D7.4: Restoring marine ecosystems cost-effectively: lessons learned from the MERCES project

Marine Ecosystem Restoration in Changing European Seas MERCES

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1. Introduction

Worldwide coastal, marine, and estuarine systems have been degraded due to anthropogenic pressures such as reclamation, pollution, and destruction (Lotze et al., 2006). Practically no marine area has not been affected by human activities (Halpern et al., 2008). This degradation has led to considerable losses in biodiversity and ecosystem services (Worm et al., 2006), many of which are highly valuable (Barbier et al., 2011).

Similar trends are visible in the European Union. A review of marine habitats in the EU28 (Gubbay et al., 2016) found that of 125 habitats where sufficient data were available, 47 (38%) were categorised as either critically endangered, endangered, or vulnerable. The majority of these sites were in either the northeast Atlantic (20 out of 34 evaluated) or the Mediterranean (15 out of 24 evaluated). Data are sorely lacking, however, as an additional 122 habitats were investigated but considered data deficient.

The EU Biodiversity Strategy to 2020 (European Union, 2011) aims to have restored at least 15% of degraded ecosystems by 2020. Marine ecosystems can be restored in a number of ways, including transplantation of seeds, juvenile plants, or pieces of coral; removal of natural grazers or predators; or translocation of entire populations or habitats. Such efforts, however, require considerable resources. Therefore, it is imperative that policy makers understand the order of magnitude of the costs of restoration, the factors that determine restoration costs, and the trade-offs at stake.

A number of reviews are available on the costs of marine ecosystem restoration (Spurgeon, 1999; Bayraktarov et al., 2016, 2019). These reviews demonstrate that the costs of restoring coastal and marine ecosystems can vary substantially, depending on the technique, the habitat, and the scale of the operation. The costs of restoring seagrass, for example, vary between US$ 6,654 ha^{-1} and US$ 4,106,047 ha^{-1} (in 2010 prices), with a median of US$ 106,782 ha^{-1}; for coral reefs in developed countries these numbers were US$ 7,647 ha^{-1}, US$ 143,000,000 ha^{-1}, and US$ 1,826,651 ha^{-1}, respectively (Bayraktarov et al., 2016). It is difficult to extrapolate estimates with such variation to new restoration projects, even more so considering the experimental nature of most of the studies that these estimates are based on.

The MERCES project aimed to build on existing knowledge, to gap filling, and to find innovative ways to restore marine ecosystems, in a wide range of ecosystems in shallow soft bottom, shallow hard bottom, and various deep-sea habitats. MERCES has developed several cases looking at the pressures and activities impacting key European habitats, the key attributes that frame the restoration potential of these habitats (Bekkby et al. 2017; Gerovasileiou et al. 2019, Dailianis et al. 2018, Papadopoulou et al. 2017). MERCES has conducted a world-wide review of restoration efforts (over 400 articles focussing specifically on active restoration interventions) looking at issues of which habitat, region and what scale as well as success and failure factors (Papadopoulou et al. 2017) and a review on published information on restoration costs and benefits for key marine habitats (Papadopoulou et al. 2017, and references therein).

We carried out a survey among MERCES case studies in order to obtain cost estimates as well as the main factors determining those costs. In this article we describe the main lessons learned from this survey, and demonstrate how cost-effectiveness analysis can help select best alternative.

2. Costs of restoring marine ecosystems

MERCES investigated marine ecosystem restoration in three types of marine or coastal substrate: soft substrate, hard substrate, and deep sea. For each of these types of substrate the costs were analysed in MERCES restoration projects as well as restoration efforts elsewhere.

2.1. Soft substrate

In soft-bottom habitats MERCES investigated the restoration of a variety of seagrass (notably *Zostera marina*, *Zostera Noltii*, and *Posidonia oceanica*) and shellfish (mainly *Pinna nobilis*) species, either separately or combined.

2.1.1 Seagrass

MERCES investigated seagrass restoration in, among others, Gökova Bay (Turkey), the Dutch part of the Wadden Sea, the Estonian part of the Gulf of Riga, the Åland Islands (Finland), and Fårö (Sweden). All efforts involved the transplantation of seed, shoots, or both from a donor site to the restoration site (Bekkby et al. 2017; Papadopoulou et al. 2017).

The costs of the seagrass experiments varied from about € 13,000 to slightly more than € 80,000. The experiments varied considerably in scale, however, which limits a fair cost comparison. For example, the experiments in the Åland Islands regarded six plots of 25 cm by 25 cm, albeit planted over an area of 900 m^2; on the other hand, the Wadden Sea experiment regarded the replanting of a surface of 290 m^2.

Sites also varied considerably in the distance between donor sites and restoration sites, as well as the accessibility of sites, which is determined by the site's distance from the shore and its depth. On one hand, the Wadden Sea sites were very accessible because this area falls dry every day. This allowed researchers to reach sites on foot, and to apply shoots or seed without having to dive. A considerable part of the costs of the Wadden Sea experiments, however, regarded the collection of seed and shoots from the German island of Sylt, 500 km from the restoration site, and their storage. The sites near the Åland Islands required dives of up to 5 m, whereas a species such as *Posidonia oceanica* can occur at depths of up to 35 m.

In all projects labour costs made up more than half of total costs, despite considerable differences in wage rates between countries. On one hand these observations may be biased by the fact that equipment such as boats may have been borrowed from other projects or organisations; on the other hand, labour costs are probably underestimated as most estimates only reported wages paid to experts as many restoration efforts depend on a considerable amount of volunteer effort.

2.1.2 Noble pen shells

Translocation of noble pen shells (*Pinna nobilis*) is done to protect them against local disturbances such as construction and pollution. Therefore, unlike seagrass, this restoration activity regards translocation of species rather than transplantation.

P. nobilis occurs at depths between 0 and 60 m (Zavodnik et al., 1991), and its translocation requires careful digging in order to avoid damage to its byssus gland. Therefore it has to be done by experienced divers, each of which can transplant about 10 to 15 shells per dive. The MERCES experiment to translocate about 185 individuals in Javorike Bay, Croatia, cost about € 14,800, not including overhead costs. This is about ten times other estimates of about € 8 per individual (Katsanevakis, 2016), no doubt due to the small scale of the experiment.

2.2. Hard substrate

On hard substrate MERCES carried out experiments with restoration of coralligenous assemblages (*Eunicella singularis*, *Corallium rubrum*) and macroalgae (*Cystoseira*, *Saccharina latissima*, *Laminaria hyperborea*).

2.2.1 Coralligenous assemblages

Coralligenous assemblages occur at depths between 20 and 120 m (Papadopoulou et al., 2017). Deep habitats require deeper dives, and hence shorter dive time and more experienced divers than shallower habitats. Most experiments involved the transplanting of coral, which could be a single species or a mix of gorgonians, red corals, and sponges, from donor sites, which are glued on rocks and other hard surfaces in the restoration site.

Costs varied considerably, from € 5,600 for transplanting about 200 gorgonian and 50 red coral fragments to a 30 m^2 area near Gallinara Island, Italy, to € 11,500 for transplanting assemblages of gorgonians, red corals, and sponges to a an area 10 m^2 near the Portofino Promontory, Italy. Both experiments required a total of 40 dives, but the latter dives were more expensive due to the greater depth. In both experiments more than half the expenses regarded labour costs, despite extensive participation of volunteer divers. In both cases monitoring took place until a year after the restoration. Upscaling these efforts from their current size to the preferred size of about 100 m^2 is likely to double or triple the total costs.

2.2.2 Macroalgae

The MERCES experiments on macroalgae restoration focused on three interventions: removal of sea urchins, which prevent the return of kelp; transplantation of seeds or branches; and using artificial reefs.

All the three interventions were carried out in order to restore *Laminaria hyperborea* and *Saccharina latissima* in Northern Norway. Collecting, developing and transplanting of kelp forest using chains (Vega) for an area of 100 m^2 cost about € 10,473. Removing sea urchin by using lime near Porsanger and Hammerfest is the cheapest method among the three which costs about € 129,000 for an area of 0.9 km^2. Putting down artificial reefs are the most expensive method for investment which cost € 209,466 for 500 m^2. A fair comparison of these interventions, however, would require success rates, which are yet unknown.

Collecting, cultivating, and outplanting *Cystoseira* in 18 plots of 20 by 20 cm in four locations in southern Italy (Porto Cesareo, Marittima, Torre Guaceto, Sant'Isidoro) cost about € 20,250, € 13,000 of which regarded labour costs. Much of the work went into the preparation of the restoration, i.e. selection of donor and restoration sites, building and fixing metal cages against herbivores, collection of fertile receptacles, and culturing in the laboratory.

2.3. Deep sea

Deep-sea experiments under MERCES included transplantation of deep-sea corals. The great depth of these operations required very specific equipment, such as remotely operated underwater vehicles (ROVs) and landers. Therefore, unlike the other two habitat types in the project, equipment costs in some experiments were higher than labour costs. Equipment costs included such expenses as the creation of facilities to maintain cold-water corals, purchase of ROVs, or hiring research vessels. Monitoring times were the longest of all due to the slow growth of the target species.

3. Cost-effectiveness analysis of marine restoration

If the benefits of restoration are not expressed in monetary terms alternatives can be compared by means of a cost-effectiveness analysis. A policy alternative is deemed cost-effective if, of all potential alternatives under consideration, it achieves the objective at the lowest costs. When different restoration methods achieve restoration goals at different time spans and with different degrees of certainty, a fair comparison requires that the costs are compared at similar degrees of effectiveness.

In this chapter we propose what might be a straightforward procedure to compare restoration methods with different time spans, success rates, and costs.

3.1. A procedure to compare cost-effectiveness

Suppose we need to compare restoration methods (i) with different time spans (d_i), success rates (p_i), and costs (c_i). We assume that success rates are constant, and no learning takes place. In other words, if a given method has a success rate of 50% (p_i=.5), then this probability does not change with the number of attempts. In reality, repeated lack of success can be taken as a sign that the method is probably not effective, so the estimate of p_i would usually decline with every failed attempt. Nevertheless, for reasons of explanation we ignore this possibility and assume that p_i is constant. This implies that the overall probability of success increases with the number of attempts: if one attempt has a success rate of 50%, with two attempts the probability that at least one is successful is 75%, with three it is 87.5%, and so on.

Under these assumptions the overall success rate approaches 100% with the number of attempts, but such absolute certainty would require an infinite number of attempts. Therefore, the first step is to set a target (x) for the overall success rate, and to calculate the minimum number of attempts (N_i) needed to reach that target:

$$1-(1-p_i)^{N_i} > x \Rightarrow N_i > \frac{ln(1-x_i)}{ln(1-p_i)} \tag{1}$$

Second, we need to decide when we want to have achieved our overall success rate. To enable the comparison of all restoration methods, this would have to be as long as the most time-consuming method:

$$T = \max_i\{d_i N_i\} \tag{2}$$

Third, we calculate the expected present value of the costs of each method. All methods will feature at least one attempt, but we assume that after one successful attempt the restoration activity stops. Therefore, at a 50% success rate there is a 50% probability that the second attempt is not necessary, a 75% percent that the third attempt is not necessary, and so on. In other words, the present value of the costs of a given method is equal to

$$V_i = c_i \sum_{a=0}^{N_i-1} \frac{(1-p_i)^a}{(1+r)^{T-N_i d_i + a d_i}} \tag{3}$$

3.2. Numerical example

Let's demonstrate this with the following numerical example. Suppose we have two alternatives: one cheaper method that takes one year (and can hence be repeated annually), albeit with a low probability of success; and one method that has a higher success rate but that is more expensive and time-consuming (Table 1).

	Cheap method	**Expensive method**
Success rate per trial	.3	.6
Trial duration	1 year	2 years
Cost per trial	**€ 10,000**	**€ 20,000**

Table 1. Numerical example: one cheap restoration method with a low success rate and short duration, and one expensive method with high success rate and longer duration

Suppose we want to select the method that will give us a 90% chance of restoration success. The cheap method will require at least seven attempts to meet that chance of overall success, as $1-(1-0.3)^7 \approx 0.92$. The expensive method would require only three attempts ($1-(1-0.6)^3 \approx 0.94$), but because each attempt will take two years the full sequence of attempts will take six years. Nevertheless, the cheap method takes more time so we compare the costs of the methods under the condition that each has a 90% probability of success after 7 years. The shorter time span needed for the expensive method can be taken into account by assuming that it can start a year later than the cheap method. Table 2 compares the two methods.

Year	**Cheap method**			**Expensive method**		
	Probability	Expected Current Value	Expected Present Value	Probability	Expected Current Value	Expected Present Value
1	1	€ 10,000	€ 10,000			
2	.7	€ 7,000	€ 6,667	1	€ 20,000	€ 19,048
3	.49	€ 4,900	€ 4,444			
4	.34	€ 3,430	€ 2,963	0.4	€ 8,000	€ 6,911
5	.24	€ 2,401	€ 1,975			
6	.17	€ 1,681	€ 1,317	0.16	€ 3,200	€ 2,507
7	.12	€ 1,176	€ 878			
Total			**€28,244**			**€ 28,466**

Table 2. Net present value of the two methods to meet 90% overall probability of success after 7 years

These results suggest that despite its lower probability of success, the cheap method attains the 90% overall success rate at a lower expected present value of costs than the expensive method. Figure 1 shows the dependency of this ranking on the minimum required probability of overall restoration success. We see that besides each method's costs and success rate the minimum required probability of overall success also determines which method is the most cost-effective. Note that in a few instances the expected present value of the expensive method's costs appears to decline. This happens when an increase in the required number of 'cheap' attempts allows postponement of the expensive method by one year as the time horizon is expanded.

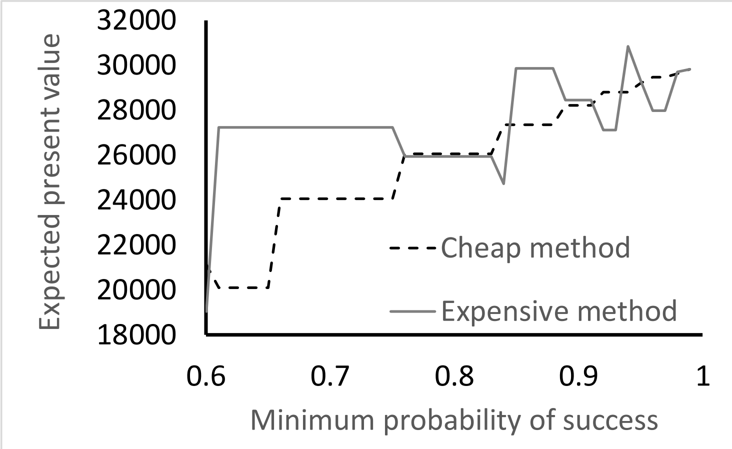

Figure 1. Expected value of the cheap method and the expensive method as a function of the required probability of restoration success

4. Discussion and Conclusions

Coastal and marine habitats are different from terrestrial habitats in a number of respects (OECD, 2016). The sea is not mankind's natural habitat, so that we need special equipment such as boats, diving gear, and drones to access them; moreover, water is much less transparent than air so that remote monitoring is also more difficult. Coastal and marine habitats are strongly interconnected with other habitats because substances, such as pollutants, and organisms, such as pathogens and predators, travel more easily through water than over land. They are more volatile and therefore less predictable than terrestrial habitats. Lastly, coastal and marine areas can have a very different ownership than terrestrial areas. Unlike land, coastal and marine areas are seldomly private property, but more likely to be public property, and because of the problems mentioned earlier with observation and monitoring, whatever property rights are there are much more difficult to enforce. They are also more likely to be used by a variety of users, albeit at different depths or times.

These differences matter for the costs of coastal and marine ecosystem restoration, particularly with respect to depth and interconnectivity. The three-dimensionality of marine habitats implies that restoration of such habitats as coral reefs requires expertise in diving, possibly at depths that require highly skilled divers. Deep-sea habitats require highly expensive equipment. Moreover, deeper habitats typically contain slower-moving species, which means that monitoring, which is already expensive due to the limited accessibility of deeper sites, needs to take place over longer time periods.

Because coastal habitats like seagrass beds are intimately linked with the rest of the water body, polluting activities hundreds of kilometres from a site can impede restoration success. Likewise, the restoration success of macroalgae like kelp depends on the control of herbivores, notably sea urchins, which in turn may depend on the management of their natural predators, such as crabs.

Although not immediately visible in the MERCES experiments, the use and ownership structure of coastal and marine areas can be much more complicated than on land. Most MERCES experiments took place in Marine Protected Areas, so that biodiversity conservation had priority over such uses as fishing and recreation. In some areas, notably the Åland Islands, ownership could be a patchwork of public areas and privately owned islands. With regard to use, because one marine location can serve different uses at different depths and different points in time, avoiding disturbance of restoration sites requires a very different approach than terrestrial restoration sites where often a fence suffices.

In all cases except for some of the deep-sea experiments, labour costs form the bulk of the expenses, even though many projects already depend heavily on volunteers. Volunteers will therefore most likely remain indispensable for marine restoration. This dependency, however, also makes restoration vulnerable to the tastes and preferences of volunteers, who might find some species or habitats more charismatic than others, or who might prefer easily accessible habitats over more remote ones. To what extent this affects the prioritization of restoration efforts is yet unknown.

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