring

Monitoring was carried out over a period of several years. This involved replacing dead or damaged corals, removing harmful species and monitoring the balance in the area, with particular attention being paid to the operation of the circulation pumps.



Reef Ball with coral transplants (Petit and Chevalier, 2011)

Results

After a few weeks, a 95% survival rate as the transplants had acclimatized well. Only a few massive corals succumbed to the stress of transplantation and did not survive. Medium- and long-term survival rates were not reported.

Success rate (%): N/A	**Duration of experiment (including follow-up): several years**		
Sequence phase	A	R	**M**
Type of measure	Restoration	Rehabilitation	**Creation**
Project aimed at providing for or implementing one of the above measures (Restoration-Rehabilitation-Creation)			
Technical factors affecting risk:			
Species transferred	10		
Removal technique	removal of coral fragments that were already broken, displaced or destined to be destroyed		
Attachment technique	not specified		
Means of transportation	submerged beneath a boat for the massive corals and in the open air for the branching corals		
Transportation time	10 mins minimum		

References

❶ **Te mana o te moana, Petit M., Chevalier F.,** Rapport final d'activités : Création d'un jardin de corail artificiel au sein du Lagoonarium de l'InterContinental Tahiti Resort [Final activity report: Creation of an artificial coral garden within the lagoonarium of the InterContinental Tahiti Resort]. August 2011

COR n° 3

CORAL TRANSPLANTATION ON MBUDYA ISLAND

Tanzania

Coral transplantation carried out on Mbudya Island, Tanzania, by local fishermen.

Project	Coral transplantation following degradation
Site	Mbudya Island, Tanzania
Species	*Galaxea sp., Acropora sp., Porites sp., Montipora sp.*
Surface area	N/A
Success rate	Between 70 and 100%
Cost	N/A
Year	2001
Field officer	Wagner *et al.*, 2001

Objective

The objective of the transplantation was to rehabilitate/restore reef areas degraded by blast fishing.

Experimental monitoring

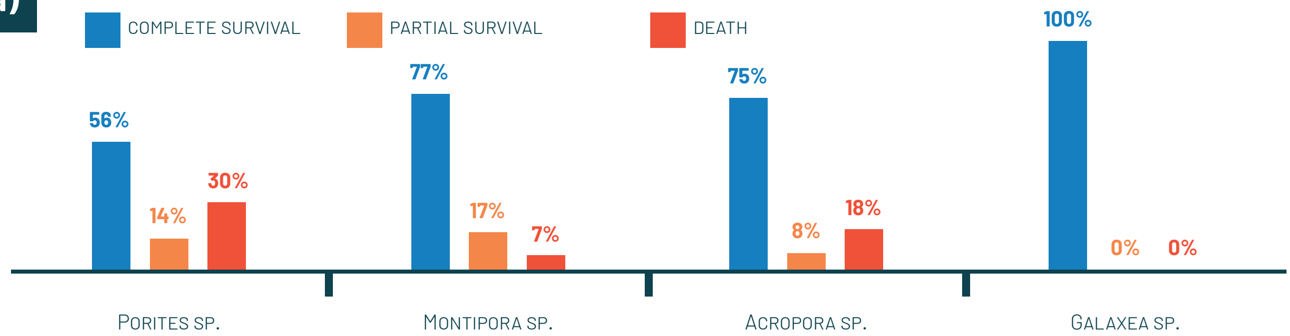
Three months after the coral transplantation, the fishermen measured the survival rate and health status of the transplants.

Technique

500 coral fragments were transplanted by local fishermen to the north-west and south-west coasts of Mbudya Island. The technique involved taking fragments from healthy colonies in the vicinity of the degraded sites and then attaching the fragments to the substrate using plastic plates and cement. On average, one plate could hold five fragments.

Photograph illustrating a transplantation. Note that this is not from the project described.

a)



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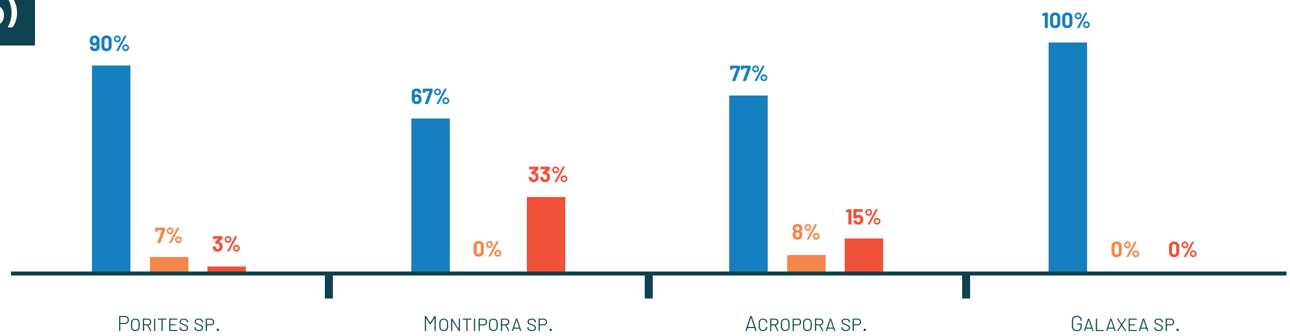


Figure 1 Survival rate (%) of the coral transplants: (a) three months after transplantation; and (b) eight months after transplantation. *Note:* For *Porites sp.*, the differences in mortality between three and eight months are explained by a difference in the random sampling of the measured fragments.

Results

Of the 500 initial fragments, only 342 were randomly selected for follow-up. Galaxea sp. had a 100% survival rate, even after eight months (figure 1). However, for the other species, the survival rates were poorer, but relatively high, ranging from 70 to 90% after eight months (figure 1). These results are thought to be attributable to the action of the swell on the fragments. The transplantation method used seems to have been effective nonetheless.

Success rate (%): between 70 and 100%	**Duration of experiment (including follow-up): approx. 8 months**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	Creation
C2: Project in an environment degraded by man or by natural evolution, aimed at changing the environment to a state more favourable to its proper functioning or to biodiversity, requiring work.			
Technical factors affecting risk:			
Species transferred	4		
Removal technique	removal of coral fragments		
Attachment technique	plastic plates and cement		
Means of transportation	N/A		
Transportation time	N/A		

References

❶ **Wagner, G. M., Mgaya, Y. D., Akwilapo, F. D., Ngowo, R. G., Sekadende, B. C., Allen, A., ... and Mackentley, N.** (2001, June). Restoration of coral reef and mangrove ecosystems at Kunduchi and Mbweni, Dar es Salaam, with community participation. In: Marine science development in Tanzania and eastern Africa. Proceedings of the 20th Anniversary Conference on Advances in Marine Science in Tanzania (Vol. 28, pp. 467–488).

COR n° 4

CORAL TRANSPLANTATION IN BALHAF (SOUTHERN YEMEN)

Yemen

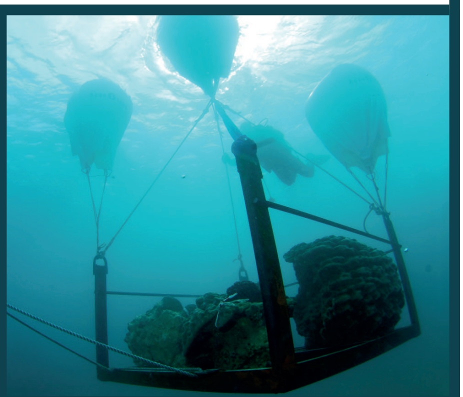
Transplantation of coral colonies by Créocéan as part of the construction of a liquefied natural gas (LNG) plant on the coast.

Project	Coral transplantation prior to site destruction
Site	Balhaf, Yemen
Species	*Acropora, Acanthastrea, Coscinarea, Cysphastrea, Echinopora, Favia, Favites, Fungia, Galaxea, Goniastrea, Goniopora, Hydnophora, Leptastrea, Leptoria, Lobophyllia, Millepora, Montipora, Pavona, Platygyra, Pocillopora, Psammocora, Porites, Stylophora and Turbinaria*
Surface area	1,553 m^2 (donor site)
Success rate	Between 70 and 90%
Cost	N/A
Year	2007–2009
Field officer	dutrieux@creocean.fr

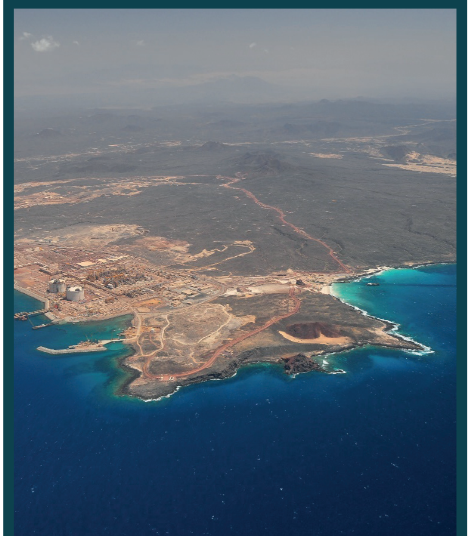
Objective

The construction of the onshore LNG plant involved some offshore development, namely the construction of seawalls, trenches and shoreline riprap, which would result in the destruction of existing corals. The objective of the operation was to remove these coral colonies and place them in a suitable area so as to preserve them.

Transportation of a coral fragment © Eric Dutrieux



Massive colonies are stored underwater in a steel cage tied to parachutes © Eric Dutrieux



Construction site of the liquefied natural gas plant © Eric Dutrieux

Technique

❶ The first step is to make an inventory of the corals suitable for relocation according to criteria related to the health of colonies and their size, and then to identify the receptor site on the basis of its ecological characteristics. ❷ The second step is to collect the corals. This work is done using a hammer and chisel for medium-sized colonies, taking care not to touch the living parts of the colony. Large colonies are removed with specially developed tools. Massive colonies are stored underwater in a steel cage, lifted by parachutes. They are then towed to the receptor sites ❸ The third step is to reattach the colonies in their new environment. Once positioned, the colonies are glued with a cement containing an additive that allows them to set quickly. ❹ The last step is to create a detailed map of the transplanted colonies to establish a baseline status for monitoring purposes.

Observations

Transplantation operations are cumbersome and require a team of scientific divers and technical scuba divers. Between 50 and 100 corals can be moved in one day (about one month is needed to transfer 1,000 corals, including time for mobilization and organization). The team is composed of two groups of four divers each, with at least one scientific diver per group. Commercial divers are particularly useful for transporting very large and heavy colonies, which ensures the safety of the operations.

Results

A total of 1,500 colonies were moved to four different sites. Among these were 140 colonies of Porites weighing more than one tonne. Only the most sensitive and healthy corals were collected, including 100% of the *Acropora downingi, Lobophyllia hemprichii, Leptoria phrygia* and *Goniopora lobata.* The coral colonies were relocated, taking care to recreate a natural environment in terms of density, diversity and topology. The results of the transplantation operations were more than satisfactory. The overall survival rate of the transplanted colonies reached 95% in October 2007, but decreased slightly thereafter owing to the residual effects of the marine works. After two years, 79% of the colonies had survived (figure 1).

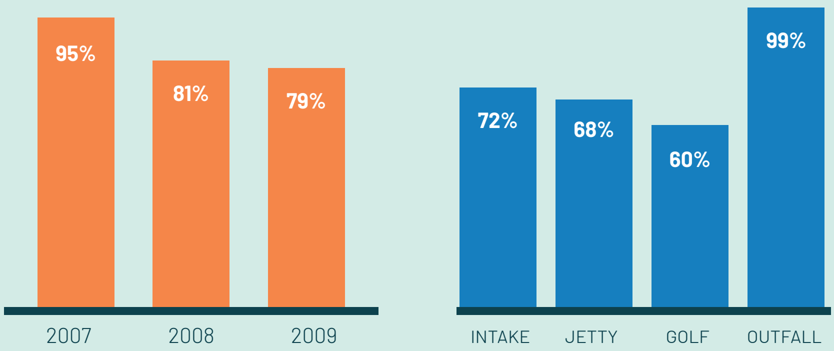


Figure 1 Coral survival rates.

Lessons learned

The relocation of corals does not make it possible to establish a new ecosystem.
While the operations themselves reduce individual coral mortality, they do not prevent total habitat loss, and they should be used only as a last resort.

Technical parameters:
- 1,500 colonies moved
- 70% to 100% of the corals present were transferred
- Donor sites spanning 1,553 m^2
- Colonies weighing between one kilogram and four tonnes
- 120-day operation involving eight divers

Success rate (%): 79%	**Duration of experiment (including follow-up): 2 years**		
Sequence phase	A	R	**M**
Type of measure	Restoration	Rehabilitation	**Creation**

C1: Creation/restoration of the environment
Project aimed at creating a habitat on a site where there was not one initially

Technical factors affecting risk:

Species transferred	>24
Removal technique	removal of coral fragments
Attachment technique	bonding with quick-setting cement
Means of transportation	by boat, avoiding contact with the open air by means of a system comprising a steel cage and parachutes
Transportation time	N/A

References

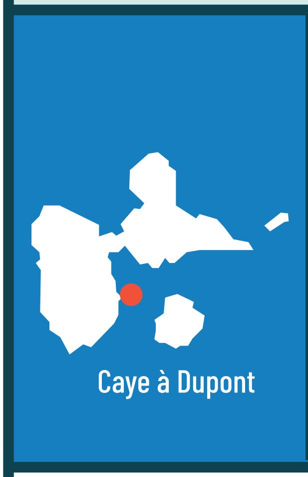
F. Seguin, O. Le Brun, R. Hirst, I. Al-Thary, E. Dutrieux, 2010. Large coral transplantation in Bal Haf (Yemen): an opportunity to save corals during the construction of a Liquefied Natural Gas plant using innovative techniques. Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, Florida, 7–11 July 2008 (Session number 24)

COR n° 5

CORAL TRANSPLANTATION IN POINTE-À-PITRE BAY

Guadeloupe

Coral transplantation in Pointe-à-Pitre Bay as part of the construction of the Grand Port Maritime de la Guadeloupe. The transplantation was carried out by a consortium led by the company Créocéan.



Project	Transfer of coral colonies from a channel (donor sites) to receptor sites
Donor sites	East of Îlet à Cochons (2,100 m^2) and Caye Sans Nom (6,256 m^2)
Receptor sites	Caye à Dupont (11,205 m^2) and Îlet du Gosier (1,800 m^2)
Species	22 species of coral transplanted (16 genera – 7 families)
Survival rate	98.4% after one year
Cost	N/A
Year	From January to March 2015
Field officer	lebrun@creocean.fr and degaulejac@creocean.fr

Objective

As part of works to extend the port of Jarry within the Grand Port Maritime de la Guadeloupe, a port hub had to be created to improve the entrance channel and create a second terminal covering an area of 10 hectares. However, the works to improve the entrance channel would directly affect the corals located at Caye Sans Nom and east of Îlet à Cochons, destroying them by mechanical means. The port wished to relocate and transplant the majority of the coral colonies to areas of Pointe-à-Pitre Bay not affected by the works.

Transportation of the corals
© Olivier Le Brun

Technique

The method for transplanting the corals was broken down into two phases:

Project feasibility study performed beforehand:

This made it possible to: ❶ Determine which of the different species were to be transplanted, how many there were, and how their health was ❷ Draw up layout plans for the donor sites by selecting the areas of ecological interest of the colonies to be transplanted and of the receptor sites ❸ Specify, confirm and optimize the transplantation techniques chosen according to the areas selected, the size of the colonies and the substrate, and define precisely how the work was to be carried out ❹ Plan the work, establishing the phases ❺ Check how well the coral would stand up to transplanting under possibly turbulent conditions ❻ Propose coral monitoring and establish the baseline status of the receptor sites and associated fish populations.

Coral transplantation:

This was divided into five tasks: ❶ Delimit and precisely mark out the working areas ❷ Collect the corals from each donor site in order to transport them to the relevant receptor site ❸ Transfer the collected coral colonies to the receptor sites for replanting ❹ Attach the collected coral colonies to the receptor sites ❺ Mark the colonies for long-term monitoring and position the scientific monitoring transects.

Scientific monitoring

The corals were scientifically monitored for four years after transplantation at the following intervals:
- year 1: campaigns at 1, 3, 6 and 12 months
- years 2 to 4: one campaign every six months.

This involved: ❶ Monitoring 62 control colonies that had been transplanted and marked ❷ Monitoring permanent transects on each of the receptor sites.

Agaricia after transplantation © Olivier Le Brun

Meandrina after transplantation © Olivier Le Brun

Lessons learned

The transplantation made it possible to relocate massive coral colonies that were going to be destroyed by the levelling of two shoal areas. This loss of habitat was mitigated by the relocation. The maintenance of coral cover demonstrated that the methods used had been effective and that the receptor sites had been well chosen. However, the impact of the coral transplantation, three and a half years after the work, is not yet detectable on these sites in terms of recovery and numbers of juvenile corals.

Results

The results of the transplantation operations revealed a survival rate at t+3.5 years of 72.6% (figure 1)

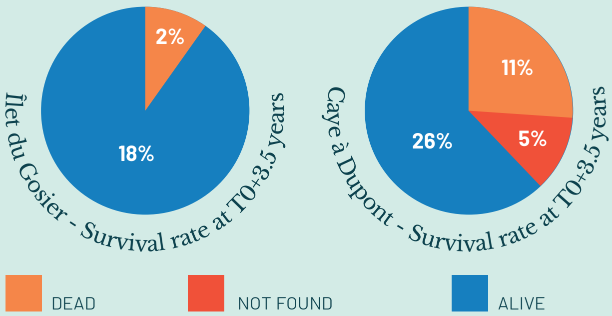


Figure 1 Colony survival rate (%) from March 2015 to January 2019.

Success rate (%): 72.6%	**Duration of experiment (including follow-up): 4 years**		
Sequence phase	A	R	**M**
Type of measure	Restoration	Rehabilitation	**Creation**
C1: Creation/restoration of the environment Project aimed at creating a habitat on a site where there was not one initially			
Technical factors affecting risk:			
Species transferred	4,188 colonies transplanted (91% between 20 and 40 cm).		
Removal technique	removal of entire colonies with hammer and chisel.		
Underwater transportation technique:	storage in perforated fisherman's crates.		
Attachment technique	cement/sand mixture.		
Means of transportation	pools on a barge, colonies kept wet in crates under tarpaulins.		
Transportation time	30 minutes		

References

❶ **Créocéan,** Guadeloupe Port Caraïbes - Coral transplantation to mitigate dredging impacts on coral reefs for a port extension project. Guadeloupe, French West Indies - 13th International Coral Reef Symposium, 19–24 June 2016 - Honolulu, Hawai'i.

❷ **Créocéan -** Travaux de transplantation de coraux. Grand projet de port. Phase 2. Exécution des Travaux. Rapport 150037 [Coral transplantation. Major port project. Phase 2. Execution of the works. Report No. 150037] - Grand Port Maritime de la Guadeloupe – April 2015.

❸ **Créocéan -** Travaux de transplantation de coraux – Grand Projet de Port. [Coral transplantation – Major port project.]

❹ Suivi scientifique des coraux transplantés. Campagne n°9. 4ème année. Rapport 180977 [Scientific monitoring of the transplanted corals. Campaign No. 9. Year 4. Report No. 180977] – Grand Port Maritime de la Guadeloupe – February 2019.

COR n° 6

CORAL TRANSPLANTATION ON ARTIFICIAL REEFS ("SULU-REEF PROSTHESES") IN SHARK FIN BAY

Philippines

Project carried out around Pangatalan Island in "Shark Fin Bay", Taytay, Palawan, Philippines. The Sulubaaï Environmental Foundation developed the method and collected the data.

Project	Coral reef restoration
Site	Pangatalan Island, Taytay, Philippines
Species	28 species of coral
Surface area	230 m^2
Success rate	76.6%
Cost	€82/m^2
Year	since 2017
Field officer	Laure de Ville d'Avray and Cinzia Alessi – Sulubaaï Environmental Foundation, contact@sulubaai-foundation.com

Objective

Increase the resilience and reduce the recovery time of unstable corals located on coral debris, remnants of reefs blown up by blast fishing. The study covers four sites and 1,647 transplanted coral colonies.

Technique

The project began in 2016 with four restoration sites selected because of their high coral mortality and structural weakening. Sulu-Reef Prostheses (SRPs) were created and manufactured by the Sulubaaï Environmental Foundation (figure 1). They are made of reinforced concrete and are available in three sizes: SRP 1,000 (0.91 m^2), SRP 700 (0.87 m^2) and SRP 450 (0.73 m^2). They are composed of two parts manufactured on site. Between 8 and 12 coral fragments are attached to the top and sides of each SRP with steel bars (figure 2). The evolution of the ecological volume of the coral fragments was analysed at three of the four restoration sites. At each of these three sites, 60 coral fragments were randomly selected for attachment to the 15 SRPs at the site. Ecological volume monitoring was performed for a total of three sites * 15 SRPs * four fragments = 180 coral colonies (figure 3). The monitoring was conducted once a month. The measurements required to calculate the ecological volume were recorded from photographs taken *in situ*. The photos were obtained by diving with a camera equipped with a 30 cm stand displaying a ruler (for calibration of the measurement). The attachment of the corals and their colours were observed *in situ* with the naked eye. The measurements required to calculate the ecological volume were taken using ImageJ software: length, width and height. The volume was calculated using the formula of Frias-Torres *et al.*, 2018. The initial values were used to divide the coral fragments into three size categories: small (volume <21 cm3), medium (volume between 21 and 215 cm3) and large (volume >215 cm3). The analysis covers volumes calculated 3, 6 and 12 months after the date of attachment of the fragments to the SRPs.

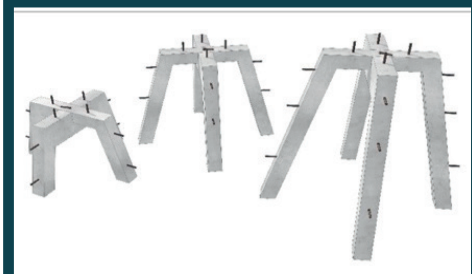


Figure 1 Sulu-Reef Prosthesis (SRP)

Figure 2 Example of attachment of a coral colony to the SRP

Cost

Total cost: €18,875
Materials and equipment: €3,275
Salaries: €15,600
Total per m²: €82

Assessment

Through its artificial reef modules (SRPs), the Sulubaaï Environmental Foundation offers a new restoration technique with low manufacturing costs that uses no plastic or toxic products and has resulted in a coral survival rate of 76%.

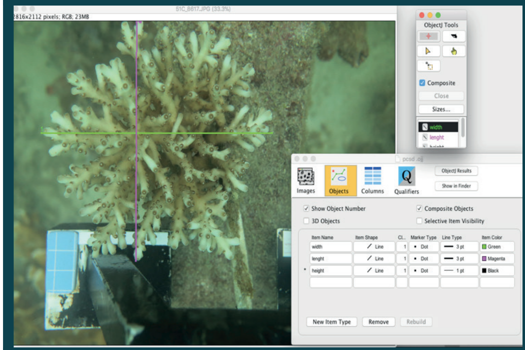


Figure 3 Taking the measurements required to calculate the ecological volume with ImageJ software

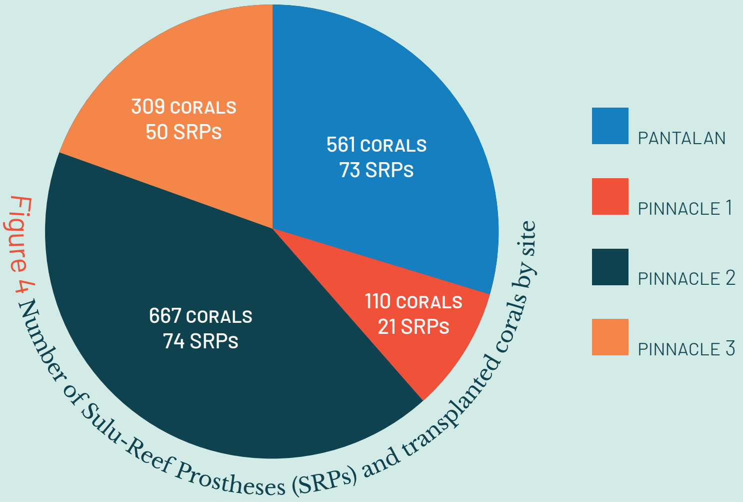


Figure 4 Number of Sulu-Reef Prostheses (SRPs) and transplanted corals by site

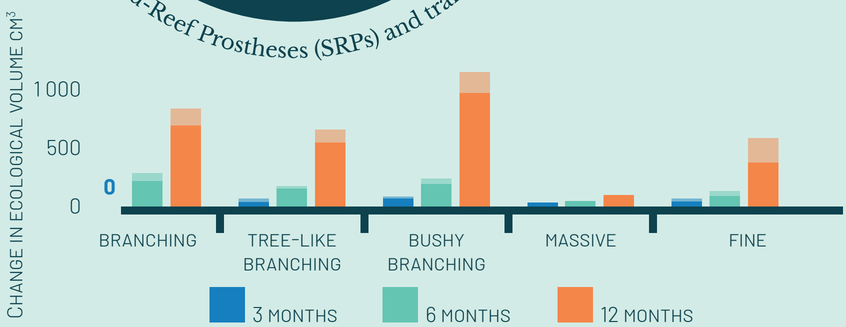


Figure 5 Evolution of ecological volumes after 3, 6 and 12 months by coral shape

Results

From 2017 to 2019, more than 200 SRPs were positioned at four sites in the damaged Pangatalan reef for a total of 1,647 coral fragments (figure 4) from 28 species. SRPs are highly adaptable, enabling the attachment of corals of all shapes (branching, massive or fine).

After 12 months, the cumulative survival rate of the corals transplanted onto the SRPs was 76.6% and the attachment rate was 71%: 14.3% on the concrete part, 27.3% on the steel bar and 29% on both parts (steel bar and concrete). The ecological volumes of the branching and fine corals are growing exponentially, with the bushy branching varieties being the most successful. The massive varieties exhibited a progressive variation in ecological volume at 3, 6 and 12 months, with no clear differences over time (figure 5).

Success rate (%): 76%	**Duration of experiment (including follow-up): 1.5 years**		
Sequence phase	A	R	**M**
Type of measure	Restoration	Rehabilitation	**Creation**

C1: Creation/restoration of the environment
Project aimed at creating a habitat on a site where there was not one initially

Technical factors affecting risk:

Type	restoration
Removal	coral fragments
Attachment technique	twisting of a steel bar to wedge the fragment onto the cement SRP
No transfer or removal from the water	the corals are collected and attached directly on site by divers

COR n° 7

CORAL GARDENING IN BOLINAO

Philippines

Establishment of coral nurseries for the University of Haifa (Israel) according to the concept of "coral gardening".

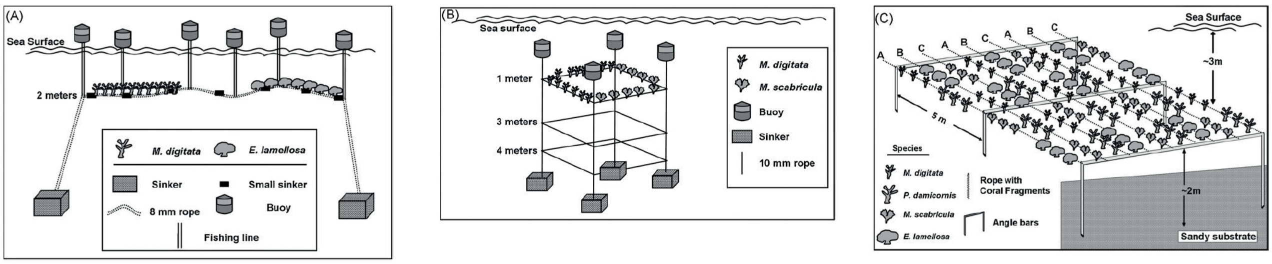
Project . . . . Creation of a coral gardening in Bolinao
Site . . . . Bolinao, Philippines
Species . . . . Finger coral *(M. digitata)*, cauliflower coral *(P. damicornis)*, spiny coral *(E. lamellosa)*, M. scabricula
Surface area . . . . N/A
Success rate . . . . Between 51 and 100%
Cost €171.80/month
Year 2007
Field officer. . . . . Levy *et al.*, 2010.

Objective

The aim of the experiment was to find a viable and effective solution for future reef restoration work through the use of three types of rope nursery.

Technique

Three types of rope nursery were tested. The nurseries were placed at a sufficient water depth to avoid the effects of tides and above the substrate to avoid sedimentation.
The sites were chosen on the basis of their environmental quality, as they were sheltered from thunderstorms and swells.



Type I
Floating rope nurseries
The coral fragments were positioned below the surface buoys, which meant that the swell had an impact on them.

Type II
Floating rope nurseries suspended above the sea floor
The coral fragments were connected to ropes stretched between sinkers and buoys. With levels stacked on top of one another, this type of nursery saved space. It also protected the fragments from the swell. A total of 1,191 coral fragments were cultivated.

Type III
Nurseries fixed to the sea floor
The coral fragments were placed on ropes stretched and held in place by crossbars. The whole structure was fixed onto a sandy substrate. This type of structure was suitable for all types of hydrodynamics.

Cost

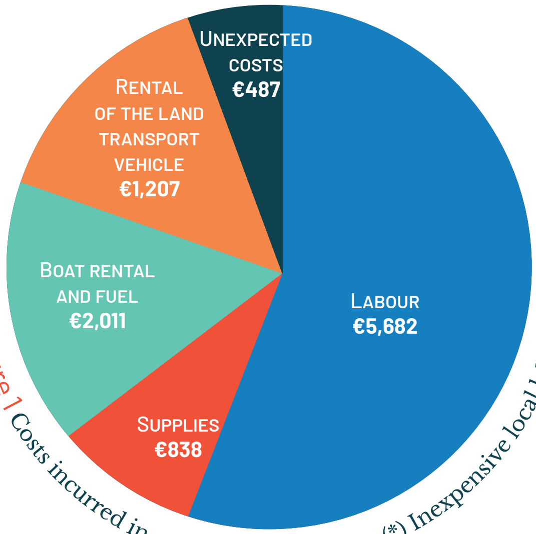


Figure 1 Costs incurred in establishing nurseries (*) Inexpensive local labour

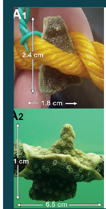
For the 1,191 fragments used, (US$ to € conversion at 2007 rates).

Experimental monitoring

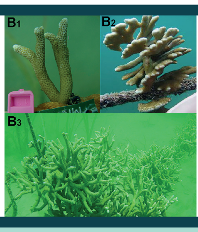
Monitoring was performed every three months to check the condition of the structures, remove any algae that might have grown, count dead colonies and take photographs.

Table 1 Survival rate of fragments by species of coral after 10 months of cultivation. Note: Averages have been rounded.

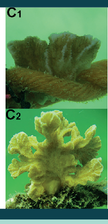
10 months after cultivation			
Nursery type	**Type I**	**Type II**	**Type III**
E. lamellosa	70%	87%	51%
M. digitata	60%	/	100%
M. scabricula	/	54%	75%
P. damicornis	/	/	97%



E. lamellosa
A_1 = T0
A_2 = T170 days



M. digitata
B_1 = T0
B_2 = T0
B_3 = T170 days



M. scabricula
C_1 = T0
C_2 = T302 days

Figure 2 Photographs of the evolution of fragments from three coral species after cultivation (Levy *et al.*, 2010)

Results

The rope nursery concept was developed into a reef restoration technique. The fragments grew successfully (table 1, figure 2). The nurseries proved to be inexpensive and very quick to set up, making it possible to design this type of nursery on a larger scale.

Success rate (%): between 51 and 100%	**Duration of experiment (including follow-up): approx. 1 year**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	**Creation**
Project aimed at providing for or implementing one of the above measures (Restoration-Rehabilitation-Creation)			

Technical factors affecting risk:	
Species transferred	4
Removal technique	removal of coral fragments
Attachment technique	small coral fragments inserted in the coil of a rope
Means of transportation	N/A
Transportation time	N/A

References

❶ **Levy, G., Shaish, L., Haim, A., and Rinkevich, B.** (2010). Mid-water rope nursery —Testing design and performance of a novel reef restoration instrument. Ecological Engineering, 36(4), 560-569.

COR n°8

CORAL GARDENING IN ZANZIBAR AND ON MAFIA ISLAND

Tanzania

Establishment of coral nurseries for the University of Haifa (Israel) according to the concept of "coral gardening".

Project .... Creation of a coral gardening in Zanzibar and on Mafia Island
Site .... Zanzibar and Mafia Island
Species .... Staghorn coral (*A.formosa*), cream coral (*A.nasuta*), *A.hemprichii*, rasp coral (*P.verrucosa*), *P.cylindrica*, fire coral (*Millepora sp.*)
Surface area .... N/A
Success rate .... Between 85 and 100%
Cost .... €2,148.40 per 10,000 fragments excluding labour
Year 2007
Field officer........... Mbije *et al.*, 2010.

Objective

The aim of the experiment was to find a viable and effective nursery method for future reef restoration work.

Cost

The total cost for the 21,600 coral fragments was estimated at €2,148.40 excluding labour.

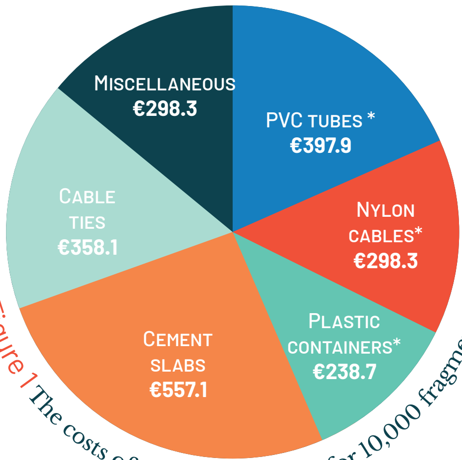


Figure 1 The costs of creating nurseries for 10,000 fragments.

Note: (*) The use of reusable materials resulted in lower costs.

Table nurseries made of PVC and nylon cables (Mbije *et al.*, 2010)

Technique

Tables measuring 6 m² were made using one-metre-long PVC tubes, assembled end to end, and nylon cables (photos 1 and 2). The nurseries were built in collaboration with local fishermen. The installation sites were chosen based on local environmental conditions:

❶ Sheltered areas
❷ At a depth of four metres (to avoid accidental damage)

A total of 21,600 fragments were planted on the nurseries at the Zanzibar and Mafia Island sites (table 1). The fragments were cultivated for nine months.

Table 1 Number of coral fragments by installation site.

Species	Zanzibar	Mafia Island
Staghorn coral	1 296	1 728
Cream coral	1 296	1 728
A. hemprichii	1872	2 304
Rasp coral	1 296	2 304
P.cylindrica	2 304	2 304
Fire coral	1 440	1 728
TOTAL	**9 504**	**12 096**

Results

Nine months after the fragments were attached to the nurseries, the survival rates of the species concerned were found to be relatively satisfactory at the Zanzibar site (between 85 and 100%). In contrast, on Mafia Island, survival rates were between 60 and 100% (figure 3).
Nursery cultivation yielded satisfactory results for the fire coral (100% success rate).
For the other species, the mortality rate was generally low (between 60% and 95%). There were a couple of unfortunate reasons for this mortality: ❶ Poaching ❷ Stress due to fragmentation and the transportation of the fragments.

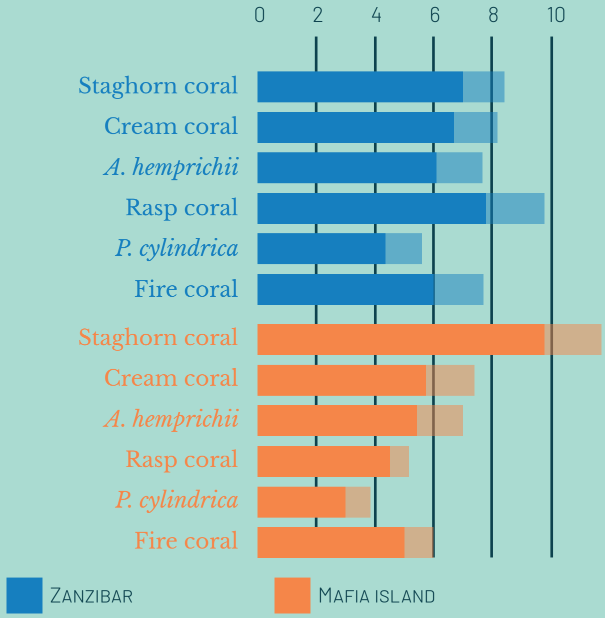


Figure 2 Fragment growth after nine months (in cm)

The fragments were observed to have grown fairly rapidly over the nine months (figures 2 and 4), by up to 9 cm in the case of the staghorn coral. This study demonstrated the effectiveness of nurseries for growing small coral fragments. The technique used proved to be practical for producing a large number of colonies in under a year and at a lower cost.

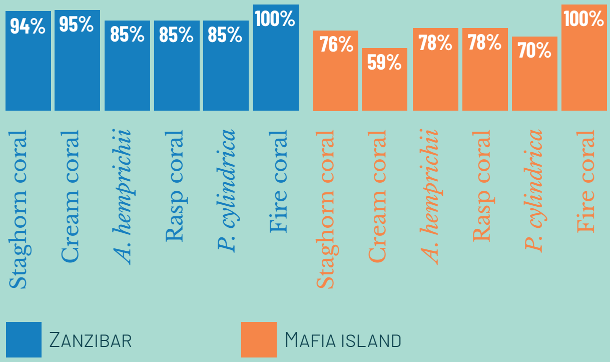


Figure 3 Species survival rates nine months after the start of the experiment

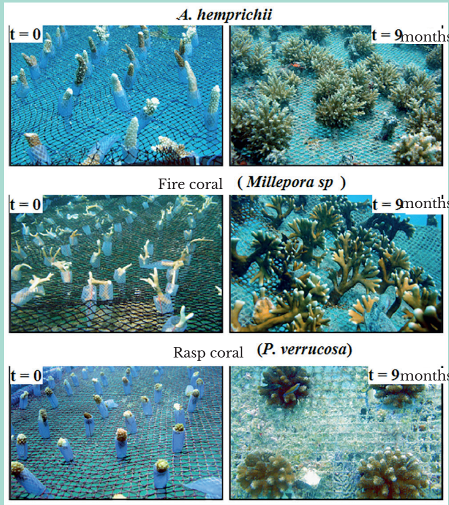


Figure 4 Examples of fragment evolution after nine months of growth

Success rate (%): between 85 and 100%	**Duration of experiment (including follow-up): 9 months**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	**Creation**
Project aimed at providing for or implementing one of the above measures (Restoration-Rehabilitation-Creation)			
Technical factors affecting risk:			
Species transferred	6		
Removal technique	removal of coral fragments		
Attachment technique	inserted in PVC tubes		
Means of transportation	N/A		
Transportation time	N/A		

References

❶ **Mbije, N. E., Spanier, E., and Rinkevich, B.** (2010). Testing the first phase of the 'gardening concept' as an applicable tool in restoring denuded reefs in Tanzania. Ecological Engineering, 36(5), 713-721.

COR n° 9

CORAL GARDENING IN LE DIAMANT

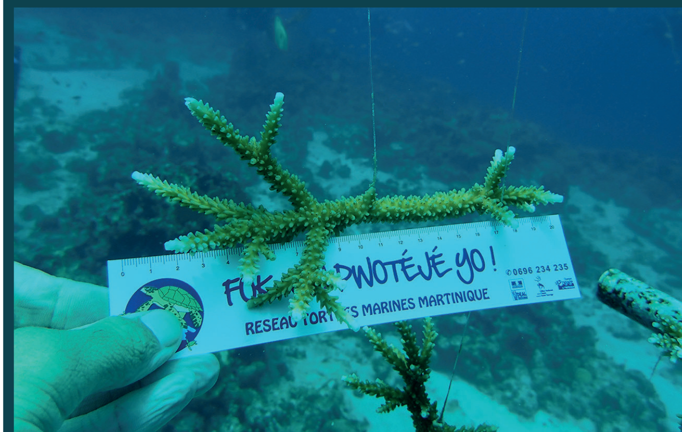
Martinique

Project to establish coral nurseries carried out by the association L'ASSO-MER.

Project	Management of a coral gardening
Site	Commune of Le Diamant
Species	Staghorn coral *(Acropora cervicornis)*, elkhorn coral *(A. palmata)*
Surface area	N/A
Success rate	five times higher than in the original state
Cost	€7,114
Year	2016
Field officer	lassomer972@gmail.com

Objective

The aim of the project was to counteract the decline observed in recent decades in the populations of *Acropora sp.* in the Caribbean. The creation of nurseries is one of the solutions envisaged to enable the recolonization of coral reefs in the Sainte-Luce area. The mission was also aimed at testing methods for growing coral cuttings on two species: staghorn coral *(Acropora cervicornis)* and elkhorn coral *(A. palmata)*.



A. cervicornis cuttings ©Alexandre Arqué

Tree nursery ©Alexandre Arqué

Technique

The technique developed by L'ASSO-MER was to duplicate using cuttings. Small fragments of coral were collected from a mother colony on the Atlantic coast and then placed in a nursery in the commune of Le Diamant. Three tree nurseries were built to implement this technique with the help of PVC tubes and purchased cuttings. The nurseries were weighted down with pieces of recycled concrete. The coral cuttings were attached to the PVC tubes with nylon thread. The attachment of the cuttings started at the end of 2015. A total of 54 staghorn coral cuttings and seven elkhorn coral cuttings were planted on the trees.

Feedback from field officers

According to Alexandre Arqué (director of L'ASSO-MER), elkhorn coral must be bonded to a hard, non-wire support (concrete blocks). Several types of glue should be tested. The growth rate for the staghorn coral, meanwhile, was very good.

The cutting of this species was a success.

The environmental conditions at the site were ideal. The nursery area needed to be protected to avoid damage, particularly from fishing.

At present, the tree nurseries are full and the cuttings are waiting to be transplanted in their natural environment. This phase takes time because authorizations linked to the protected status of the species in question are required.

Environmental monitoring

Eleven trips have been made to the nursery in one year to maintain the cutting equipment and monitor the progress of a few cuttings.

Cost

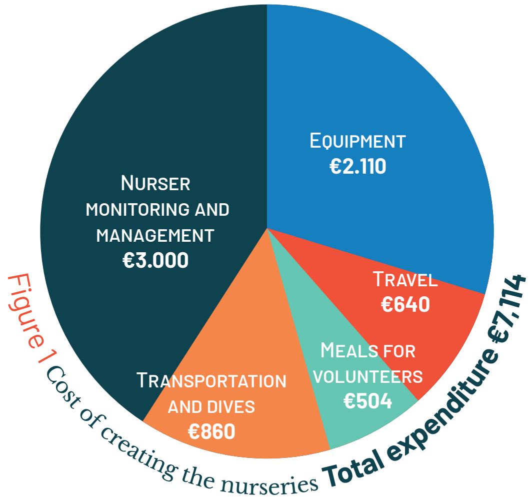


Figure 1 Cost of creating the nurseries

Attaching *A. cervicornis* cuttings to the nursery. ©Alexandre Arqué

Results

The results of the experiment have been highly satisfactory with regard to the staghorn coral. In one year, the number of cuttings has increased fivefold, from 54 to the present total of 294. For the elkhorn coral, the number of cuttings has not increased because this species does not develop well in tree nurseries.

Some regrettable incidents:

❶ The displacement of a tree caught in a fishing net.
❷ The death of some cuttings due to stress during the cutting process.
❸ The detachment of a float causing one of the trees to fall.
❹ The glue used to attach the cuttings to some concrete blocks was not suitable.

Note The purpose of this project is not environmental mitigation. Rather, the project is aimed at managing two species classified as critically endangered, and in particular at reintroducing colonies off the Caribbean coast of the island, where they have almost disappeared. Its aim is not to restore the reef habitat directly based on traditional objectives of biodiversity, functionality, surface area and productivity.

References

❶ Rapport intermédiaire : Installation et gestion de nurseries coralliennes à Acroporidae en côte caraïbe-Martinique. [Interim report: Installation and management of Acroporidae coral nurseries off the Caribbean coast of Martinique.] April 2017
❷ Interview with **Alexandre A**rqué (director of L'ASSO-MER)

COR n° 10

CORAL GARDENING IN CAYE À DUPONT

Guadeloupe

The Grand Port Maritime de la Guadeloupe was the contracting authority for the coral gardening in Caye à Dupont, Guadeloupe. The project was managed by CDC Biodiversité and Coraïbes, a limited liability company devoted to marine ecological restoration.

Project . . . . Establishment of a coral gardening
Site . . . . Establishment of a coral gardening
Species . . . . Staghorn coral *(Acropora cervicornis)*, elkhorn coral *(Acropora palmata)*
Surface area . . . . 12 supporting structures for tree nurseries
Success rate 94%
Cost €160,869
Year 2015–2017
Field officer. . . . . mariane@coraibes.com

Objective

In response to the critical danger of extinction faced by two endemic coral species, namely staghorn coral *(Acropora cervicornis)* and elkhorn coral *(Acropora palmata)*, a project was launched to create a coral gardening. The aim was to produce "cuttings" that could be transplanted in the reefs off Guadeloupe in order to strengthen existing populations.

Staghorn coral *A. cervicornis*	883 seedlings
Elkhorn coral *A. palmata*	50 seedlings

Table 1 Number of seedlings planted for each species

Technique

The construction of the nursery began in 2016. To establish a nursery suitable for the cultivation of these two species of coral, fragments were collected in natura from the reefs of the Petit Cul-de-Sac Marin. The cuttings were then hung from the "branches" of a PVC structure installed in the water column. After a growth phase of 8 to 12 months, the cuttings were divided again in order to increase the number of corals growing in the nursery. Eventually, the fragments will be transplanted in severely degraded reefs.

Staghorn coral on the tree nursery ©Mariane Aimar-Godoc

Environmental monitoring

Every 10 days, an inventory was taken of the nursery and the growth of the cuttings was monitored.
❶ Measurements were taken of the total length of five cuttings per supporting structure.
❷ The survival rate of all the cuttings was also calculated.
❸ At the same time as the monitoring, the trees were cleaned to remove colonizing organisms (algae, barnacles, bivalves, etc.) that could cover the cuttings and hinder their development.

Staghorn coral on the tree nursery ©Mariane Aimar-Godoc

Success rate (%): 94%	**Duration of experiment (including follow-up): 3 years**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	**Creation**
Project aimed at providing for or implementing one of the above measures (Restoration-Rehabilitation-Creation)			
Technical factors affecting risk:			
Species transferred	4		
Removal technique	removal of coral fragments		
Attachment technique	small coral fragments attached to PVC tubes with nylon threads		
Means of transportation	N/A		
Transportation time	N/A		

References

❶ **Nedimyer K., Gaines K., Roach S.,** 2011. Coral tree nursery ©: An innovative approach to growing corals in an ocean-based field nursery. AACL Bioflux 4(4): 442-446.
❷ Analyse régionale Guadeloupe, synthèse des connaissances. [Regional analysis Guadeloupe, knowledge synthesis.] University of the French West Indies and Guiana, Guadeloupe National Park and the Marine Protected Areas Agency, 2013
❸ Coraïbes. Restauration des récifs coralliens. Rapport de synthèse 2016 : Collecte, bouturage et mise en culture de coraux [Coral reef restoration. Synthesis report 2016: Coral collection, cutting and cultivation]. 2016. p. 73.

COR n° 11

CORAL CUTTING IN SOUTHERN YEMEN FOR REPLANTING ON VIRGIN SUBSTRATE

Yemen

The aim of the operation carried out by Créocéan following the construction of an LNG plant was to plant coral cuttings on concrete structures and dead coral colonies.

Project .... Coral cutting following the construction of an LNG plant
Site .... Balhaf, Yemen
Species .... *Acropora cf. muricata, Pocillopora damicornis, Pavona cactus, Montipora sp., Stylophora pistillata, Porites cf. lutea, Echinopora gemmacea, Favorites pentagona. Pavona clavus, Favorites peresi, Hydnophora exesa, Cyphastrea microphthalma, Goniopora minor, Galaxea fascicularis/astreata*
Surface area .... 825 m^2 for the second phase
Success rate .... 30 to 40% survival and development of the cuttings
Cost .... N/A
Year .... restoration in 2009, monitoring in 2012
Field officer........... dutrieux@creocean.fr

Objective

Upon completion of the construction of the LNG plant, despite the precautions taken, some coral areas were degraded, leaving behind a hard substrate with no living colonies. In order to mitigate the damage observed, a project was launched to colonize the substrates with coral colonies. The objective of the operation was therefore to replant coral cuttings on the virgin substrates.

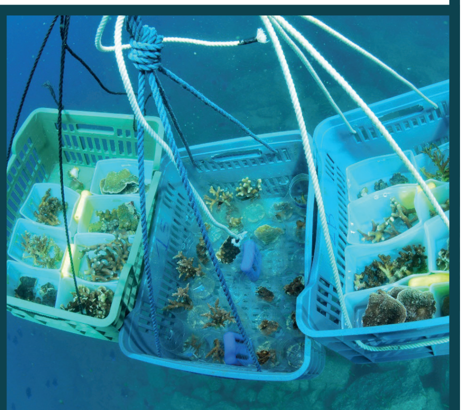
Technique

The coral cuttings were collected from healthy areas in such quantities as not to endanger native colonies. Branching corals were cut with stainless steel wire cutters. The length of the fragments was between 5 and 15 cm, with every fragment having more than one branch. Massive corals were removed using a small hammer and a sharp chisel. The fragments were placed in perforated plastic baskets and then in boxes or partitioned spaces to protect them. They were glued with cement mixed with an additive to keep them compact underwater. The fragments were protected from fish predation by various structures (square steel cages, plastic netting, etc.).

Two types of restoration were carried out:

❶ Small-scale restoration: 1,369 coral fragments from 12 genera/two areas were restored (substrates: 12 acropods, nine large rocks, one dead *Pocillopora* bank). After eight months, 50% of the coral fragments were still alive.

❷ Large-scale restoration: 8,454 coral fragments from six genera/six areas were restored (artificial concrete blocks, acropods, dead *Pocillopora* bank, dead *Porites*, basaltic flat rocks with dead *Stylophora*).



Transportation of coral fragments ©Éric Dutrieux

Coral fragments ©Éric Dutrieux

Results

The restoration project increased coral cover in all monitored areas of Balhaf, but with mixed results: where natural recruitment was low (or non-existent, on artificial substrates), the restoration was effective in accelerating coral recovery. However, on natural substrates conducive to natural recruitment, the restoration proved less beneficial than the natural colonization process. Three years after the restoration operations, the survival and development percentages vary somewhat (between 30 and 40%), with levels of adaptation and resilience depending on the species, which suggests that the restoration method could be improved by conducting a more detailed feasibility study (figure 1).

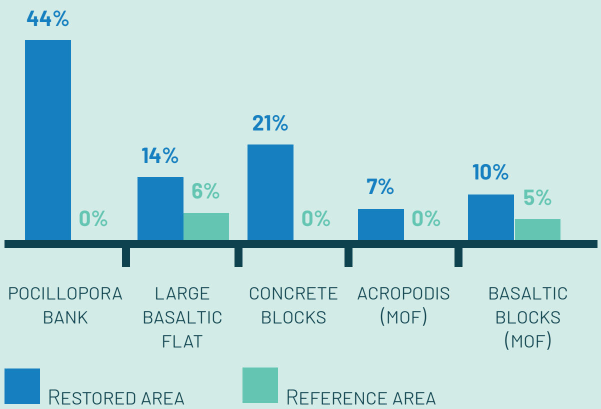


Figure 1 Coral cover percentage in the restored area and the reference area

Coral fragments three years after transplantation
©Éric Dutrieux

Lessons learned

The feasibility phase is important for identifying the best methods and species to be used in a second, larger-scale phase. With this project, only a few months passed between the two phases, which seems somewhat insufficient to make a judicious choice regarding the colonies to be planted. We recommend that more efforts be devoted to conducting preliminary studies, including hydrodynamic studies and a longer-term study on coral growth. In addition, methods need to be adapted to each site to optimize operational success. The choice of species proved to be crucial for survival rates and should be considered with great care in future. Coral growth rates must also be taken into account: they can vary greatly between species.

References

❶ **Créocéan,** 2010: Yemen LNG, Coral monitoring during the construction phase. Synthesis report. Report prepared for Yemen LNG company.
❷ **Créocéan,** 2012: Yemen LNG, Monitoring of the coral transplantation and restoration areas. Report prepared for Yemen LNG company.

CONCLUSIONS REGARDING CORAL REEFS

While the measures presented in the case studies yielded satisfactory results overall, with high survival and growth rates regardless of the type of project (transplantation, nurseries), certain precautions must be taken when implementing them. In particular, there is a need to reduce stress and coral mortality factors before considering any restoration measures.

Prior to any restoration project, it is essential to re-establish the right environmental conditions to avoid high mortality rates (Bowden-Kerby, 2003). It is also necessary to consider the risks of bacterial and viral pollution and pathogen dispersal when selecting mother colonies. Housing the colonies in a nursery for a time can serve as a form of quarantine before they are transplanted at the host site. Liman and Schopmeyer (2016) point out that the transfer of affected corals from the main nursery to a quarantine area is a method already used to limit the spread of disease.

The fragmentation of a mother colony into numerous cuttings can also lead to the genetic impoverishment of transplanted populations (Meesters *et al.*, **2015). As a result, the cuttings become particularly vulnerable to external pressures. A minimum genetic diversity should be maintained within sets of cuttings of the same species.**

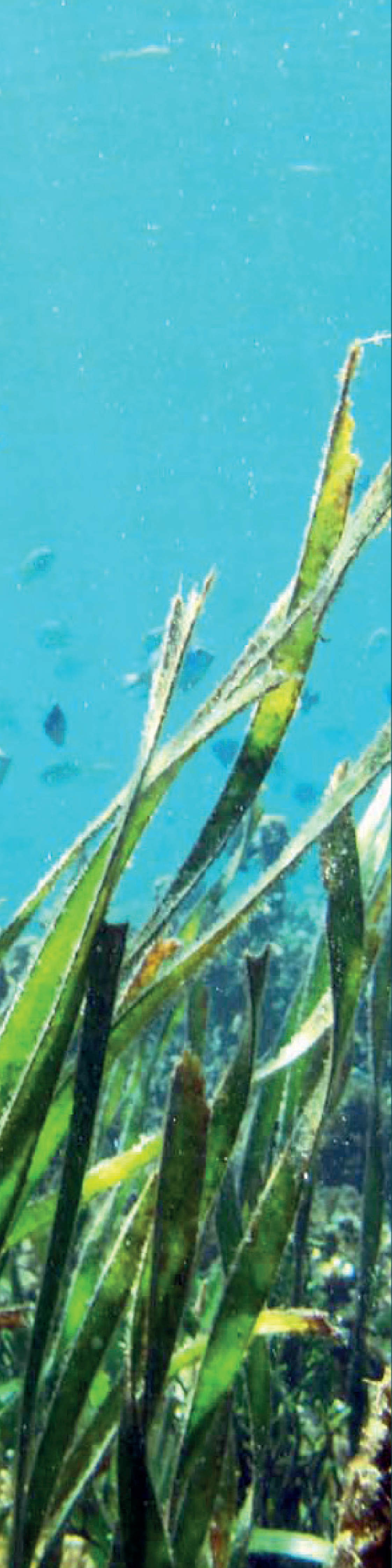
It is important to take into account the concept of density dependence in mechanisms to manage coral populations. Some species may interact favourably or unfavourably. It is essential to draw inspiration from the best-preserved natural communities in the geographic basin in which the project is to be carried out and to identify their preferred groupings (ecological succession, intra- and interspecific interactions, etc.).

Moreover, the notion of habitat creation through the establishment of coral colonies is risky in natural environments, as there is often a reason for the absence of such colonies (unfavourable environmental conditions, heavy swells, exposure to cyclones, etc.). However, it is more suitable for consideration in relation to newly submerged artificial or natural substrates, such as dykes and artificial reefs. The taking of cuttings can facilitate and accelerate the natural colonization of these newly created habitats.

Finally, it should be noted that the results reported relate to short- and medium-term follow-up, yet the development of coral colonies can take several decades, if not hundreds of years. Although frequent, regular monitoring is required during the initial phases following the handling of coral colonies, after the first months of acclimatization, monitoring that is more spaced out, but conducted over a longer period (5 to 10 years), could be envisaged.


©Gaby Barathieu

4 SEAGRASSES

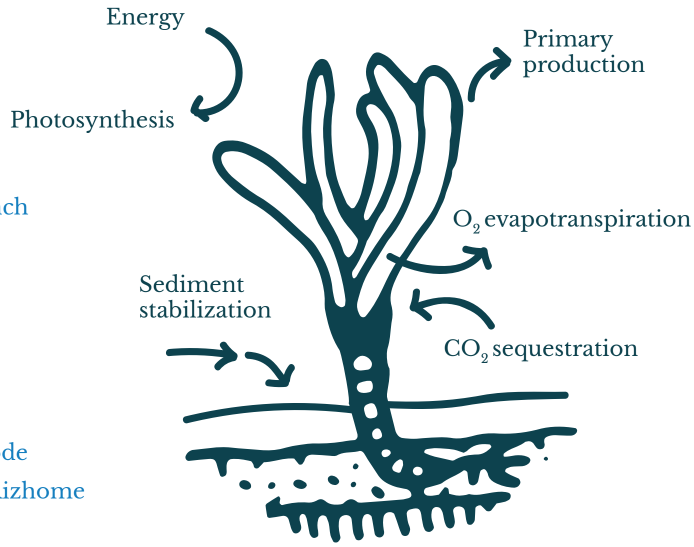


Seagrasses of marine angiosperms are widely distributed in both tropical and temperate coastal waters. They generally occur in sandy or silty substrates in clear, shallow waters, where there is enough light for photosynthesis (Green and Short, 2003). They are rich sources of biodiversity and are also considered ecosystem engineers (Short *et al.*, 2007), so it is vital to protect the habitats that they form. Indeed, the disappearance of seagrasses is the first step in a cascade effect on the trophic dynamics of a given area (Orth *et al.*, 2006). These ecosystems, frequently used as nurseries by a number of organisms, form the basis of potentially complex ecological cycles.

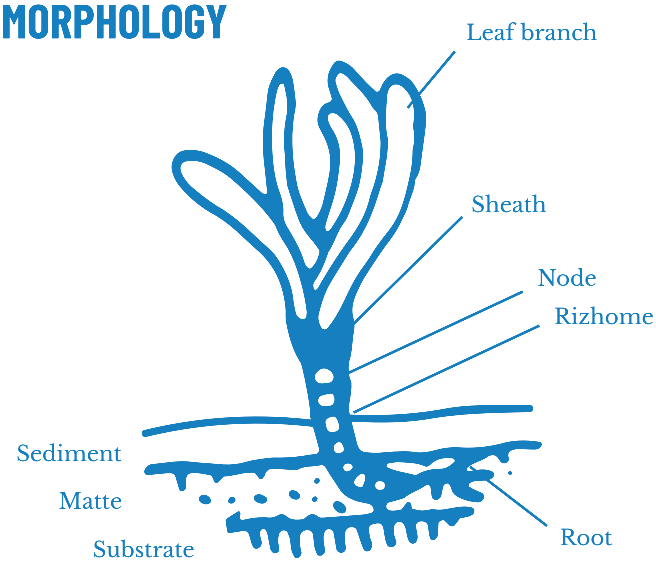
THE MAJOR CHALLENGES OF SEAGRASS CONSERVATION

Seagrasses **are underwater meadows consisting of monocotyledonous flowering plant species of the spermatophyte phylum.** They began colonizing the marine environment around 100 million years ago (Hemminga and Duarte, 2000). In the course of their evolution they have adapted to their surroundings, developing a resistance to high or variable salinity, strong root systems to better embed them in substrates, and the ability to reproduce both vegetatively and sexually (Green and Short, 2003). **While seagrasses are present in all oceans except the Antarctic** (figure 13)**, they cover only 0.2% of the ocean bed** (Fourqurean *et al.*, 2012), **equating to a surface area of 177,000 to 600,000 km²** (Duarte, 2013). They are found in six bio-regions: four temperate regions (the North Atlantic, the North Pacific, the Mediterranean and the oceans of the southern hemisphere) and two tropical regions (the Tropical Atlantic and the Tropical Indo-Pacific) (Short *et al.*, 2007). **Compared with coral reefs and mangroves, seagrasses have a very broad geographic distribution** (Orth *et al.*, 2006).

ROLES



MORPHOLOGY



SOME FIGURES

Seagrasses are present in six bio-regions: four temperate regions and two tropical regions.

Figure 13 Global distribution of seagrasses (UNEP–WCMC, 2005)

They cover

0.2% **of the ocean bed,**

equating to an estimated surface area of between

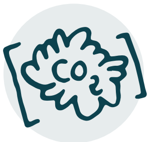
177,000 and 600,000 km²

THE ROLE OF SEAGRASSES ?

The 60 or so species of seagrasses found around the world (Short *et al.*, **2007) play a number of vital roles in coastal areas:**

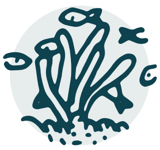
Filtration of nutrients and pollutants

Pollutants from water columns and sediments tend to accumulate. **Seagrasses play an important role in filtering water and maintaining the quality of their immediate environment and nearby habitats** (Green and Short, 2003).



Carbon sequestration

Seagrasses are able to store carbon for long periods (McLeod, 2011; Duarte *et al.*, 2013; Fourqurean *et al.*, 2012), at a rate of 48 to 122 million tonnes per year.



Nursery

The **rich and productive coastal habitats provided by seagrasses accommodate a large number of marine species** of ecological importance at all trophic levels, some of which are threatened with extinction (Christianen *et al.*, 2014; Hemminga and Duarte, 2000; Heck *et al.*, 2003; Orth *et al.*, 2006; van Tussenbroek *et al.*, 2006).

Source of organic matter from primary production

Seagrasses are at the bottom of a number of food chains (Green and Short, 2003; Orth *et al.*, 2006). Indeed, numerous species, such as turtles, dugongs and herbivorous fish, rely on them as a food source.

Thriving aquatic ecosystem

Much like coral reefs, **seagrasses accommodate and are beneficial to a whole host of different species** (Green and Short, 2003).

Ecosystem services

Seagrasses provide a number of ecosystem services. For instance, they play a mitigating role by stabilizing sediments and **preventing coastal erosion** (Boudouresque, 2001; Koch, 2007; Koch *et al.*, 2012; Christianen *et al.*, 2013). Moreover, dense seagrasses help to **alleviate climate change by sequestering carbon** (Duarte *et al.*, 2005; McLeod *et al.*, 2011; Fourqurean *et al.*, 2012). Lastly, the various species present in seagrasses ultimately serve as a **food source for human populations that reside in coastal areas and practise traditional fishing and subsistence techniques** (de la Torre-Castro and Rönnbäck, 2004; Björk *et al.*, 2008; Unsworth and Cullen, 2010; de la Torre-Castro *et al.*, 2014).

It is therefore essential to protect these ecosystems. However, seagrasses face a number of threats.

WHAT ARE THE THREATS?

NATURAL THREATS

The threats identified are often associated with widespread changes or poor management of catchment areas. The most common threat is excess sediment, which limits light penetration and, according to Orth *et al.* **(2006), causes a significant decline in seagrass meadows.**

Overgrazing by herbivores

Overgrazing can occur where the predators of herbivorous species are overfished (Boudouresque, 2001). It may also result from a reduction in the surface area of seagrasses, such that herbivore demand outstrips the natural production of the remaining areas, leading to a risk of decline.

Extreme climate events

Cyclones, hurricanes and other such phenomena also have an impact on these seagrasses insofar as they **accelerate sedimentary erosion and reduce salinity.**

Spring tides

These extreme tides **expose seedlings and cause them to dry out.**

ANTHROPOGENIC THREATS

Seagrasses are also particularly prone to direct anthropogenic pressures, including the following (non-exhaustive list):

Agricultural, industrial, urban and aquaculture pollution

These forms of pollution can result in excess sedimentation, eutrophication and the accumulation of waste products, hydrocarbons and heavy metals.

Uprooting

Uprooting can be caused by fishing gear or anchors, for example.

Dredging

Dredging results in the physical destruction of seagrass meadows and the resuspension of surrounding sediment.

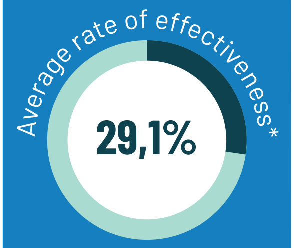
ECOLOGICAL ENGINEERING TECHNIQUES FOR SEAGRASSES

This section concerns the ecological engineering techniques used for seagrasses beds. It includes definitions of the most commonly used techniques and examples of projects carried out around the world.

page 61 **Transplantation**
page 62 **Micropropagation**
page 63 **Sowing**
page 64 **Passive management**

TRANSPLANTATION

Transplantation is the most commonly used ecological engineering technique for restoring seagrasses, as the results are visible following restoration (Oceana, 2010). It involves transferring plugs or cuttings of marine spermatophytes from donor to receptor sites. There are different methods of transplantation:



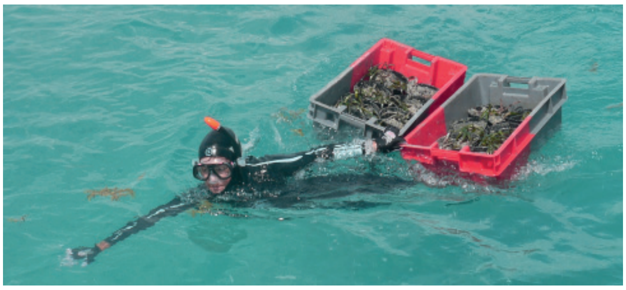
Average cost

48 430 $

international dollars/ha/year

(± 73 254,25 standard deviation)

Manual method



Transportation of seagrasses to receptor site ©Guadeloupe Port Caraïbes, 2017

Cuttings or plugs are transplanted manually at the degraded site. Seedlings can be removed in several ways:

– **Plug method:** removal of plugs using PVC or metal tubes.

Advantages of the plug method: ❶ limits removal of surrounding sediment; ❷ limits damage to roots and rhizomes. Plugs are more resistant to erosion.

Disadvantages of the plug method: impact on donor site.

– **Staple method:** grouping of seedlings using staples for subsequent transplantation in sediment (Fonseca *et al.*, 1998).

Mechanized method

Motorized transplanter (ECOSUB2) (Keulen, 2002)

Use of motorized harvesting and planting machine to collect seagrass plugs for subsequent replanting.

Advantage of mechanized technique: Speed of transplantation (44 days per hectare) (Keulen, 2002; Seddon, 2004).

Disadvantages of mechanized technique: Loss of seedlings during removal and lack of follow-up during planting at receptor site, resulting in losses (Bell *et al.*, 2008). This method is only marginally more effective than the manual technique (Fishman *et al.*, 2004).

Advantages of transplantation

❶ **Grouping seedlings in plugs** increases their survival rate (Zarranz *et al.*, 2010).

❷ Manual transplantation makes it possible to **control the fixation of plants** in the sediment (Bell *et al.*, 2008) and **minimizes damage to the donor site** (Lanuru, 2011).

Disadvantages of transplantation

❶ **This method can only be used for small areas,** since it requires physical labour, great care in collecting shoots and transplantation by hand (Björk *et al.*, 2008; Oceana, 2010).

❷ **The donor site is damaged** for the benefit of the receptor site, although such damage is managed (Oceana, 2010).

❸ **High economic and logistical costs** (Oceana, 2010).

* Average based on available data for a follow-up period of three years or more. These values are to be treated with the utmost caution. See page 102 of the guide.

MICROPROPAGATION

Also referred to as in vitro cultivation, micropropagation is a method of growth in a controlled environment that enables the regeneration of seedlings from seeds or terminal buds (Fonseca *et al.*, 1998; Zarranz *et al.*, 2010). Cultivated seedlings are then transferred to the natural environment.

Average rate of effectiveness
N/A

Average cost
N/A

Seagrass cultivation ©Mariane Aimar-Godoc

Advantages

❶ **Production of a large number of species** without seasonal constraints (Fonseca *et al.*, 1998).
❷ Monitored growth for a **higher survival rate** (Zarranz *et al.*, 2010).
❸ Ability to select species that are **resistant to disease and stress** (Fonseca *et al.*, 1998).
❹ Improved **genetic diversity** (Fonseca *et al.*, 1998; Zarranz *et al.*, 2010).
❺ **Mass production** reduces costs (Fonseca *et al.*, 1998).
❻ **Higher-yielding** alternative.

Disadvantages

❶ **Does not work for all species** (difficulties encountered with *S. filiforme* and *T. testudinum*).

SOWING

This technique involves taking mature seeds from the donor site and sowing them directly in the area to be restored.

Average rate of effectiveness

N/A

Average cost

N/A

Collecting seagrass seeds ©Mariane Aimar-Godoc

Advantages

❶ **Lower cost** (Oceana, 2010).
❷ **Low impact** on the donor site (Oceana, 2010).

Disadvantages

❶ Results **not immediately visible:** slow establishment (Oceana, 2010).

PASSIVE MANAGEMENT

Natural recruitment improvement method

Average rate of effectiveness
N/A

Average cost
N/A

The natural recruitment improvement method involves promoting the propagation and growth of seagrasses by placing hessian fabric on the sea floor, such that the seagrasses hook onto the cloth and develop *in situ* (Wear *et al.*, 2006). For this passive management method to be effective, it must be used at sites with a higher density of seedlings (Wear *et al.*, 2006).

Cultivation of seagrasses on hessian fabric (Wear *et al.*, 2006)

Advantages

❶ **Very inexpensive and non-invasive method** (bags biodegradable and removable) (Wear et al, 2006).
❷ **No impact on source sites** (Irving *et al.*, 2010).
❸ Provides a **stable sedimentary environment** for sowing conducive to the establishment of root systems (Irving *et al.*, 2010).
❹ **Non-technical method** (no particular skills required for implementation).

Disadvantages

❶ **Requires a sound understanding** of the natural mechanisms by which seagrasses spread (seeds and rhizomes).
❷ **Relatively long wait for results.**
❸ Technique enhances the natural process but **cannot fully replace it.**
❹ **Risk of competition with other organisms** (algae, molluscs, crustaceans, etc.) while seedlings are getting established.

SEAGRASS CASE STUDIES

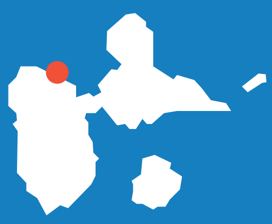
P. 66 - 67 **Seagrass transplantation at Sainte Rose**
P. 68 **Seagrass transplantation at La Riviera du Levant**

SEA n° 1

SEAGRASS TRANSPLANTATION AT SAINTE ROSE

Guadeloupe

Transplantation of seagrass from the departmental port of Sainte Rose to a nearby receptor site. Ordered by the Departmental Council of Guadeloupe and managed by Créocéan. Carried out in 2012.



Project . . . . Port of Sainte Rose mitigation project
Site . . . . Port of Sainte Rose
Species . . . . Turtle grass (*Thalassia testudinum*)
Surface area . . . . 4,635 m²
Success rate . . . . N/A
Cost €388,839
Year 2012
Field officer. . . . . N/A

Objective

The objective of the project was to create a new seagrass area to mitigate the impact of improvement works to a seawall. The receptor site was located near the departmental port of Sainte Rose and was chosen for its physical, chemical and environmental properties.

Technique

The turtle grass was transplanted manually. The operation took 10 weeks. Two techniques were used to maximize the chances of success:

Anchoring technique, accounting for 1,635 m²

Attachment of cuttings:

❶ On cement slabs drilled with 36 holes, 10 cm in diameter;
❷ On metallic meshes;
❸ On stakes or U-hooks;
❹ On hessian fabric.

Non-anchoring technique, accounting for 3,000 m²

Removal of plugs (rhizome and sediment) using a spade or core drill. Plug sizes:

❶ 10 cm x 10 cm
❷ 20 cm x 20 cm

Replanting in quadrats of 20.25 m².

Table 1 Summary of manual transplantation techniques

Anchoring	TECHNIQUES	SURFACE UNIT	SURFACE AREA RECREATED
NO	Plugs (10x10 cm) over 100 m²	Quadrat of 20.25 m²	1,500 m²
	Plugs (20x20 cm) over 400 m²	Quadrat of 20.25 m²	1,500 m²
YES	Drilled cement slabs	Slabs of 1 m²	112.5 m²
	Welded meshes	Meshes of 1 m²	112.5 m²
	Stake or U-hooks	Quadrats of 1 m²	860 m²
	Hessian fabric	Cloths of 1 m²	550 m²

Cost

The cost of replanting was **€292,611.**

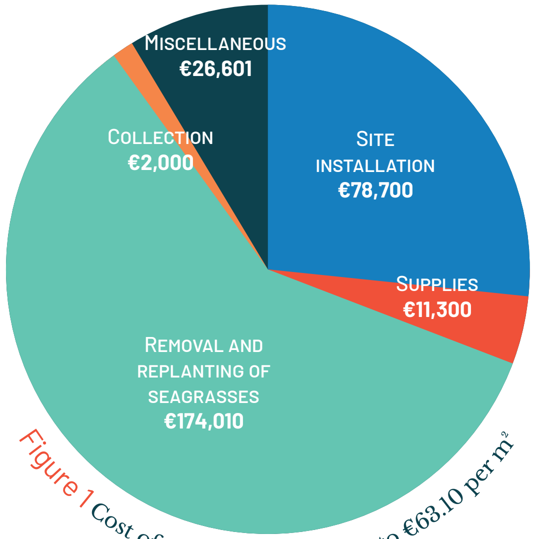


Figure 1 Cost of replanting, equating to €63.10 per m²

Environmental monitoring

Monitoring was done by field marine biologists over five years, two days per quarter for the first year and then two days per year for the next four years. The effectiveness of the two techniques used was gauged and the physical and chemical characteristics of the water were monitored. Transplant growth was measured using boundary markers. Bacteriological and chemical water tests were done and the ecological condition of the seagrass was monitored under the Water Framework Directive.

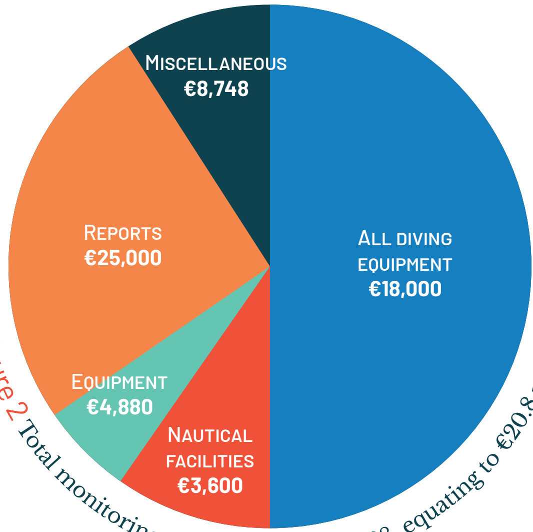


Figure 2 Total monitoring costs stood at €96,228, equating to €20.8 per m²

Success rate (%): N/A	**Duration of experiment (including follow-up): 5 years**		
Sequence phase	A	R	**M**
Type of measure	Restoration	Rehabilitation	**Creation**
Project to create a habitat on a site where there was not one initially. Intervention required.			

Technical factors affecting risk:

Species transferred	1
Removal technique	removal of plugs
Attachment technique	planting of plugs or attachment of cuttings in different substrates (*cement slabs, metallic meshes, hessian fabric, stakes or U-hooks)*
Means of transportation	small craft
Transportation time	N/A

References

❶ **Mesures de surveillance, d'analyses du port départemental de Sainte-Rose:** - surveillance de la qualité des eaux - suivi environnemental des herbiers (**Measures for the monitoring and analysis of the departmental port of Sainte Rose:** water quality monitoring – environmental monitoring of seagrasses), Créocéan and Departmental Council of Guadeloupe, June 2014.

❷ **Marché de Maîtrise d'OEuvre relatif à la réalisation des études environnementales complémentaires en vue de la réalisation des infrastructures projetées dans le port départemental de Sainte-Rose, phase 3 (Project management contract for the execution of additional environmental studies with a view to implementing infrastructure plans at the departmental port of Sainte Rose, phase 3)**

SEA n°2

TRANSPLANTATION OF SEAGRASSES AT LA RIVIERA DU LEVANT

Guadeloupe

Transplantation carried out along the southern coast of Grande-Terre. Ordered by the Grand Port Maritime de la Guadeloupe and managed by CDC Biodiversité and Coraïbes (a limited liability company devoted to marine ecological restoration).

Project . . . . Cultivation and transplantation of seagrasses
Site . . . . Petit Cul-de-Sac Marin and La Riviera du Levant
Species . . . . Turtle grass (*Thalassia testudinum*)
Surface area . . . . N/A
Success rate. . . . . N/A
Cost €45,574
Year 2017
Field officer. . . . . mariane@coraibes.com

Objective

The objective of the transplantation project was to complement existing turtle grass populations at the sites of Petit Cul-de-Sac Marin and La Riviera du Levant.

Cultivation of *Thalassia testutinum* ©Mariane Aimar-Godoc

Collection of *Thalassia testutinum* seeds ©Mariane Aimar-Godoc

Technique

Initially, turtle grass seeds were harvested along the coast of Grande-Terre and then cultivated in a controlled environment (with conditions similar to those of the receptor site). This made it possible to monitor the flowering and fruiting of the seagrasses. A total of 200 seeds were cultivated either in pots or on hessian fabric. Once the seedlings had grown sufficiently, manual transplantation was carried out.
Two transplantation techniques were used:

❶ **Anchoring technique,** where seedlings were anchored in and grown on hessian fabric.

❷ **Non-anchoring technique,** where cultivated seedlings were transplanted into pre-made holes in the sediment.

Monitoring of the experiment

To monitor the ecological condition of the transplanted seagrass, an observation phase was completed. The density of the seagrass and the physical parameters of the environment were measured for each of the sites. Monitoring was carried out fortnightly for a total of six months. The cultivation phase (launched in early July 2017) is ongoing. The physical and chemical parameters of the growing trays were monitored daily, and regular maintenance was carried out to control algae growth. The growth of the seedlings was also regularly measured.

References

❶ Analyse régionale Guadeloupe, synthèse des connaissances. (Regional analysis Guadeloupe, knowledge synthesis.) University of the French West Indies and Guiana, Guadeloupe National Park and the Marine Protected Areas Agency, 2013.

❷ Rapport des Etudes de l'Aquarium. (Aquarium study report.) 2012

CONCLUSIONS REGARDING SEAGRASS

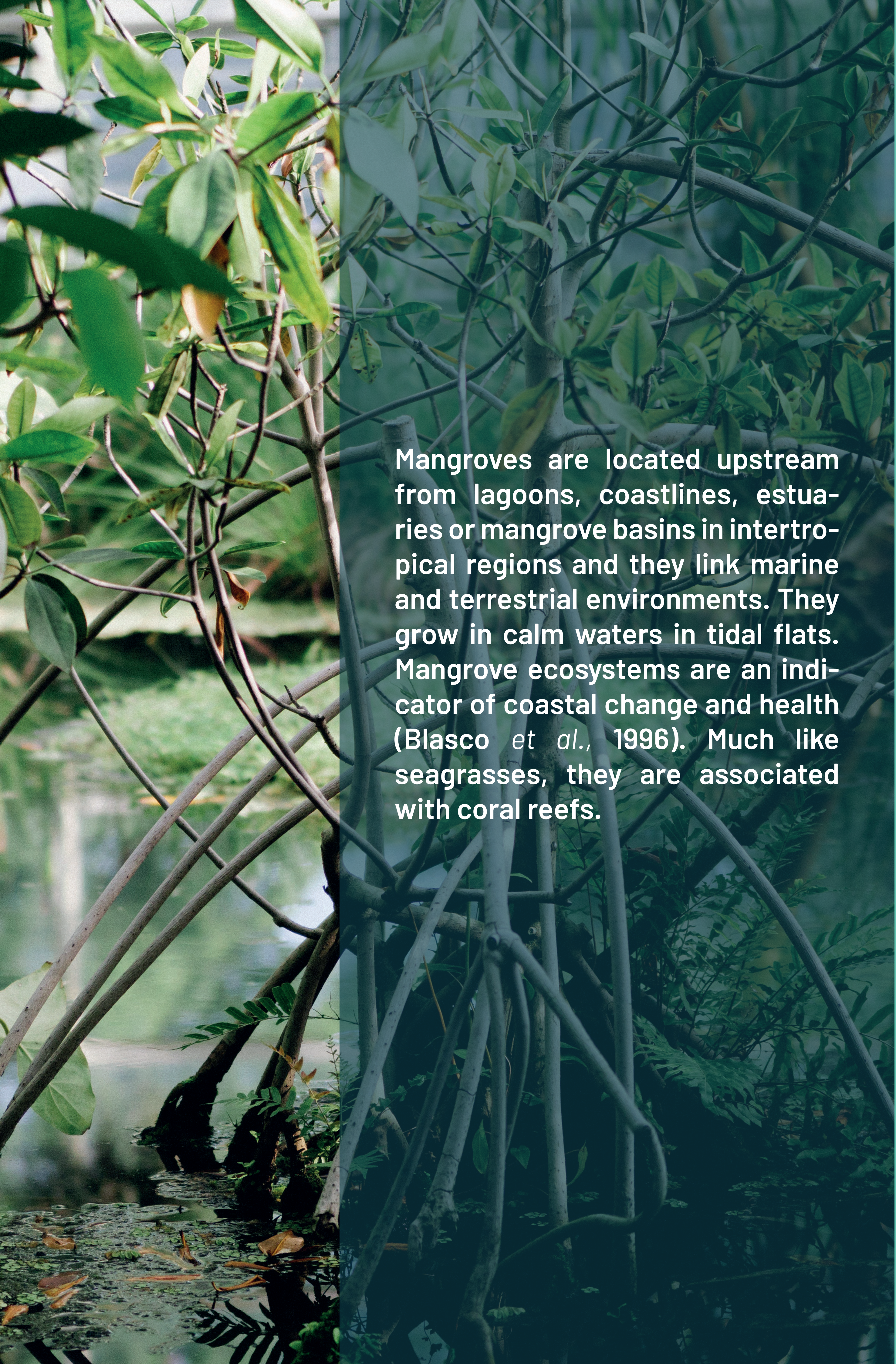
The most appropriate planting method for a given site is determined based on restoration objectives, local conditions, seagrass species and allocated budgets (Björk *et al.*, **2008).**

A number of conditions must be met to increase the chances of success of a restoration project. These include (according to Paling *et al.*, **2009; Cunha** *et al.*, **2012; and Van Katwijk** *et al.*, **2016):**

❶ Setting clear project goals and targets and choosing appropriate sites;
❷ Defining methods with due regard for site conditions, monitoring period and project success criteria;
❸ Determining and eliminating local threats (bioturbation, herbivory, hydrology, anthropogenic impact, etc.) before launching projects;
❹ Conducting small-scale restoration tests before embarking on large-scale projects;
❺ Minimizing damage to the donor site;
❻ Extending the tests to different sites and using different methods to improve the success rate and effectiveness of restoration initiatives;
❼ Demonstrating flexibility in the face of unusual events – adaptive management is foundational in restoration projects;
❽ Learning from past experiences and using the information acquired to improve methods;
❾ Publishing results and sharing experiences (essential).

It should be noted that if a given natural habitat does not naturally contain any seagrass, then restoration is not the answer. Indeed, the absence of seagrass is probably attributable to a number of factors, such as hydrodynamics, water quality, sediment and nutrient inputs.

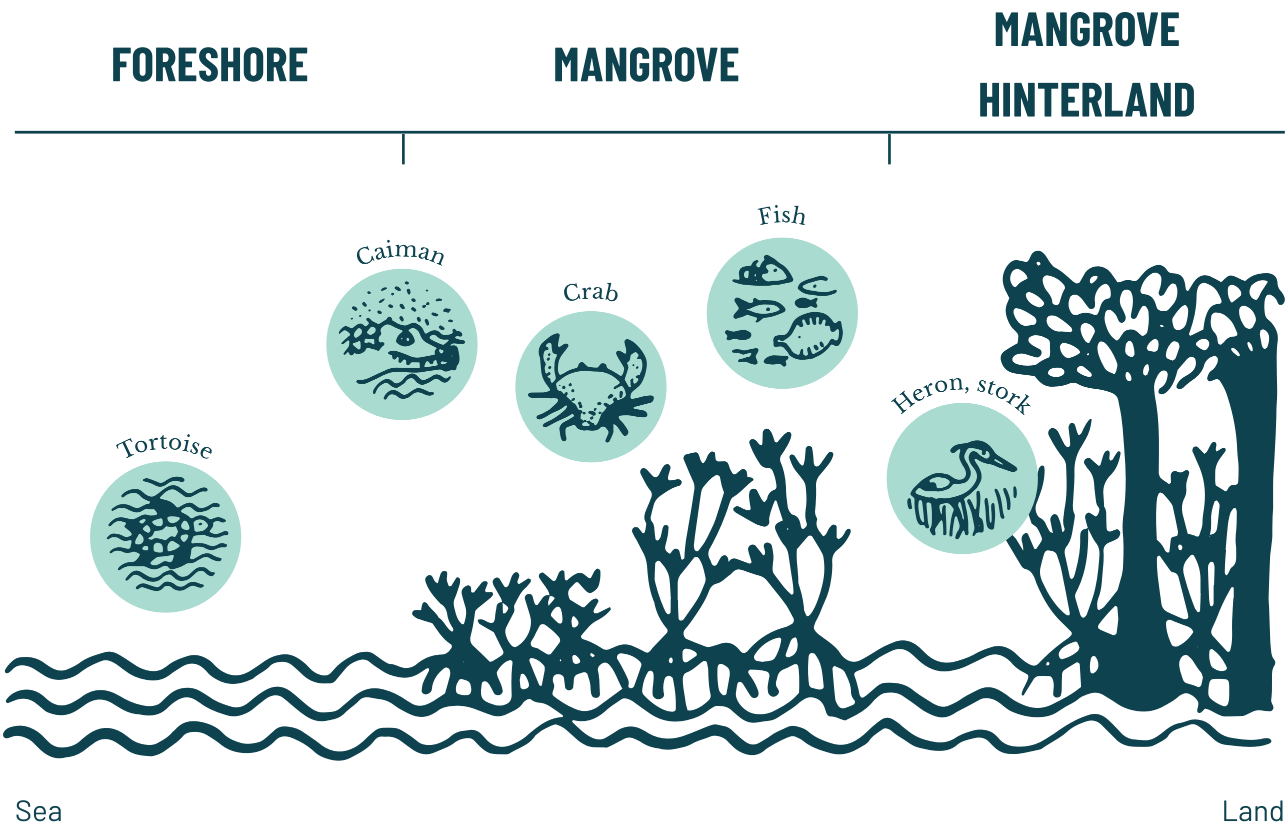
5 MANGROVES



Mangroves are located upstream from lagoons, coastlines, estuaries or mangrove basins in intertropical regions and they link marine and terrestrial environments. They grow in calm waters in tidal flats. Mangrove ecosystems are an indicator of coastal change and health (Blasco *et al.*, 1996). Much like seagrasses, they are associated with coral reefs.

THE MAJOR CHALLENGES OF MANGROVE CONSERVATION

Situated at the interface between marine and terrestrial environments, mangroves cover around 152,000 km^2 of coastal areas (figure 14). **They are found in intertropical regions, upstream from lagoons, coastlines, estuaries or mangrove basins. Mangroves are defined as trees and shrubs that grow almost exclusively in the intertidal zones of tropical coastlines. They can be found in calm waters in tidal flats.** Certain ecological requirements must be met in order for mangroves to grow, such as a loose, oxygen-poor substrate and relatively high or variable salinity.



SOME FIGURES

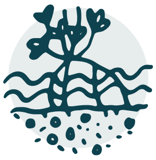
France is home to **103,427 ha** of mangroves, **ranking it 32nd globally** (Roussel *et al.*, 2010). However, the total surface area of mangroves is difficult to estimate owing to a lack of data in certain regions, an absence of historical references and the changeability of mangrove ecosystems (rapid accumulation/ erosion).

Mangroves are present in some overseas territories

Figure 14 Global distribution of mangroves (according to UNEP–WCMC data, 2011)

THE ROLES OF MANGROVES

Mangroves provide a number of services:



Sediment stabilization

Mangroves filter, retain, trap and stabilize sediment from land, protecting lagoons from excessive sedimentation (Roussel *et al.*, 2010; Quod and Malfait, 2016).

Thriving aquatic ecosystem

Mangroves are a rich source of biodiversity, serving as a breeding ground and nursery for numerous species of birds and fish of significant economic importance for local communities (Quod and Malfait, 2016).

Fertilization

According to Roussel *et al.*, (2010), **mangroves play a part in fertilizing lagoons.** The growth of seagrasses and phytoplankton is catalysed by nutrient inputs from mangroves.

Coastal protection

Mangrove root systems disperse waves. The energy of waves that pass through 200 metres of mangroves is reduced by 75% (Roussel *et al.*, 2010).

Reduction in CO_2 emissions

As primary producers, mangroves play a role in cleaning the air by exporting or sequestering CO_2. Indeed, mangroves can serve as both carbon sinks and sources (Cormier-Salem and Panfili, 2016).

Ecosystem services

A number of ecosystem services are associated **with mangroves, which accommodate a broad range of exploitable marine species.** In many countries, mangroves are used for traditional fishing (for crabs, cockles and fish) and as a source of wood for cooking and building dwellings. **They are also a tourist attraction** of increasing importance thanks to ecotourism and the establishment of hiking trails over the years (Roussel *et al.*, 2010).

WHAT ARE THE THREATS?

NATURAL THREATS

Cyclones

Cyclones are the most damaging natural threat to mangroves, leading to the uprooting and destruction of the belt of pioneer trees (Roussel *et al.*, 2010) and ultimately to sedimentary erosion.

Drought

Periods of drought primarily affect the soil, leading to increased aridity, salinity and acidity (Roussel *et al.*, 2010). Drought is also conducive to fire, which can destroy vast swathes of mangrove.

Large swells

Like cyclones, large swells can uproot seedlings and weaken roots.

ANTHROPOGENIC THREATS

Urban development

Dredging activities associated with urban development can suffocate mangroves and lead to soil acidification (Roussel *et al.*, 2010). Some types of development can also modify sediment transport or river flow upstream, leading to the suffocation or uprooting of mangroves.

Pollution and waste

Many waste products and pollutants affect mangroves, including household waste, persistent organic pollutants and toxic chemical compounds. Pollution can have multiple sources, but the consequences range from environmental dysfunction to the complete destruction of mangroves (Roussel *et al.*, 2010).

Exploitation of mangroves

Mangroves are sometimes used for construction, charcoal and other purposes.

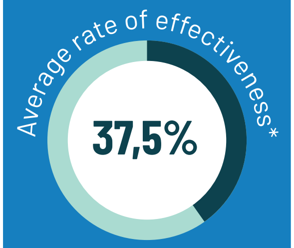
ECOLOGICAL ENGINEERING TECHNIQUES FOR MANGROVES

This section concerns the ecological engineering techniques used for mangroves. It includes definitions of the most commonly used techniques and examples of projects carried out around the world.

page 77 **Transplantation**
page 78 **Sowing**
page 79 **Nursery**
page 80 **Passive management**

TRANSPLANTATION

This method involves transplanting seedlings of varying ages to receptor sites. The species to be transplanted will depend on the transplantation site. Species already present in close proximity to the site are preferable, while monocultures are to be avoided (Pole-Relais Zones Humides tropicale [Resource Centre for Wetlands], 2018).



Average cost

62 197 $

international dollars/ha/year

(± 147 704,82 standard deviation)

Transplantation of mangroves in Indonesia (© YaGaSu)

Training programme for mangrove transplantation by children in Guadeloupe (© Guadeloupe Port Caraïbes)

Advantages

❶ Method recommended **where passive management is no longer possible** (Pole-Relais Zones Humides Tropicales [Resource Centre for Wetlands], 2018).

Disadvantages

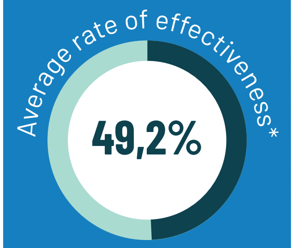
❶ **Weakening of roots** is observed when collecting seedlings from the donor site and replanting, thus reducing success rates (Guiraud et Poveda, 2014).

❷ **Potential impact on donor site** where seedlings are removed from their natural environment.

* Average based on available data for a follow-up period of one to five years.
These values are to be treated with the utmost caution. See page 103 of the guide.

SOWING

This technique involves taking seeds or propagules from a donor site and sowing them directly into the area to be restored. There are several methods of sowing.



Average cost

11 767 $

international dollars/ha/year

(± 14 324 standard deviation)

Direct planting

Direct planting involves taking seeds or propagules and forcibly establishing them in the sediment of a specific site (Guiraud and Poveda, 2014).

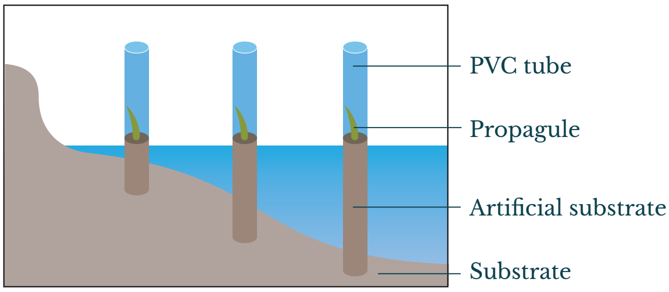
Collection of propagules (Guiraud and Poveda, 2014)

Mangrove propagules (Guiraud and Poveda, 2014)

Sowing of propagules (Guiraud and Poveda, 2014)

Riley encased methodology

The Riley encased methodology, developed by Robert W. Riley, Jr. in 1995, involves encasing propagules in translucent PVC tubes to protect them from tide-borne debris (wood, algae), predators and wave action.



Advantages of sowing

❶ Inexpensive and easy to implement, suitable for **large-scale deployment** in participative programmes with local populations (see MANA'O study project on mangroves in Ouvéa, where local communities were involved in sowing).

❷ **Non-invasive** and does not damage either the donor or the receptor site.

Disadvantages of sowing

❶ **Seedlings are often weakened** by desiccation, predation and tides (Guiraud and Poveda, 2014).

❷ During collection, **propagules present in the soil are generally weakened:** stagnation in water, mechanical action of swell (Guiraud and Poveda, 2014).

❸ **Introduction of plastic into the environment** (Riley method).

* Average based on available data for a follow-up period of one to two years.
These values are to be treated with the utmost caution. See page 103 of the guide.

NURSERIES

Average rate of effectiveness*

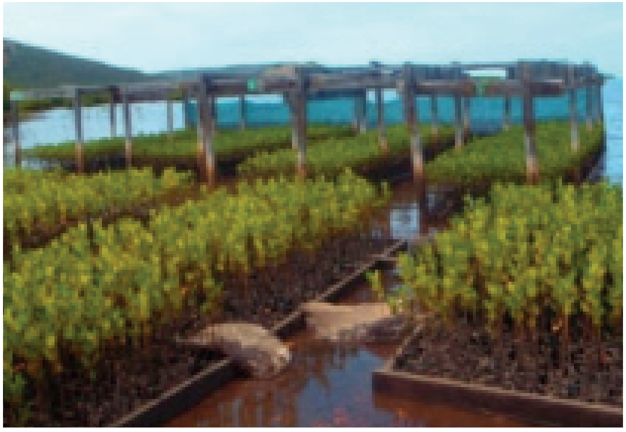
52,5%

Average cost

NA

Nurseries allow the growth of propagules to be monitored until the roots appear. The seedlings can then be transplanted in mangrove forests (Melana *et al.*, 2000; Ravishankar and Ramasubramanian, 2004).

Industrial nursery ©EMR 2012



Traditional nursery ©EMR 2012

Advantages

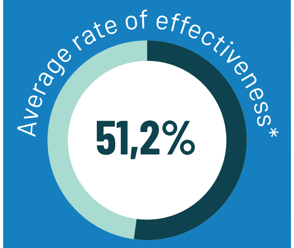
❶ Particularly useful where the **natural regeneration rate of the mangrove forest is low** (Melana *et al.*, 2000; Toledo *et al.*, 2001; Ravishankar and Ramasubramanian, 2004).
❷ Enables **adaptation to the environmental conditions** of the degraded site, thus **minimizing loss** (Nguyen, 2016).
❸ Seedlings **more developed and thus less fragile** during transplantation (Guiraud and Poveda, 2014).

Disadvantages

❶ Stress related to transfer from nursery to natural environment could lead to **failure of restoration** (Toledo *et al.*, 2001). All stress factors influencing the relevant species must be evaluated (Lewis, 2005).
❷ **Industrial nursery more costly** (Guiraud and Poveda, 2014).

* Average based on available data for a follow-up period of one to five years.
These values are to be treated with the utmost caution. See page 103 of the guide.

PASSIVE MANAGEMENT



Average cost

48 430 $

international dollars/ha/year

(± 73 244,25 standard deviation)

Natural self-regeneration

Passive management involves promoting the natural development of mangroves, which is only possible where all environmental conditions are conducive to their growth and establishment (Ravishankar and Ramasubramanian, 2004). The causes of pre-existing upstream problems should therefore be identified before a restoration project is designed (Kamali and Hashim, 2010). Factors limiting self-regeneration are essentially attributable to the presence of plant debris (Hamilton and Snedaker, 1984), the proliferation of invasive species and the abundance of household waste (Association SOS mangroves NC, 2017), but also to topography and hydraulic connectivity. These should be eliminated.

Collection of waste from site ©SOS Mangrove NC

Advantages

1. **Low cost.**
2. **Less soil disturbance.**
3. Young seedlings are **better established.**

Disadvantages

1. **Excessive wave action on bare soil** can lead to poor establishment of mangroves.
2. **Predation of propagules** can prevent regeneration of seedlings.
3. **Less control** over spacing of seedlings.
4. **Time-consuming technique**. As is the case with other passive management methods, time must be allowed, without human assistance, for the natural re-establishment of processes that have been disrupted.

* Average based on available data for a follow-up period of three years or more.
These values are to be treated with the utmost caution. See page 103 of the guide.

MANGROVE CASE STUDIES

P. 82 - 83 **Mangrove transplantation and sowing in Miréréni**

P. 84 - 85 **Mangrove transplantation and sowing in Tsoundzou 1**

P. 86 - 87 **Mangrove sowing in Mbweni**

P. 88 - 89 **Mangrove nursery and transplantation in Balandra**

P. 90 - 91 **Mangrove nursery in Bas du Fort**

P. 92 - 93 **Mangrove passive management and sowing in Nouméa**

P. 94 - 95 **Mangrove passive management and sowing in Touho**

MAN n°1

MANGROVE TRANSPLANTATION AND SOWING IN MIRÉRÉNI Mayotte

Restoration carried out in the mangrove forest of Chirongui, Mayotte, in the Comoros archipelago. Ordered by the Department of the Environment, Planning and Housing of Mayotte and managed by the ESPACES environmental engineering office (BP 168 Z.I. Kawéni, 97600 MAMOUDZOU, contact@espaces.fr).

Project .... Mangrove restoration experiment
Site .... Miréréni
Species .... Grey mangrove *(Avicennia marina)*, yellow mangrove *(Ceriops tagal)*, red mangrove *(Rhizophora mucronata)*
Surface area .... 2,047.5 m^2
Success rate .... See table below
Cost .... €40,000 or €20/m^2
Year 2013
Field officer........... contact@espaces.fr

Objective

A reduction in mangrove coverage on Mayotte over a number of years caused the coastline to retreat by 50 m between 1949 and 2011. Over the course of approximately 60 years, a surface area reduction of 6.13 ha was observed. This erosion was probably due to waves measuring 0.5 to 0.8 m, which loosened mangrove roots and destabilized their trunks. Ultimately, the erosion can be attributed to two factors: rising sea levels driven by climate change, and the general subsidence of the island, which has accelerated since a series of seismic events in May 2018. The aim of the project was thus to limit coastline retreat by replanting different species of mangrove.

Erosion of mangroves leading to uprooting of seedlings ©ESPACES

Monitoring of the experiment

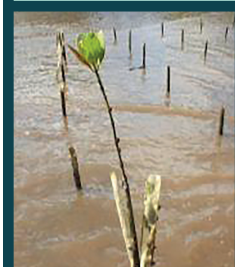
Monitoring was carried out for three years and involved measuring plant growth (height), counting the number of leaves, counting the dead plants to be replaced, and identifying signs of predation, at a frequency of two days per month for the first six months and then one day per quarter for the remaining two and a half years, for a total of 23 monitoring days over the three-year period.

Technique

In view of the above, **a mangrove restoration experiment was carried out using three species:** grey mangrove, yellow mangrove and red mangrove. The objective of the experiment was to establish a methodological guide for mangrove restoration. To that end, several **planting methods were tested at different sites:** planting of nursery-reared seedlings; direct planting of propagules; and direct planting of propagules using the Riley encased methodology (see note). Planting was done in April, at the end of the cyclone period, when water salinity was lower and wave action less severe.

Table 1 Number of seedlings planted per species

Rhizophora mucronata	288 seedling
Cerriops tagal	144 seedling
Avicennia marina	144 seedling



A. marina seedling in Riley encasement © ESPACES

Broken Riley encasement, which destroyed the seedling inside ©ESPACES

Lessons learned

This project led to the drafting of a methodological guide for mangrove restoration on Mayotte to be used by associations. The guide is currently being produced. It explains which techniques achieved the best results for each species and provides advice on how to employ the most successful methods tested in the course of the experiment. However, Olivier Soumille (Manager of ESPACES) concludes that, on Mayotte, the affected mangrove forests cannot be restored because the corresponding substrate has been washed into the bays or the lagoon such that no further mangroves can be planted, and that restoration on Mayotte would be doomed to failure in these areas. Accordingly, it would be more useful to afforest the mangrove hinterland than to work on the mangrove forests themselves.

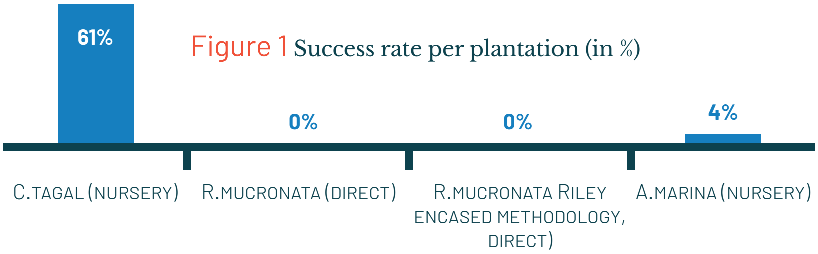


Figure 1 Success rate per plantation (in %)

Riley encased methodology

This method was devised to enable the replanting of mangroves at sites where natural recolonization is no longer possible as a result of general coastal dynamics or disruptions caused by developments. The principle is to prevent any potential damage to the seedling by encasing it in a translucent PVC pipe (measuring 3.8 cm in diameter). The pipe is split lengthwise, promoting seedling growth and water exchange with the substrate.

Results

The results obtained in September 2016 (figure 1) showed a high success rate (61%) for the *Ceriops tagal* species. However, for other seedlings, the results were markedly different: 4% for *Avicennia marina* and 0% for *Rhizophora mucronata*. The complete disappearance of *Rhizophora mucronata* can be explained by the damage caused during the 2014-2015 cyclone season or by chemical changes caused by sunlight and salt to the Riley encasements, which ultimately destroyed them . The low success rate for *Avicennia marina* was a result of the site being unsuitable for planting (high salinity) and of extensive predation by crabs.

Success rate (%): highly variable	**Duration of experiment (including follow-up): > 3 years**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	Creation
C2: Activity carried out in an environment damaged by humans or natural changes in order to establish more favourable conditions for the proper functioning of that environment or for biodiversity, requiring intervention.			

Technical factors affecting risk:

Species transferred	3
Removal technique	planting nursery-reared seedlings and propagules or planting propagules using the Riley encased methodologyà même le
Attachment technique	directly in the substrate or with the aid of a Riley encasement
Means of transportation	N/A
Transportation time	N/A

References

❶ Analyse du site envisagé pour la mise en oeuvre d'un projet expérimental de restauration de mangrove à Miréréni dans la commune de Chirongui [Analysis of the site envisaged for an experimental mangrove restoration project in Miréréni in the municipality of Chirongui]. ESPACES for Conservatoire du littoral (August 2012)

❷ Reconstitution du pont de la RN2 sur Kwalé: projet expérimental de restauration de mangroves à Tsoundzou 1 et à Miréréni. Suivi annuel des plantations 2014-2015. [Reconstruction of the RN2 bridge over the Kwalé: experimental mangrove restoration project at Tsoundzou 1 and Miréréni. Annual monitoring of plantations 2014-2015.] ESPACES for the Department of the Environment, Planning and Housing of Mayotte (November 2015)

❸ 2016 annual results. ESPACES for the Department of the Environment, Planning and Housing of Mayotte (July 2017)

MAN n° 2

MANGROVE TRANSPLANTATION AND SOWING IN TSOUNDZOU 1 Mayotte

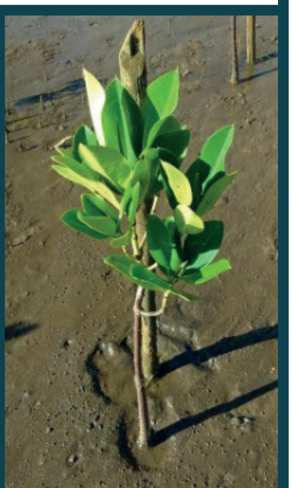
Restoration carried out at the Tsoundzou 1 mangrove, Mayotte, on the Comoros archipelago. Ordered by the Department of the Environment, Planning and Housing of Mayotte and managed by the ESPACES environmental engineering office (BP 168 Z.I. Kawéni, 97600 MAMOUDZOU).

Project .... Mangrove restoration experiment
Site .... Tsoundzou 1
Species .... Grey mangrove (*Avicennia marina*), yellow mangrove (*Ceriops tagal*), red mangrove (*Rhizophora mucronata*)
Surface area .... 2,916 m^2
Success rate .... See table below
Cost .... €80,000 or €27/m^2
Year 2013
Field officer........... contact@espaces.fr

Objective

Launched by the Department of the Environment, Planning and Housing of Mayotte, this experimental mangrove plantation project was carried out as part of mitigation measures related to the construction of a bridge over the Kwalé river, concurrently with the Miréréni project *(see mangrove case study No. 1)*.
Objectives: Implement different planting techniques; after the project, propose a procedure for expansion to other sites.

A. marina seedling (January 2016) ©ESPACES



A. marina seedling (January 2016) ©ESPACES

Monitoring of the experiment

Monitoring was carried out for three years and involved measuring plant growth (height), counting the number of leaves, counting and replacing dead plants, and identifying signs of predation, at a frequency of two days per month for the first six months and then one day per quarter for the remaining two and a half years, for a total of 22 monitoring days over the three-year period.

Technique

The mangrove restoration experiment was carried out using three species: grey mangrove, yellow mangrove and red mangrove. **Several planting methods were tested at different sites:** planting of nursery-reared seedlings; direct planting of propagules; and direct planting of propagules using the Riley encased methodology. The project was carried out in April 2013, at the end of the cyclone period, when the water salinity was lower and the wave action less severe.

Table 1 Number of seedlings planted per species

Rhizophora mucronata	288 seedling
Cerriops tagal	360 seedling
Avicennia marina	504 seedling

Lessons learned

This project led to the drafting of a methodological guide for mangrove restoration on Mayotte to be used by associations. The guide is currently being produced. It explains which techniques achieved the best results for each species and provides advice on how to employ the most successful methods tested in the course of the experiment. However, Olivier Soumille (Manager of ESPACES) concludes that, on Mayotte, the affected mangrove forests cannot be restored because the corresponding substrate has been washed into the bays or the lagoon such that no further mangroves can be planted, and that restoration on Mayotte would be doomed to failure in these areas. Accordingly, it would be more useful to afforest the mangrove hinterland than to work on the mangrove forests themselves.

Problems encountered

In addition to the significant problem of predation by animals, the following issues were identified: damage caused by crabs during the first few months of the experiment (to address this, Riley encasements were placed at the foot of the trees); accumulation of waste around young plants following storms, leading to their suffocation; damage to the site through vandalism.

Results

The results obtained in September 2016 (figure 1) showed survival rates of 33% and 56% for the *Avicennia marina* species. These relatively low rates can be explained by zebu grazing. For *Ceriops tagal*, the success rate stood at 40% for one area, in contrast to another area where the survival rate was close to 0% as a result of trampling by zebus. Lastly, the success rate for *Rhizophora mucronata* was very high, at around 75%.

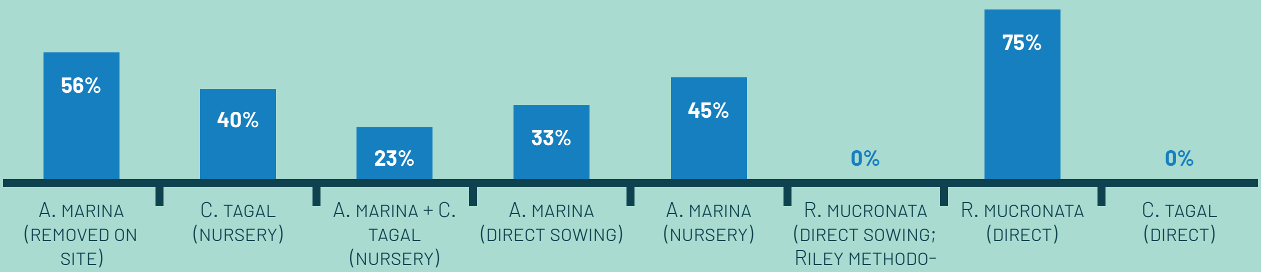


Figure 1 Success rate by plantation (in %)

Success rate (%): highly variable	**Duration of experiment (including follow-up): > 3 years**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	Creation

C2: Activity carried out in an environment damaged by humans or natural changes in order to establish more favourable conditions for the proper functioning of that environment or for biodiversity, requiring intervention.

Technical factors affecting risk:

Species transferred	3
Removal technique	planting of nursery-reared seedlings, propagules, and propagules using the Riley encased methodology
Attachment technique	directly in the substrate or with the aid of a Riley encasement
Means of transportation	N/A
Transportation time	N/A

References

❶ Reconstitution du pont de la RN2 sur Kwalé: proposition d'implantation d'un projet expérimental de restauration de mangroves à Tsoundzou 1. [Reconstruction of the RN2 bridge over the Kwalé: proposal for the establishment of an experimental mangrove restoration project in Tsoudzou 1.] ESPACES for the Department of the Environment, Planning and Housing of Mayotte
❷ Reconstitution du pont de la RN2 sur Kwalé: projet expérimental de restauration de mangroves à Tsoundzou 1 et à Miréréni. Suivi annuel des plantations 2014-2015. [Reconstruction of the RN2 bridge over the Kwalé: experimental mangrove restoration project at Tsoundzou 1 and Miréréni. Annual monitoring of plantations 2014-2015.] ESPACES for the Department of the Environment, Planning and Housing of Mayotte (November 2015)
❸ 2016 annual results. ESPACES for the Department of the Environment, Planning and Housing of Mayotte (July 2017)

MAN n° 3

MANGROVE SOWING IN MBWENI

Tanzania

Restoration carried out in Mbweni, Tanzania, by community organization Mbweni Environment and Women's Group.

Project . . . . Mangrove transplantation
Site . . . . Mbweni – mangrove forest
Species . . . . *Rizophora mucronata*, grey mangrove (*Avicennia marina*)
Surface area . . . . N/A
Success rate 36%
Cost . . . . N/A
Year 2001
Field officer. . . . . Wagner *et al.*, 2010

Objective

Years of overexploitation left the mangrove forest in the village of Mbweni degraded and exposed in some places. The restoration project was the result of a spontaneous initiative taken by community organization Mbweni Environment and Women's Group, which recognized the importance of protecting this ecosystem. The aim of the project was to restore the mangrove forest and increase its density using a transplantation technique.

Technique

The project involved the planting of 3,000 seedlings, primarily *Rhizophora mucronata* with some grey mangrove *(Avicennia marina).* The technique consisted of collecting and transplanting newly fallen propagules in open areas.

Monitoring of the experiment

Three months after planting, data were obtained on growth conditions, plant health, number of dead plants, soil organic matter content and soil saturation rate.

Lessons learned

While only a third of the transplants survived, the project has had a significant positive impact on the overall health of the mangroves. Moreover, the restoration was carried out by villagers, which fostered a desire to protect the mangroves and raised awareness of ecological problems among the general population. The subject of cost was not broached, but the participation of villagers limited the financial outlay.

Mangrove seeding. Note: This is not a photograph of the project described. © Food and Agriculture Organization of the United Nations

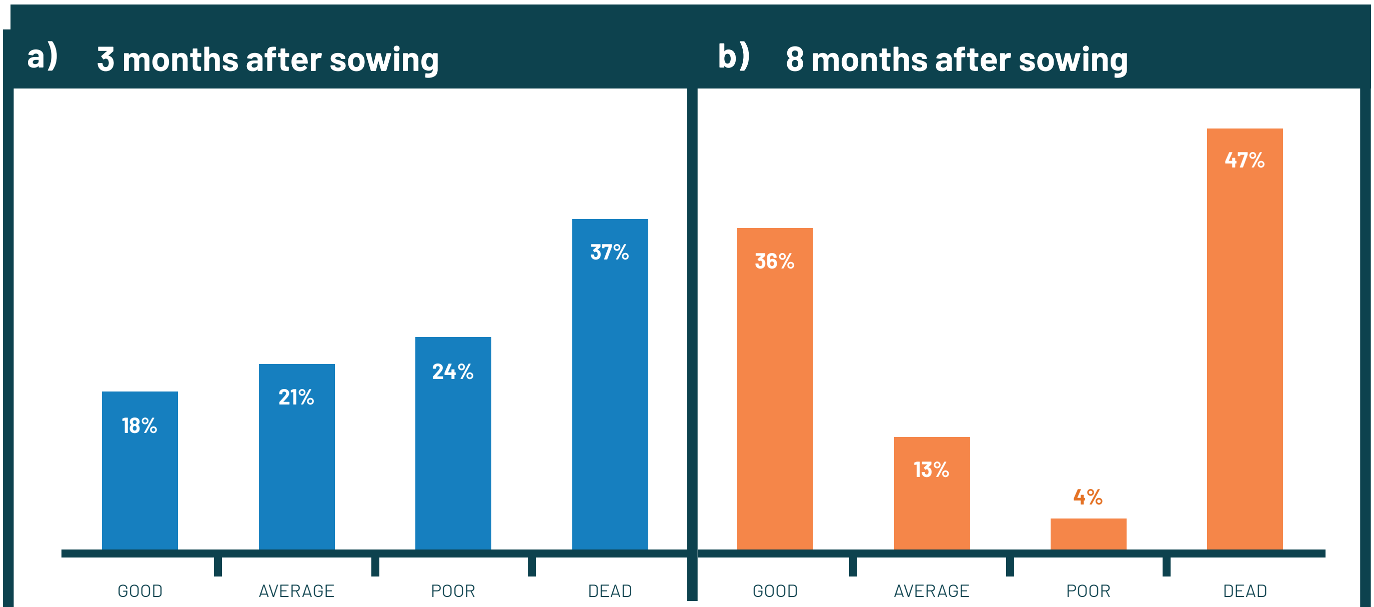


Figure 1 Health of *Rhizophora mucronata* a) 3 months and b) 8 months after sowing.

Results

The mortality rate for *Rhizophora mucronata* seedlings was rather high, standing at 37% and 47% at three and eight months after transplantation, respectively (figure 1). **The possible causes of these relatively low survival rates include:** significant exposure of soil to sunlight, such that the soil organic matter content and saturation rate were too low to sustain the seedlings; insufficient tidal movement both within and outside the mangrove forest, a phenomenon that appears to be worsening year after year (Note: this is a personal observation only and has not been scientifically verified); the fact that sowing was done by villagers who lack expertise in mangrove ecology, leading to occasional root damage or to planting in inappropriate areas. Thus, of 3,000 propagules planted, only 1,000 were completely healthy, equating to a success rate of 36% eight months after transplantation (figure 1). However, the mortality rate, which was high in the first few months of monitoring, tended to stabilize, underlining the need to improve sowing techniques and to choose more appropriate sites. Following the initial stage of natural selection of viable propagules, mortality rates were relatively low (10% in five months).

Note: No results are available for A. marina.

Success rate (%): 36%	**Duration of experiment (including follow-up): approx. 1 year**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	Creation

C2: Activity carried out in an environment damaged by humans or natural changes in order to establish more favourable conditions for the proper functioning of that environment or for biodiversity, requiring intervention.

Technical factors affecting risk:	
Species transferred	2
Removal technique	planting of propagules
Attachment technique	directly in substrate
Means of transportation	N/A
Transportation time	N/A

References

❶ **Wagner, G. M., Mgaya, Y. D., Akwilapo, F. D., Ngowo, R. G., Sekadende, B. C., Allen, A., and Mackentley, N.** (2001). Restoration of coral reef and mangrove ecosystems at Kunduchi and Mbweni, Dar es Salaam, with community participation. In: Marine science development in Tanzania and eastern Africa. Proceedings of the 20th Anniversary Conference on Advances in Marine Science in Tanzania (Vol. 28, pp. 467–488).

MAN n° 4

MANGROVE NURSERY AND TRANSPLANTATION IN BALANDRA Mexico

Restoration carried out in the Balandra lagoon, Mexico.

Project	Creation of a nursery to grow seedlings that were hardy under the environmental conditions of the site
Site	Balandra lagoon, Mexico
Species	White mangrove *(Avicennia germinans)*
Surface area	53,000 m^2
Success rate	76%
Cost	N/A
Year	1994

Objective

The Balandra lagoon is an arid zone (precipitation: <150 mm/year). It also includes a number of sites that have been converted for aquaculture. The combination of these factors led to a reduction in mangrove coverage. The aim of this project was therefore to rear seedlings in a nursery that were resistant enough for mangrove reforestation.

Monitoring of the experiment

The growth of the seedlings was initially monitored one, two and four weeks after planting in the nursery and then every six months for two years. Data on plant height, number of leaves and survival rate were collected.

Technique

White mangrove was cultivated for its abundance of propagules and its compact morphology, which made its seedlings easier to transplant. A total of 555 propagules were collected and planted in groups of five in biodegradable plastic bags. Growing the seedlings in groups helped to reduce their mortality rate.
The decision was made to use open-air nursery systems that were separated from the tide to avoid exposing the seedlings to salt stress. However, the temperature and humidity of the nurseries had to be checked frequently to ensure the survival of the seedlings, given the aridity of the region. Once the seedling roots were long enough, the plastic bags were transferred directly to the lagoon.

Mangrove transplants. Note: This is not a photograph of the project described. © Byron Hubbard

Mangrove transplants. Note: This is not a photograph of the project described. © Byron Hubbard

Results

The mangrove transplants survived and grew well under natural conditions, with 74% successfully established at the receptor site (lagoon) four years after transplanting (figure 1). **The open-air nurseries demonstrated the effectiveness of this mangrove reforestation technique in areas where natural regeneration is slow.**

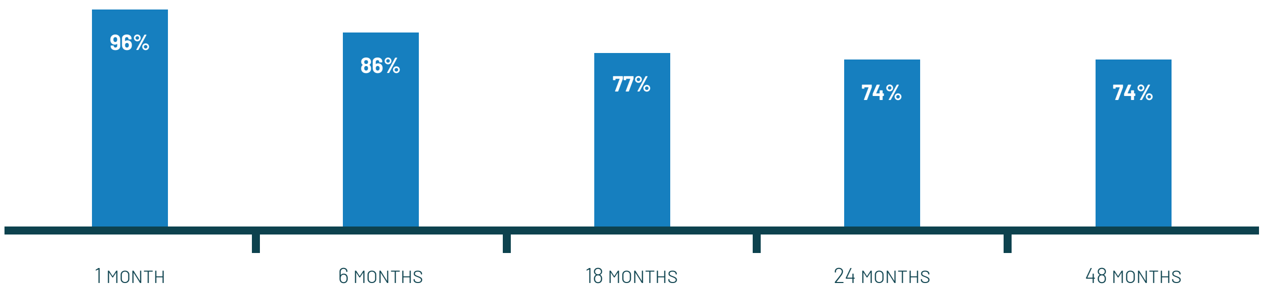


Figure 1 Survival rate (in %)

Success rate (%): 76%	**Duration of the experiment (including follow-up): approx. 4 years**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	Creation
C2: Activity carried out in an environment damaged by humans or natural changes in order to establish more favourable conditions for the proper functioning of that environment or for biodiversity, requiring intervention			
Technical factors affecting risk:			
Species transferred	1		
Removal technique	planting groups of propagules		
Attachment technique	directly in substrate in biodegradable plastic bags		
Means of transportation	N/A		
Transportation time	N/A		

References

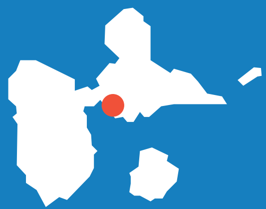
❶ **Toledo, G., Rojas, A., et Bashan, Y.** (2001). Monitoring of black mangrove restoration with nursery-reared seedlings on an arid coastal lagoon. Hydrobiologia, 444, 101-109.

MAN n° 5

MANGROVE NURSERY IN BAS DU FORT

Guadeloupe

Nursery created in Bas du Fort, Guadeloupe. Ordered by the Grand Port Maritime de la Guadeloupe and managed by CDC Biodiversité and Coraïbes (a limited liability company devoted to marine ecological restoration).



Project .... Creation of a mangrove nursery
Site .... Bas du Fort
Species .... Red mangrove *(Rhizophora mangle)*, white mangrove *(Avicennia germinans)*, grey mangrove *(Conocarpus erectus)*
Surface area .... 800 m^2
Success rate .... *R. mangle:* 93%; *C. erectus:* 13%; *A. germinans:* currently unavailable
Cost €70,461
Year 2017
Field officer........... mariane@coraibes.com

Objective

Creation of a nursery with three species of mangrove – red, white and grey – with a view to producing seedlings that can be transplanted to sites affected by coastal developments to strengthen existing populations.

Monitoring of the experiment

The growth of the control propagules was monitored fortnightly. This involved measuring propagule height, counting the number of leaves on each seedling and estimating the percentage of leaves having fallen prey to predators (which is harmful in the early stages of growth). The survival rate of all propagules was also calculated.

Testing mangrove supports ©Mariane Aimar-Godoc

Technique

The propagules were collected in natura from a number of sites between September and October 2017 and subsequently planted in bamboo pots filled with a loose substrate. For *Conocarpus erectus*, transplantable seedlings were also produced from branch cuttings.

Table 1 Number of seedlings planned for the first phase of production

Avicennia germinans 35 seedling
Conocarpus erectus 40 seedling
Rhizophora mangle 175 seedling

Mangroves in bamboo pots ©Mariane Aimar-Godoc

Results

The results showed a survival rate of 93% for red mangrove and 13% for grey mangrove. The results are as yet unavailable for white mangrove.

Success rate (%): variable	**Duration of the experiment (including follow-up): approx. 4 years**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	Creation
C2: Activity carried out in an environment damaged by humans or natural changes in order to establish more favourable conditions for the proper functioning of that environment or for biodiversity, requiring intervention			
Technical factors affecting risk:			
Species transferred	3		
Removal technique	planting of propagules		
Attachment technique	directly in substrate in bamboo pots		
Means of transportation	N/A		
Transportation time	N/A		

References

❶ Analyse régionale Guadeloupe, synthèse des connaissances. [Regional analysis Guadeloupe, knowledge synthesis.] University of the French West Indies and Guiana, Guadeloupe National Park and the Marine Protected Areas Agency, 2013.

❷ Mise en place d'une pépinière de palétuviers *Rhizophora mangle, Avicennia germinans* et *Conocarpus erectus.* Caraïbes. [Establishment of a mangrove nursery for *Rhizophora mangle, Avicennia germinans* and *Conocarpus erectus.* The Caribbean.] 2017.

MAN n° 6

MANGROVE PASSIVE MANAGEMENT AND SOWING IN NOUMÉA

New Caledonia

Restoration carried out at the Rivière Salée mangrove forest in Nouméa, by volunteers between 2007 and 2010, by the Nature Conservation Association of New Caledonia (Association de Sauvegarde de la Nature de Nouvelle-Calédonie) and SOS Mangroves RS between 2010 and 2014, and by SOS Mangroves NC between 2014 and 2017.

Project	Cleaning of mangrove forest to promote site regeneration
Site	Rivière Salée mangrove forest, Nouméa
Species	7 species, but primarily *Rhizophora selala*
Surface area	30 ha
Success rate	N/A
Cost	€61,800 or €0.21/m^2
Year	2007
Field officer	sosmangrovesnc98@gmail.com

Objective

The Rivière Salée mangrove forest, home to a wealth of bird species (46 identified) and seven different mangrove species, is under extreme pressure from various forms of pollution, the spread of invasive species and poor water circulation, leading to the build-up of mud and the asphyxiation of seedlings. In addition, urban growth has led to a reduction in the surface area of the mangrove forest from 90 to 30 ha. From 2007, to conserve the mangrove hinterland, an effort was made to eradicate creepers in line with a protocol provided by the New Caledonia Agronomic Institute (Institut Agronomique néo-Calédonien) in Nouméa. The site was cleaned up with a view to promoting the natural regeneration of seedlings.

Technique

Beginning in 2007, 10 people (young people experiencing social problems) cleaned for four hours a day over a period of 10 months. Their duties involved managing invasive species, cleaning the area and sowing propagules of three species: grey mangrove *(Avicennia marina)*, milky mangrove *(Excoecaria agallocha)* and red mangrove *(Bruguiera gymnorhiza)*.

Clearing and burning invasive species at the Rivière Salée site
©SOS Mangrove NC

Monitoring of the experiment

The association SOS Mangroves RS, has been taking follow-up photographs of the mangrove forest for 10 years. To maintain the area, local authorities dredge the channel once or twice a year to prevent mud from asphyxiating the mangroves.

Cost

Between 2007 and 2010, work was done solely by volunteers, with the first funding appearing in 2010 in the form of grants from private, regional and European Union funds and IFRECOR (figure 3).
Total expenditure **€61,800** or **€0.21/m²** restored.

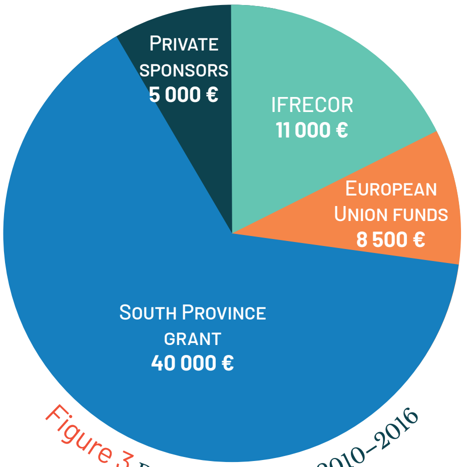


Figure 3 Restoration costs 2010–2016

Collecting household waste from the mangrove forest ©SOS Mangrove NC

Lessons learned

The method used was well adapted to the specific characteristics of the country and was a good fit for the issues faced by young volunteers supporting the association, who met with the association directly and raised awareness in the local population. Nowadays, the use of social networks such as Facebook allows for a much quicker and more positive response on the part of the local population.
However, lack of reactivity at the institutional level caused major damage, resulting in the destruction of certain areas. The voluntary restoration scheme provided an opportunity for young people enrolled in job creation programmes to contribute to the regeneration of the mangrove forest. Through awareness-raising, the local population now understands the value of protecting this area.
Local people have even taken ownership of the site and are participating in raising public awareness. The area regenerated in 2019 amounts to around a hectare. The mangrove forest is in good health, and equilibrium has been restored in the area despite the current waste disposal issue in New Caledonia, which directly affects mangrove forests in the territory. In July 2019, the mangrove restoration project will be presented at the International Mangrove, Macrobenthos and Management Conference in Singapore, on the theme of mangroves and people.

Success rate (%): satisfactory	**Duration of the experiment (including follow-up): > 10 years**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	Creation
C2: Activity carried out in an environment damaged by humans or natural changes in order to establish more favourable conditions for the proper functioning of that environment or for biodiversity, requiring intervention			
Technical factors affecting risk:			
Species transferred	7		
Technique used	Cleaning of the natural regeneration zone, occasionally complemented by direct sowing		

References

❶ Interview with Monik Lorfanfant (President of SOS Mangroves)
❷ **Facebook:** @sos.mangroves.nc

MAN n° 7 PASSIVE MANAGEMENT AND SOWING OF MANGROVE IN TOUHO New Caledonia

Passive management and sowing were carried out in Touho, New Caledonia, by inhabitants of the Tribu de Koé district, located in the coastal part of the Touho municipality. Most of those involved in mangrove sowing are now members or volunteers of Association Hô-üt, which means "deciding while walking", in New Caledonian Creole. The association is involved in the conservation of sites included on the World Heritage List of the United Nations Educational, Scientific and Cultural Organization (UNESCO). The commune of Touho is home to 415 hectares of mangrove, which equates to 1.2% of the 35,000 hectares of mangrove found in New Caledonia (Virly, 2008).

Project	Replanting mangroves
Site	Tribu de Koé, Touho (Tuo Cèmuhî)
Species	Species of the *Rhizophora* and *Brugueria genera* only
Surface area	N/A
Success rate	N/A
Cost	N/A
Year	1980–2017
Field officer	asso.hout@gmail.com

Objective

The lagoons and reefs of New Caledonia have been included on the UNESCO World Heritage List since 2008.

The heritage site includes six areas:

❶ Grand Lagon Sud;
❷ Western coastal area;
❸ North-eastern coastal area;
❹ Grand Lagon Nord;
❺ Atolls of Ouvéa and Beautemps-Beaupré;
❻ Atoll of Entrecasteaux.

The commune of Touho belongs to sub-zone 4 of the north-eastern coastal area.

The New Caledonia coast suffers from significant erosion linked to climate change, rising water levels and tropical depressions and cyclones, with the latter affecting the east coast in particular. There is also considerable anthropogenic pressure, including from wastewater flows, pollution from mining companies, household waste, uprooting of young plants, urbanization and the use of mangrove wood for heating. Moreover, there is empirical evidence of a decline in certain species in the affected ecosystems, including crabs, oysters and various species of fish, which triggered the replanting of mangroves along the coast of the Tribu de Koé district. The aim of the inhabitants was to manage and sow mangroves in areas affected by woodcutting and to restore and protect the local mangrove forest.

Planting of mangroves by the Kowei tribe

Cost

Mangroves were planted individually by the inhabitants of the Tribu de Koé district, on a voluntary basis only.

Technique

The inhabitants began planting mangroves in the 1980s. These individual initiatives were driven by the reduction in mangrove coverage (caused by the felling of mangroves for heating fuel or by tropical depressions and cyclones). During their trips out to sea, the inhabitants began gathering propagules that had fallen to the ground and replanting them directly in the area.
According to the inhabitants, mature propagules collected directly from trees take longer to grow, so for sowing, the collection of propagules that had fallen to the ground was prioritized. The technique used was to plant in groups of three to four propagules or more (see photograph 1). Propagules planted in groups of at least three grow more quickly and embed themselves more securely once the roots begin to grow. Since 2012, waste collection has also been carried out alongside sowing (see photograph 2).

Waste collection by Association Hô-üt

Monitoring of the experiment

No monitoring was carried out in the field, but generally speaking, mangrove coverage has increased. Key indicators include the return of certain species to the area, namely *Rhizophora sp.* and *Brugueria sp.*

Lessons learned

The inhabitants of the Tribu de Koé district mastered propagule planting in the wake of a series of tropical depressions and cyclones. Their preferred technique was to plant in groups of three. The Touho municipality experiences severe coastal erosion. The inhabitants of Touho and local institutions (town halls and provincial authorities) realized the important role played by mangroves in reducing coastal erosion, preventing floods and increasing fishing resources. Other mangrove sowing and management initiatives were launched by the Tiponite and Tiwaé tribes. Thus, between the 1980s and 2017, around 2,000 mangrove seedlings were planted in Touho. Mangrove projects are ongoing throughout the municipality, including the creation of an educational walking trail by the Kowei tribe and awareness-raising of the role of mangroves among school pupils and the wider public.

Success rate (%): N/A	**Duration of the experiment (including follow-up): > 37 years**		
Sequence phase	A	R	**M**
Type of measure	**Restoration**	**Rehabilitation**	Creation
C2: Activity carried out in an environment damaged by humans or natural changes in order to establish more favourable conditions for the proper functioning of that environment or for biodiversity, requiring intervention			
Technical factors affecting risk:			
Species transferred	N/A		
Removal technique	planting in groups of 3-4 propagules or more and cleaning of the area		
Attachment technique	directly in the substrate		
Means of transportation	N/A		
Transportation time	N/A		

References

❶ **Virly, S.** Atlas des mangroves de la Nouvelle-Calédonie. Programme ZoNéCo. [Atlas of mangroves of New Caledonia. ZoNéCo programme.] 208p. (2008)

CONCLUSIONS REGARDING MANGROVES

At first glance, mangrove restoration techniques appear simpler than for the other ecosystems studied in this guide, given their link with land forest ecosystems. However, whereas these techniques borrow heavily from traditional arboriculture and horticulture (technical itineraries, biomass production, sexual and asexual reproduction), a number of characteristics specific to the marine environment and the land-sea interface must be taken into account to achieve the objectives set. The NGO Mangrove Action Project (2017) briefly summarizes the steps to be taken to implement integrated and sustainable mangrove restoration projects.

The first of these steps is to understand the practices and customs relating to the mangrove forest to be restored. For instance, owing to their coastal situation, mangrove forests serve as a habitat and an exploitable resource for human populations. The success of a project will depend on the acquisition of information on these uses and on the motivation of the villagers to support the initiative.

Another vital step in ensuring the longevity of any restoration project is identifying the initial factors causing the degradation of the ecosystem (invasive development projects, overexploitation of resources, excessive removal of freshwater, waste input, alteration of sediment transport and so on) and estimating the resources required to alleviate or eradicate these pressures. If the sources of degradation are not at least alleviated, curbing the destruction of the ecosystem will not be possible in the short or medium term.

The next step is to identify the desired condition of the ecosystem after restoration. The focus here is on the ecological objectives of the restoration, which means defining a baseline ecological condition, preferably one in which the mangrove forest is not affected by the pressures identified and is maintained in a state most closely approximating its ecological optimum. This forest will serve as a control site and its ecological structure will be studied with a view to devising an appropriate intervention strategy. It may also be necessary to identify sites and species to be replanted according to their ecological preferences (water level, salinity, hydrodynamics, *etc.***).**

Only once these steps have been taken can the focus shift to actual ecological engineering techniques. Which techniques to use may be determined by the species in question, their methods and periods of reproduction, the risks faced by young plants and any difficulties encountered during their natural regeneration, as well as by the area to be restored. It is not a matter of simply planting young trees, but of devising a complex ecological restoration project to be addressed hierarchically and chronologically in order to achieve objectives as fully and sustainably as possible.

6

COST AND EFFECTIVENESS OF ECOLOGICAL ENGINEERING TECHNIQUES

COST AND EFFECTIVENESS OF ECOLOGICAL ENGINEERING TECHNIQUES

In the sections above, data on cost and effectiveness have been linked to each of the ecological engineering techniques developed. **The following information is provided for further clarification:**

Table 1 Summary of available data for the ecosystems under review

	CORAL REEFS	SEAGRASSES	MANGROVE FORESTS
Time scale	1991 - 2017	1975 - 2016	1977 - 2016
Number of available articles projects	79	27	81
Volume data on survival rate	259	68	123
Volume data data inputs on cost	20	10	92

EFFECTIVENESS

To gauge the effectiveness of a restoration project, the actual rate of re-establishment following restoration must be evaluated. The extent to which this can be done depends on the time spent on follow-up, and since follow-up time varies considerably from one project to another, gauging the effectiveness of the measures taken can be difficult. This is one of the problems outlined in an article published in 2017 by Hein *et al.*, which states that a minimum of five years should ideally be spent on follow-up in order to measure the resilience of a given ecosystem.

COST

To calculate the average cost of ecological engineering techniques relating to coral reefs and associated ecosystems, we adjusted the costs for inflation (consumer price index) against a base year (2010) and for the difference in purchasing power between countries (purchasing power parity). This provided us with comparable data for multiple countries. All costs were expressed in international dollars/ha/year based on the base year (2010). The results are given in the tables below and in the corresponding pages of the guide.

CORAL REEFS

Data on follow-up time for coral reef restoration projects (figure 15) shows that, whichever ecological engineering technique was used, follow-up time did not generally exceed three years. Follow-up periods of three years or more were observed for only 9% of projects (9% for transplanting; 5% for nurseries; 0% for electrodeposition). Estimating the actual effectiveness of techniques was thus difficult. The estimated rate of effectiveness given in this guide was determined based on the values available for follow-up periods of three years or more. This average rate of effectiveness should be treated with caution as not enough data was available for the values to be considered robust. The estimate that these values support is intrinsically linked to the implementation conditions of the examples cited **(figure 16).**

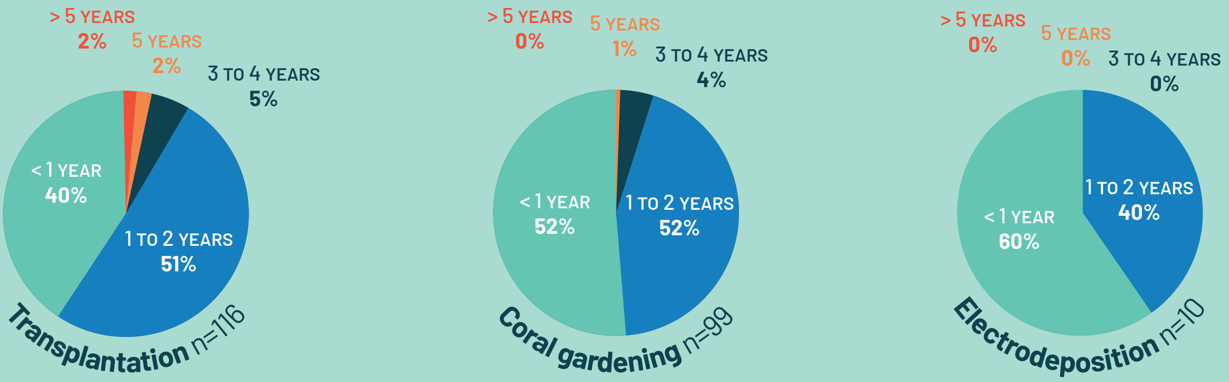


Figure 15 Follow-up time for coral reef ecological engineering techniques

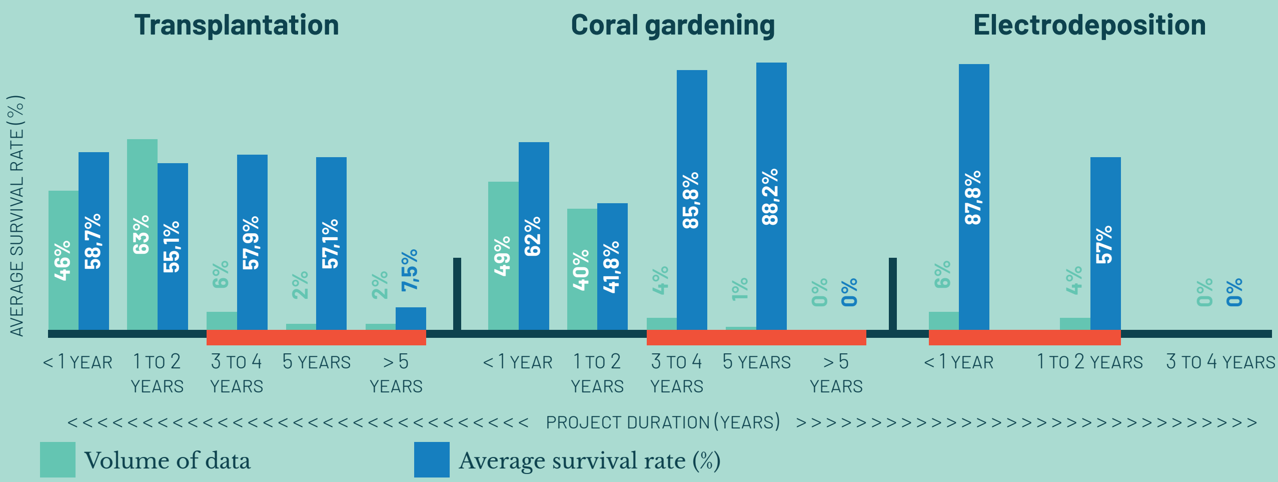


Figure 16 Average survival rate and data available according to duration of coral reef ecological engineering projects. The red area indicates the values used to determine the average rate of effectiveness on **pages 25 to 27** of the guide.

Table 2 Summary of data on the costs (int. dollar/ha/year) associated with each technique for coral reefs. Average costs are detailed on **pages 25 to 27** of the guide. Note: These data comprise all project-related costs, meaning that scientific follow-up costs are also included in the data set.

Cost in international dollars/ha/year

	Transplantation	Nursery	Electrodeposition
Median	39 238,87	615,75	NA
Mean (+- standard deviation)	6 618 058 (±28 517 285,9)	6 351 665,96 (±74 315,19)	NA
Minimum	298,36	338,95	NA
Maximum	143 000 000	189 936,71	NA
Number of related projects	25	8	0

SEAGRASSES

For seagrasses, feedback was provided for transplantation only. No data was available for the other techniques used, namely sowing, passive management and micropropagation. Figure 17 below shows that follow-up periods of under two years applied to most (88%) of the projects cited (one to two years for 74% of projects and under one year for 14% of projects). Follow-up periods of five years or more applied to only 2% of projects. It was thus difficult to determine the average rate of effectiveness of seagrass transplantation projects, although averages were taken of calculated survival rates (of three years or more) to give a general idea (figure 18). In addition, the limited data did not allow for robust statistical values, so caution must be exercised in interpreting the results.

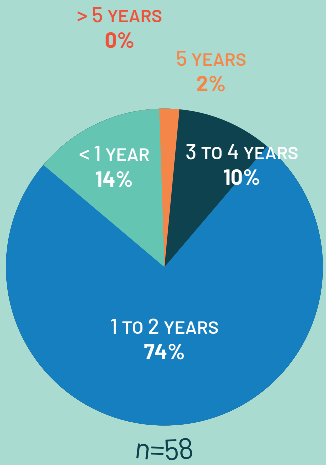


Figure 17 Duration of follow-up periods for seagrass transplantation (n=58)

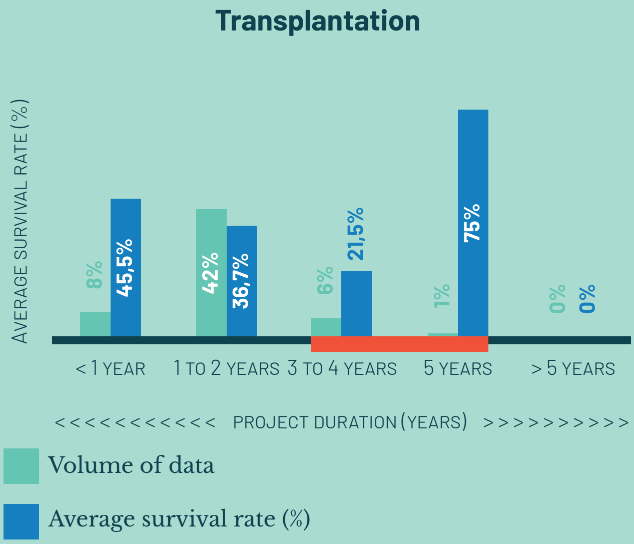


Figure 18 Average survival rate and volume of data available according to duration of seagrass transplantation projects. The red area shows the values used to determine the average rate of effectiveness set out on **page 61** of the guide.

Table 3 Summary of data on the costs (int. dollars/ha/year) associated with each technique for seagrass restoration. Average costs are detailed on **pages 61 to 64** of the guide. Note: These data comprise all project-related costs, meaning that scientific follow-up costs are also included in the data set.

Cost in international dollars/ha/year		Transplantation	Sowing
	Median	107 101	N/A
	Mean (+- standard deviation)	327 289 (±429 460)	N/A
	Minimum	33 962	N/A
	Maximum	1 306 804	N/A
	Number of related projects	10	0

MANGROVES

The same observation can be made for mangroves as was made above for the other ecosystems: few projects had a follow-up period of more than three years (figure 19). The findings were more nuanced in the case of mangrove nurseries and natural self-regeneration, although few projects were studied in these areas. The values used to determine the average rate of effectiveness of each ecological engineering technique for mangroves are highlighted in red in figure 20.
Caution should be exercised in interpreting these averages, however.

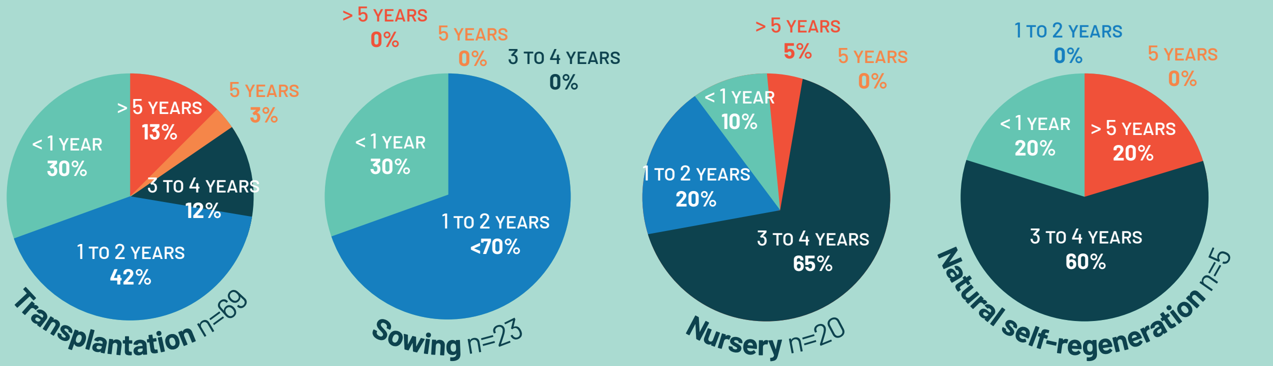


Figure 19 Duration of follow-up for mangrove ecological engineering technique

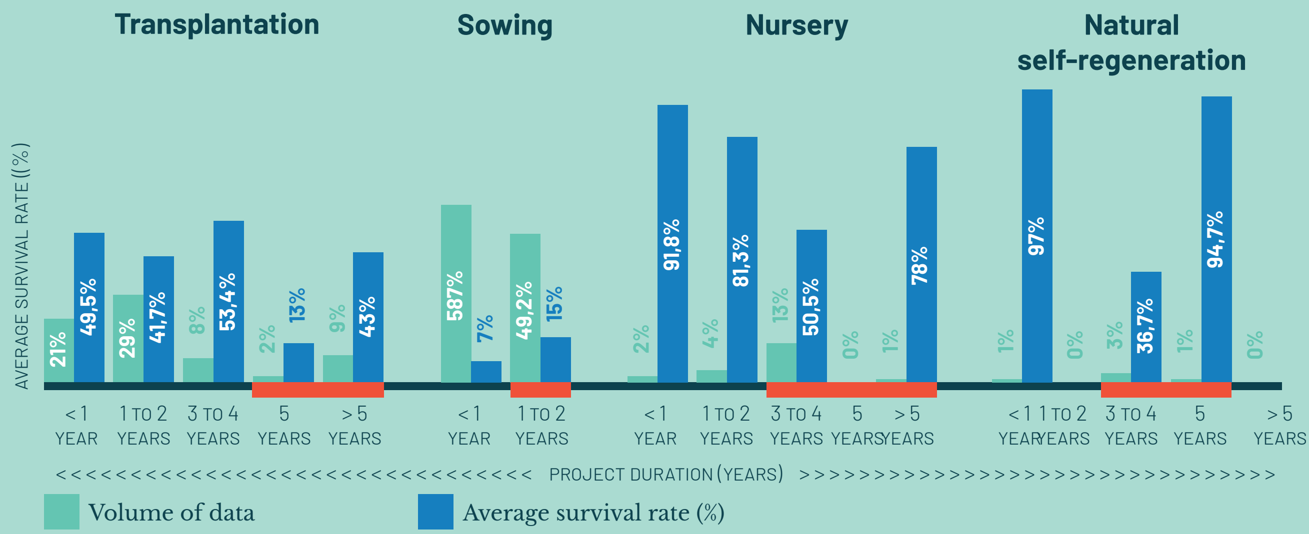
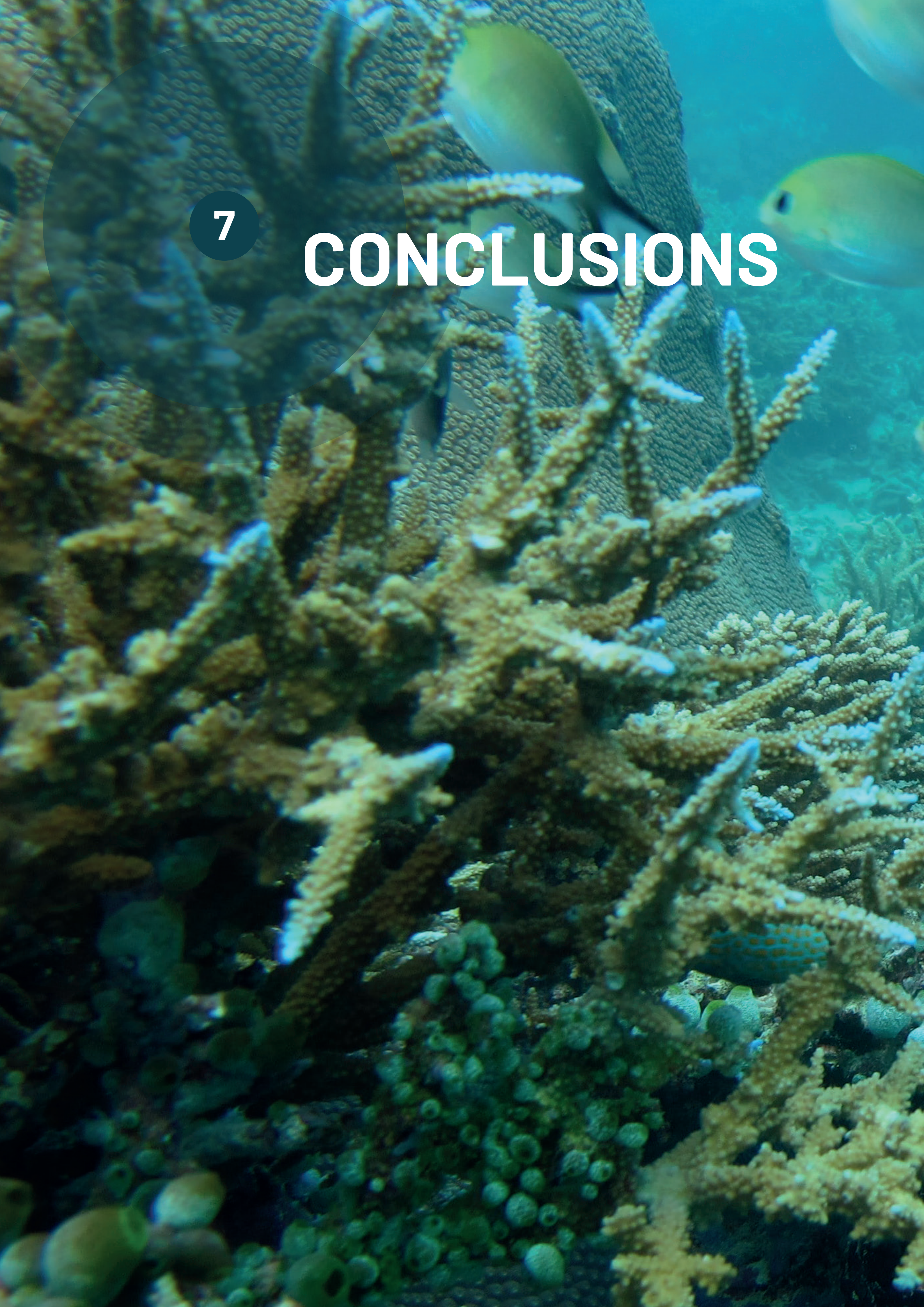


Figure 20 Average survival rate and volume of data available according to duration of mangrove ecological engineering projects. The red areas signify the values taken to determine the average rate of effectiveness detailed on **pages 77 to 80** of the guide.

Table 4 Data summary of the costs (int. dollars/ha/year) associated with each technique for mangroves. The average costs are detailed on **pages 77 to 80** of the guide. Note: These data comprise all project-related costs, meaning that scientific follow-up costs are also included in the data set.

Cost in international dollars/ha/year		Transplantation	Sowing	Nursery	Natural self-regeneration
	Median	248	4 117	61	3 877
	Mean (+- standard deviation)	62 197 (±147 704,82)	11 767 (±14 324)	61 (±0)	48 430 (±73 244,25)
	Minimum	1	6	61	16
	Maximum	705 613	40 963	61	247 520
	Number of related projects	51	25	1	15



7 CONCLUSIONS

CONCLUSIONS

This paper is intended to encourage contracting authorities and developers to learn more about and evaluate ecological engineering techniques and their effectiveness. It is a tool to aid decision-making on ecological engineering matters based on feedback from around the world. In this respect, the information on survival rates and costs associated with the various techniques is geared towards improving the effectiveness of humanity's response to marine and coastal ecosystems.

It would appear that the effectiveness of the techniques illustrated in this guide is similar in each case. To improve the effectiveness of ecological restoration in a given environment, Abelson (2006) recommends employing multiple ecological engineering techniques at the same time, although this hybrid approach is not well covered here (accounting for around 1% of projects).

It is worth remembering that the cost of implementing ecological engineering techniques in marine environments, at $110,000/ha, is high compared with continental terrestrial or aquatic ecosystems (Jacob, 2017; Bayraktarov, 2016).

Of course, there are many different techniques, some of which are given limited or no coverage here. The purpose of this guide is to establish an inventory of the most commonly used techniques for the ecosystems in question and to provide feedback on the projects discussed.

Note that passive management of coral reefs as an ecological restoration technique is not discussed here. French public policy currently considers that this type of restoration is a matter for voluntary citizens' associations in the areas of environmental education and participatory science. Grants are sometimes awarded to associations for passive management, but this is considered as maintenance of natural spaces rather than restoration.

Summary of ecological restoration techniques
for coral reefs and associated ecosystems

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GLOSSARY

ARM sequence Avoid, reduce, mitigate – a sequence aimed at avoiding and reducing residual impacts as much as possible, and then mitigating them, with a view to alleviating the environmental damage caused by a development project as much as possible.

Conservation Protection of an ecosystem based on legislation (conservation covenants, nature reserves, etc.) and/or physical measures (restriction of physical access to protected areas).

Ecological engineering All techniques and processes for solving socioeconomic and/or environmental problems in the short term through the use of living organisms or other materials of biological or non-biological origin.

Ecological equivalence An essential step in implementing mitigation measures is to determine their scale. Mitigation outcomes should be ecologically equivalent. Thus, to ensure "no net loss" in biodiversity, it is important to gauge whether the mitigation gains are equivalent to the biodiversity losses caused.

Ecological restoration The Society for Ecological Restoration defines ecological restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed". This definition implies the need for human intervention to initiate and/or promote the natural restoration of a damaged ecosystem. Ecological restoration thus follows on from anthropogenic impacts (pollution, grounding of vessels, development work, etc.) and natural impacts (cyclones, typhoons, tsunamis, etc.). The aim is to return the ecosystem to its historical evolutionary trajectory rather than to its ideal state. Thus, an ecosystem is considered to have been restored where it can continue its development without human assistance. However, ecological restoration is difficult to implement in marine environments, as knowledge of how aquatic ecosystems work is still limited (Pioch *et al.*, 2019).

Ecosystem creation Establishment of an ecosystem for a useful purpose, or intentional replacement of an ecosystem with another type of ecosystem presumed to be of greater value on the site in question (Clewell and Aronson, 2010, p.295).

Ecosystem resilience Ability of an ecosystem to return to normal functioning, development and dynamic equilibrium after a natural or anthropogenic disturbance.

Ecosystem service Service provided by ecosystems to human beings.

Environmental mitigation Environmental mitigation consists of implementing actions to create an equivalent environmental gain for an instance of environmental damage observed elsewhere, generally in line with a stated objective of ecological neutrality ("no net loss"). Equivalences can be evaluated in terms of plant or animal populations, habitats, resources, ecological functions or ecosystem services. Environmental mitigation can be based on legislation (the "avoid, reduce, mitigate" sequence) or on voluntary procedures. The ultimate aim is to maintain biodiversity and ecosystems at the scale of a particular territory.

Habitat Place where a plant or animal population or biological community lives. Includes different environments used at different stages of development and activity of those plant and animal populations.

Mitigation measure See "environmental mitigation".

Rehabilitation Process of re-establishing the roles and functions of a damaged ecosystem, giving less regard to the indigenous species in the baseline model than restoration projects would, with the overarching aim of restoring productivity or, more generally, enabling the provision of ecosystem services (Clewell and Aronson, 2010, p.300).

Resilience Ability of an ecosystem to tolerate disturbances and re-establish itself autonomously through natural regeneration, without going through another stage controlled by other processes. In other words, the ability of an ecosystem to recover from a disturbance without human intervention. In social or socio-ecological systems, resilience enables people to anticipate and plan for the future (Clewell and Aronson, 2010, p.300).

Symbiosis An intimate and lasting association between two different species that ensures the survival of both.

ACRONYMS

ARM avoid, reduce, mitigate

IFRECOR French Coral Reef Initiative

MERCI-Cor Method to Avoid, Reduce and Mitigate Impacts in Coral Areas

N/A not applicable

SER Society for Ecological Restoration

UNEP-WCMC United Nations Environment Programme World Conservation Monitoring Centre