RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

PRACTICAL ARTICLE

Optimizing canopy-forming algae conservation and restoration with a new herbivorous fish deterrent device

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The role of herbivorous fish in threatening marine forests of temperate seas has been generally overlooked. Only recently, the scientific community has highlighted that high fish herbivory can lead to regime shifts from canopy-forming algae to less complex turf communities. Here, we present an innovative herbivorous fish deterrent device (DeFish), which can be used for conservation and restoration of marine forests. Compared to most traditional fish exclusion systems, such as cages, the DeFish system does not need regular cleaning and maintenance, making it more cost-efficient. Resistance of DeFish was tested by installing prototypes at different depths in the French Riviera and in Montenegro: more than 60% of the devices endured several years without maintenance, even if most of them were slightly damaged in the exposed site in Montenegro. The efficacy of DeFish in limiting fish herbivory was tested by an exclusion experiment on *Cystoseira amentacea* in the French Riviera. In a few months, the number of fish bite marks on the seaweed was decreased, causing a consequent increase in algal length. The device here presented has been conceived for Mediterranean canopy-forming algae, but the same concept can be applied to other species vulnerable to fish herbivory, such as kelps or seagrasses. In particular, the DeFish design could be improved using more robust and biodegradable materials. Innovative engineering systems, such as DeFish, are expected to become useful tools in the conservation and restoration of marine forests, to complement other practices including active reforestation, herbivore regulation, and regular monitoring of their status.

Key words: *Cystoseira amentacea*, ecological restoration, fish, herbivore exclusion, herbivory, macroalgae, marine forests

Implications for Practice

- Fish herbivory on marine forests can lead to regime shifts, resulting in less complex turf communities, and can hinder targeted conservation actions.
- Specifically designed management-free exclusion devices, such as DeFish (fish deterrent device), can be used for controlling fish herbivory to foster recovery of degraded forests, mitigate the effects of invasive species, and increase the success of restoration actions.
- DeFish is a simple and cost-efficient method that can be made with inexpensive materials and can be used in different wave exposure conditions.
- When scaling up marine restoration actions, it can be necessary to use fish exclusion systems. DeFish-like tools, possibly built with biodegradable materials, can represent a good option to increase the success of these practices.

Introduction

Algal forests of kelps and fucoids have experienced extensive regression in many temperate ecoregions (Mineur et al. 2015; Krumhansl et al. 2016). Among the potential disturbance factors, increased temperature (Straub et al. 2019) and sedimentation rates (Schiel & Gunn 2019), urbanization (Mangialajo et al. 2008), and changes in water quality (Gorgula & Connell 2004) are some of the most critical for algal forests. In particular, in Northern Europe and the Mediterranean Sea, rocky shores have been physically altered and water quality has been reduced, causing local extinction or reduced distribution of canopy-forming species (Mineur et al. 2015; Thibaut et al. 2015).

Algal forests are also threatened by fluctuations in herbivore populations. Sea urchin outbreaks, typically caused by trophic cascade effects associated with the overfishing of top-predators (Jackson et al. 2001), induce a phase shift from kelp forests to barren grounds in the subtidal zone (Ling et al. 2015). Similarly, in the intertidal zone, limpets can control recruitment of macroalgae, pushing them to refuges where grazers are absent (Lorenzen 2007). Therefore, extensive events of algal forest depletion have been ascribed to high herbivory rates of macroinvertebrates, such as sea urchins and mollusks, considered as the

Author contributions: FG, FB, LM conceived the research; all authors performed the experiments; FG, LM analyzed data; FG, LM wrote the manuscript; all authors contributed to the editing of the manuscript.

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doi: 10.1111/rec.13143
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.13143/suppinfo

main herbivores in the subtidal and in the intertidal zone of temperate systems, respectively (Lorenzen 2007; Ling et al. 2015).

In recent years, a growing number of studies have demonstrated that both native and invasive herbivorous fish can also shape marine habitats in temperate areas (Taylor & Schiel 2010; Vergés et al. 2016; Gianni et al. 2017). Grazing by native herbivorous fish may be particularly intense on algal forests, as observed for salema (*Sarpa salpa*) in the Mediterranean (Gianni et al. 2017) and for *Odax pullus* in the South Pacific (Taylor & Schiel 2010). Fish can strongly reduce algal biomass and reproductive potential (Gianni et al. 2017), affect algal vertical distribution (Vergés et al. 2009), and entirely remove adult kelp (Taylor & Schiel 2010). In addition, the recent spread of tropical fish in many temperate areas, due to increased water temperatures, has shifted the system to deforested areas (Vergés et al. 2016).

Herbivory can be considered not only as one of the major threats to marine forest conservation, but also an obstacle to ecological restoration. For instance, fish herbivory led to the failure of some restoration efforts in the urban shores of Sydney (Campbell et al. 2014), while both fish (Gianni et al. 2018) and invertebrates (Ferrario et al. 2016) were responsible for restoration failure on artificial structures in the Mediterranean Sea. The negative effect of herbivores in restoration projects is often due to density-dependent effects and concentration of resources (Hoey & Bellwood 2011) that make target species more vulnerable. Generally, a small number of juvenile or adult seaweeds are transplanted in unvegetated areas, such as barren grounds or artificial substrates, representing a concentration of food that attracts herbivores.

Thus, the use of effective herbivore regulations is suggested for algal conservation and restoration actions, in order to maintain a high reproductive potential (Gianni et al. 2017), favor recruits' development, and accelerate population growth.

Most of the ecological studies or experimental restoration actions involving herbivore regulation have successfully excluded herbivores using cages (Sala et al. 2011; Poore et al. 2012; Tsirintanis et al. 2018). However, cages require regular cleaning to avoid fouling by epiphytes, which can completely cover the cages, and strongly reduce light intensity. This level of effort can be supported in small spatial–temporal scale studies, but it would not be feasible in large-scale restoration where there is the need for cost-efficient management-free techniques (Terawaki et al. 2001; Bennett et al. 2017).

The aim of this article is to present an innovative herbivorous fish deterrent device (DeFish), which may be used as an alternative to the traditional fish exclusion methods. The device was tested in several conditions, assessing its efficacy in terms of resistance and herbivory reduction on *Cystoseira amentacea*, a brown seaweed, forming belts in the Mediterranean shallow infralittoral fringe. Opportunities to use such a system within projects of algal forest conservation and restoration are also discussed, with some considerations on how it would be particularly suitable in wide-scale actions.

Methods

DeFish Design

The concept of the DeFish consists of vertical structures fixed into the rock, acting as a deterrent for fish (Fig. 1). DeFish are made with a 20 cm long metal threaded rod, on which three groups of five cable ties (20 cm long) are fixed parallel to the rod at different heights with another cable tie surrounding the rod. A plastic bolt is screwed onto the rod above each group of cable ties in order to keep them straight. Smaller cable ties (10 cm long) are fastened on the main cable ties in order to deter

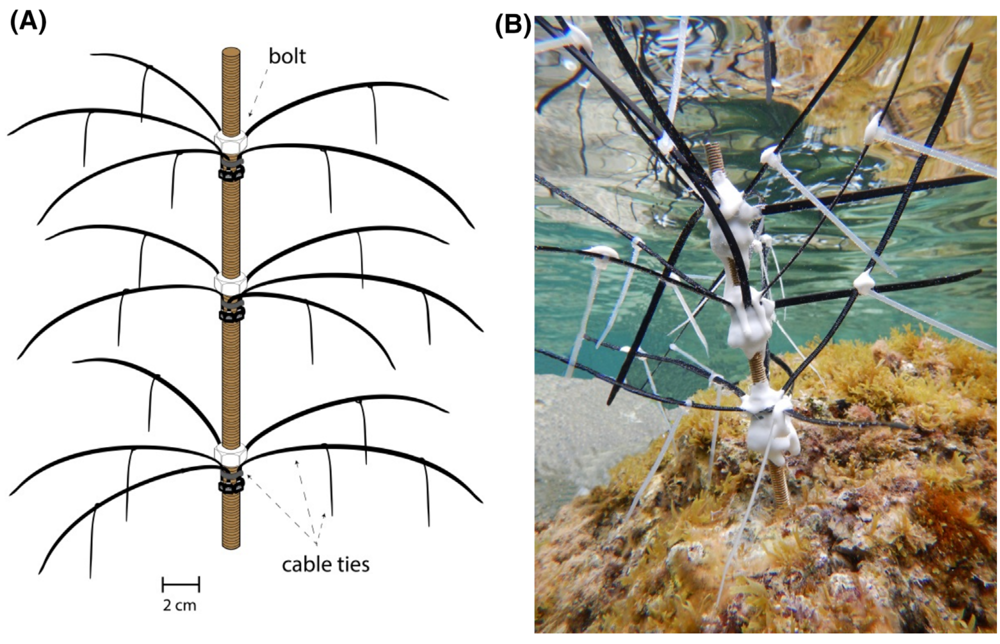

Figure 1. Schematic illustration of DeFish (A); DeFish device set up in the infralittoral fringe (B).

fish from passing through the device (Fig. 1A). Finally, a silicon glue is used to strengthen bolts and cable ties, to keep them firmly in place, and to reduce loss due to wave action (Fig. 1B). The deterrent device is fixed by screwing it to a drop-in anchor placed inside a hole drilled into the rock. It can be easily replaced when needed, and removed at the end of the experiment/restoration action.

Light penetration under the device was not directly measured, and we cannot eliminate the possibility that the DeFish device has an effect on light. However, the DeFish is made with a thin rod and a few thin cable ties, whose limited surface is not expected to shade algae considerably, especially taking into account that they are constantly in motion due to wave action.

Practical Applications

Resistance of DeFish was tested by installing five devices in June 2014 at 8 m below mean sea level (MSL) at Grotte à corail (Villefranche Bay, France), a relatively sheltered site, and 48 devices at the same depth in July 2014 in Platamuni Bay (Budva, Montenegro), exposed to waves. In February 2015, 72 supplementary devices were set up at 0.5 m below MSL at Grasseuil (Villefranche Bay), characterized by dense and healthy belts of *C. amentacea* and relatively exposed to waves. The number of devices still present in the field was quantified in summer 2018. The sites in Villefranche Bay were chosen since many *Cystoseira* species were present in the past, but they disappeared in recent decades likely due to fish herbivory together with habitat destruction (Thibaut et al. 2015). Sea urchins are not abundant in Villefranche Bay, while salema, the only strict native herbivorous fish in the NW Mediterranean Sea, are particularly abundant, reaching densities among the highest recorded in literature (Gianni et al. 2017). Turfs and Dictyotales currently characterize macroalgal communities of this Bay. The Montenegro site was chosen since it is characterized by an extensive barren ground due to date-mussel harvesting and sea urchin proliferation. The objective here was to test the exclusion of herbivorous fish in view of future restoration. Salema are not particularly abundant here, but they are present in the area and are expected to affect restoration actions.

DeFish efficacy in limiting fish herbivory on *C. amentacea* was assessed in an experiment performed in Villefranche Bay (see also Gianni et al. 2017). In spring 2014, at the beginning of the *C. amentacea* growing season, 24 plots (40 × 40 cm), spaced several meters apart, were set up at two randomly chosen sites in the infralittoral fringe, assigned to three treatments (protected, unmanipulated control, and artifact control) and replicated four times. In the protected plots, fish access was prevented by installing five DeFish devices along the sides of each plot: two in each lateral side and one in the middle of the bottom side (40 DeFish overall). In the artifact control plots, smaller DeFish devices (10 cm long) were set up in order to assess an eventual disturbance effect on *C. amentacea*. Control plots were not manipulated.

Since *C. amentacea* has a basal creeping axis with multiple vertical axes, the identification of a single individual is not often possible in the field. Therefore, algal size (maximum length of the primary branches in cm) was measured with a ruler (accuracy 1 mm) in a 12.5 cm^2 reference surface (4 cm diameter circle) together with the number of fish bite marks on both the primary and secondary *C. amentacea* branches. Fish bite marks are easily recognizable since branches are cleanly cut. Three replicates of each measurement were carried out in each plot in March, May, and June 2014. The experiment ended in June in order to avoid a confounding factor due to the high summer temperatures that cause the loss of *C. amentacea* primary ramifications.

In order to account for temporal autocorrelation in our data, algal length and number of bites were analyzed with a repeated measures analysis of variance (ANOVA), running separate analyses for the two variables. Homogeneity of variance and normality were verified with the Cochran test and Shapiro–Wilk test, respectively. Since data did not meet both assumptions, they were square root transformed prior to running the tests. In our design we considered three factors: "Treatment" (fixed factor with three levels: "Protected," "Control," "Artifact Control"), "Time" (fixed factor with three levels: March, May, June) and "Site" (random factor with two levels: Site 1 and Site 2). Post hoc analyses were conducted with Tukey's test on statistically significant terms of ANOVA. Statistical significance was set at the conventional $p < 0.05$ level. All the analyses were performed in R (R Core Team 2019).

Results

DeFish devices proved to be solid and able to endure, with no maintenance, for more than 4 years. In both subtidal sites, more than 60% of the devices (3 out of 5 in Grotte à corail and 30 out of 48 in Platamuni) were still in place in 2018. In Grotte à corail, the devices were in good condition (Fig. 2), while in Platamuni most cable ties had been lost, highlighting the need to find a more robust material (possibly biodegradable) capable of enduring high wave energy. In Grasseuil, the shallow exposed site, more than 50% of the devices (37 out of 72) were still in place with most of the cable ties at the end of the experiment.

At the beginning of the experiment aimed at testing the efficacy of DeFish, the mean number of salema bites in 12.5 cm^2 was similar in all treatments (3 ± 0.8, mean ± standard error, Fig. 3A). Afterwards, particularly in June, the mean number of bites in protected plots was lower (3.8 ± 1) than in unprotected plots (10 ± 1.1), proving that the deterrent devices were effective in limiting fish grazing (Fig. 3A). These results were confirmed by the analysis of variance: the interaction between the factors "Time" and "Treatment" was significant (p value <0.0001) and the pairwise comparisons showed that protected treatments had significantly lower number of bites than the unprotected treatments in May and June, but not in March. In the three sampling times, artifact and control treatments were not significantly different (Tables S1 & S2).

In agreement with these results, an opposite trend was observed concerning the algal size. In March, ramifications were small in all treatments (mean 4.6 cm ± 0.4, Fig. 3B), according to the seasonal pattern of *C. amentacea* growth. After 3 months, the deterrent devices effectively allowed the growth of algae in

Figure 2. Set up of DeFish in the subtidal zone of Villefranche Bay. Left: June 2014; right: September 2018.

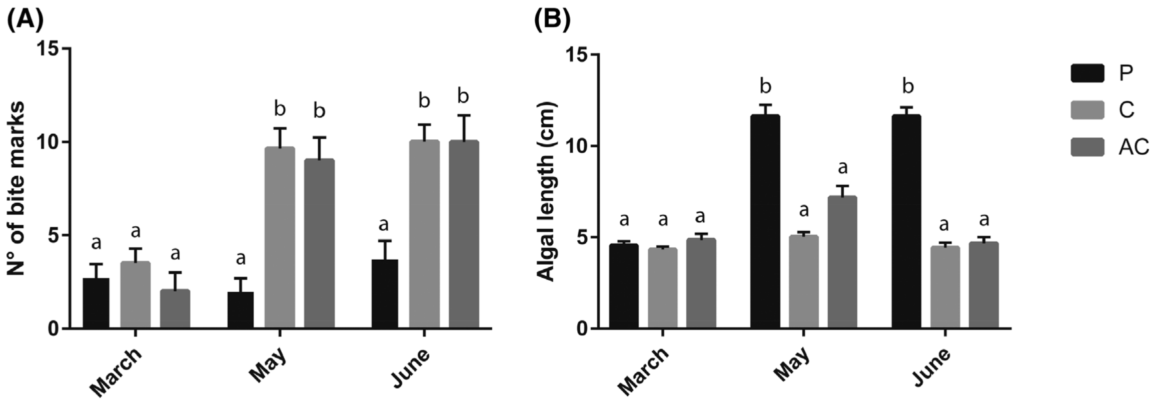

Figure 3. (A) Mean number of fish bites on 12.5 cm^{-2} with +SE bars in all sites (n = 16); (B) Mean algal size (cm) on 12.5 cm^{-2} with +SE bars in all sites (n = 16). P: protected, (C) control, AC: artifact control treatment. Letters above the bars indicate significant differences of ANOVA's pairwise tests (Tables S1).

the protected plots: the maximal algal length was equal to 27 cm and the mean was 11.6 ± 1 cm. In contrast, in the unprotected plots, *C. amentacea* individuals were heavily grazed, with a mean value of 4.5 ± 0.7 cm (Fig. 3B). Again, the interaction "Time-Treatment" was statistically significant in the analysis of variance (p value <0.0001) and pairwise comparisons showed that the length of ramifications was not statistically different in March, while in May and June, ramifications were significantly longer in the protected plots compared to the control and artifact plots. Unprotected treatments were never statistically different from each other (Tables S3 & S4).

Discussion

Scientists, together with decision makers and managers, have recently turned their attention to the strategies needed to halt the extensive regression of marine forests documented in several temperate areas (Mineur et al. 2015; Krumhansl et al. 2016; Unsworth et al. 2019). Recent studies show that herbivorous fish may also represent a major threat for marine forests (Taylor & Schiel 2010; Ferrario et al. 2016; Vergés et al. 2016; Gianni et al. 2017, 2018) and suggest that their potential role, in hindering reforestation actions, have to be considered in restoration plans.

The innovative herbivorous DeFish device presented in this study was conceived for reducing fish herbivory pressure on marine forests. Our results proved that DeFish is effective in protecting canopy-forming algae from grazing, allowing their complete development and reproduction. The prototypes lasted several years in the field, demonstrating their resistance to environmental factors and their potential use in long-term studies. DeFish has several advantages compared to the traditional fish exclusion systems, such as cages or fishing nets, generally used in restoration or ecological experiments (Poore et al. 2012). Once the setup is prepared, the devices can be fixed and removed quickly, so they can be easily replaced if needed and removed at the end of the experiment/restoration action. Exclusion cages need regular cleaning from epiphytes (e.g. Tsirintanis et al. 2018), in order to avoid light reduction, potentially affecting the target species. The DeFish device does not cover algal communities considerably; hence, it is not expected to reduce light and does not require any cleaning. Although light under the devices was not directly measured in this study, the results of our experiments confirm that an eventual light decrease due to the DeFish would have a lower effect than the herbivore impact on algal growth, as also demonstrated by the absence of differences between the artifact control and control treatments. Only a few epiphytes were observed growing on the cable ties (Fig. S1) which are unlikely to influence light penetration at a level that could affect the normal algal development. These characteristics make the DeFish a more interesting system than cages. An attempt of cost comparison of cages and DeFish, on a 1 year long setup, seems to prove that the cages are three times more expensive than DeFish (Table S5). Conservation and restoration actions have to be simple and cost-efficient: for this reason, the use of DeFish-like systems should be preferred to cages.

Recent studies showed the considerable consequences that ocean pollution by plastic debris has on marine ecosystems and on public health (Eriksen et al. 2014 and references therein). DeFish prototypes proposed here were partly made of plastic for practical reasons, and we think that the potential advances that such a device can have in scaling up restoration actions compensate the limited plastic pollution from our trial. However, we suggest that in future applications, efforts have to be made to find alternative solutions to plastic materials, in order to prevent pollution in the sea and avoid generating a negative social perception of restoration actions. Innovative and biodegradable materials such as cellulose, starch, lactic acid, or different biodegradable polymers that have been recently tested for building fishing nets and containers or other similar devices (Scannavino et al. 2014) could be used. Also natural products such as bamboo or clay (De La Fuente et al. 2019) could be considered. The use of three-dimensional printers in collaboration with engineering companies at the industrial level would optimize production of an eco-friendly DeFish device.

DeFish devices can be useful in ecological studies when experiments involve regulating fish herbivory (Gianni et al. 2018), but also in conservation actions, in order to protect healthy forests from outbreaks of herbivore populations and/or to foster natural recovery of degraded forests. Indeed, high fish density can be particularly critical for marine forests causing a regime shift to less complex turf communities, as observed in many temperate seas after the spread of tropical fish (Vergés et al. 2016). In addition, recovery processes in marine forests are complex and herbivores can hamper or slow down the natural development (Piazzi et al. 2016). In the framework of restoration, the first steps of an action establish a population of the target species that is often characterized by lower density or smaller patches than the natural populations. Herbivores are attracted by the new available resource and consume it rapidly (Campbell et al. 2014), especially in forestation projects aimed at increasing the ecological value of artificial structures, such as enrockments and harbor seawalls (Gianni et al. 2013). Fish herbivory pressure on artificial structures can be very high and its effects on forestation actions are well known (Ferrario et al. 2016; Gianni et al. 2018). In these circumstances, the use of deterrent devices would increase the likelihood of success of such actions. New artificial structures should be conceived in order to facilitate deterrent device setup, for instance with preinstalled drop-in anchors.

A restoration action can only be considered successful when forest populations are self-maintaining, resilient to perturbations such as herbivory and display a continuity in terms of structure, functioning, and biological composition (Jacob et al. 2018). Also, variables suggested by early warning indicators of population collapse studies could be considered (i.e. variance, Benedetti-Cecchi et al. 2015; recovery length, Rindi et al. 2017) together with socioeconomic attributes (Wortley et al. 2013) to assess the status of the restored forests. When the restoration is considered successful, the devices can be removed, and a regular monitoring of the forests should be performed.

It is worth noting that DeFish was designed to protect Mediterranean algal species from fish herbivory, but it could be easily modified and applied to protect other species, such as kelps or seagrasses, whose regression and management needs are widely recognized (Krumhansl et al. 2016; Unsworth et al. 2019).

The declining trend of canopy-forming algae is not expected to be reversed in the future with the increase of cumulated impacts and climate change effects. Ecologically important and sensitive habitats such as algal forests should become a conservation priority, and it is extremely urgent to integrate actions for the conservation and restoration of marine vegetation in environmental management plans. Where marine vegetation has already suffered an extensive decrease, ecological restoration should be planned, including the assessment of locally existing threats, such as herbivore density or the spread of invasive species (Gianni et al. 2013).

In conclusion, recent studies show that fish herbivory from both native and invasive species may represent a threat for marine forests of brown seaweeds in temperate areas (Campbell et al. 2014; Vitelli et al. 2015; Vergés et al. 2016; Gianni et al. 2017). Active actions are extremely urgent and low-cost simple conservation strategies should be given priority in order to decrease the costs of protecting marine habitats (Jacob et al. 2018). DeFish-like devices may represent a good tool to be considered to complement other practices, such as active reforestation (Verdura et al. 2018; De La Fuente et al. 2019), herbivore regulation, and regular monitoring of marine forests.

Acknowledgments

This study was funded under the EU-FP7 (MMMPA 290056 and COCONET 287844), by the French government, through the UCAJEDI Investments in the Future project managed by the National Research Agency with the reference number ANR-15-IDEX-01, and under the EMFF program (AFRIMED, EASME/EMFF/2017/1.2.1.12/S4/01/SI2.789059). Authors wish to thank the participants who contributed to the field activities, including Daniela Catania and the IMEV divers (G. de Liège and D. Luquet). Authors are particularly grateful to Alexandre Meinesz for the fruitful exchanges on the DeFish design and the partners of the projects cited above for the enriching discussions. Many thanks to the anonymous referees, whose comments helped to improve the manuscript. The authors declare they have no conflict of interest.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Epiphytes on DeFish devices. DeFish in Villefranche Bay at 8 m depth, 5 years after installation.

Table S1. Repeated measures ANOVA on the number of bites. Significant *p* values are highlighted with asterisks.

Table S2. Post hoc comparisons (Tukey's test) on the statistically significant terms of the repeated measures ANOVA run on the number of bites.
Table S3. Repeated measures ANOVA on algal length. Significant *p* values are highlighted with asterisks.
Table S4. Post-hoc comparisons (Tukey's test) on the statistically significant terms of the repeated measures ANOVA run on algal length.
Table S5. Cost evaluation for construction, installation, and maintenance of a complete exclusion cage compared to five DeFish devices needed to protect a plot of 40 cm × 40 cm for a year.

Coordinating Editor: Susan Bell

Received: 18 April, 2019; First decision: 28 June, 2019; Revised: 18 February, 2020; Accepted: 21 February, 2020;