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Assessment of an alternative *Pinctada margaritifera* spat collector in French Polynesia

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ABSTRACT

Plastic waste in the oceans is a growing concern due to its size diversity, its ubiquitous nature and its impact on both marine organisms and ecosystems. While threatened by this marine plastic litter, the aquaculture industries also represent one of its major sources. In French Polynesia, black-lip pearl oyster (*Pinctada margaritifera*) farming is no exception. Wild spat collection has been described as a source of pollution because of the numerous particularly fragile and brittle shade-mesh plastic collectors used locally and often mismanaged when no longer usable. Thus, with the aim of helping to reduce this pollution, the present study is focused on the assessment of reusable plate collector as a potential alternative. We tested, using an *in situ* approach, the influence of the collecting surface position (*i.e.* horizontal *vs* vertical), plate color (*i.e.* black *vs* orange) and density (*i.e.* 25 plates *vs* 50 plates) on *Pinctada margaritifera* and *Pinctada maculata* spat settlement. Our results showed that 50-plates collectors, whatever their color and position, were more efficient to collect both kinds of spat than shade-mesh collectors ($P < 0.0001$). They also induced a higher number of *Pinctada margaritifera* spat than on the 25-plates collection device although there was no significant difference in numbers of *Pinctada maculata* spat ($P < 0.0001$). However, every type of plate collector presented a decreased mean length of the spat collected ($P < 0.0001$) compared to the shade-mesh collector. Furthermore, horizontal positioning of the collecting surface greatly improved the spat numbers on plate collectors ($P < 0.0001$) although there was no effect on shade-mesh collectors ($P > 0.05$). Finally, our results indicated that, among all the devices tested, the black horizontal 50-plates collector was the most efficient to collect spat and particularly *Pinctada margaritifera*. These first findings thus tend to suggest that these black re-usable plate collectors could be an efficient alternative to the currently used shade-mesh collectors.

1. Introduction

With worldwide plastic production of 359 million tons in 2018 (PlasticsEurope, 2019), the management of end-of-life plastics is one of the biggest environmental concerns of our time. In the best-case scenario, after end of use, plastic waste is collected by local services to be recycled or incinerated for energy recovery purposes (PlasticsEurope, 2019), and in the worst case, is littered in the environment whether on land or in the ocean (Andrady, 2004; Geyer et al., 2017). Plastics represent 60–80 % of marine debris (Derraik, 2002; Lebreton et al., 2018), originating either in land sources (70–80 %) or sea-based sources (20–30 %) (Andrady, 2011). Ocean contamination is therefore a major issue, with about 4.8–12.7 Mt of plastic waste entering the oceans in 2010 (Jambeck et al., 2015), especially since it cannot degrade completely due to its chemical composition (Gregory and Andrady, 2004). Instead, several factors such as solar radiation, thermal oxidation or mechanical actions break the chemical bonds between plastic components (Gregory and Andrady, 2004), resulting in plastic fragments of all sizes, notably microplastics (<5 mm). Hard to remove, microplastics are abundant and present everywhere in the oceans (Barnes et al., 2009; Eriksen et al., 2014; Jambeck et al., 2015).

Size diversity and the ubiquitous nature of plastic marine debris make it available to a wide range of marine organisms, harming them chemically (Teuten et al., 2009; Le Bihanic et al., 2020) and/or physically (Gregory and Andrady, 2004). Moreover, marine ecosystems can also be affected indirectly, as demonstrated by Katsanevakis et al. (2007) showing that an addition of plastic litter on the sea-bed can induce a deviation in the structural community of benthos megafauna

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and its composition. Barboza et al. (2019) also indicated in their review that plastics could impact predator-prey relationships, smother the sea-floor (*i.e.* benthos community), disturb carbon cycling and transport invasive species, pollutants and pathogens. Furthermore, for aquaculture industries another concern is the transfer of these microplastics between trophic levels toward human (*i.e.* final consumer) as underlined by Van Cauwenberghe and Janssen (2014). Yet, while being threatened by marine plastic litter, aquaculture remains one of its sea-based sources as aquaculture materials are mainly made from plastic. In their study, Lebreton et al. (2018) showed that 1.3 % of the plastic litter found in the Great Pacific Garbage Patch, located in the North Pacific Subtropical Gyre, derived from aquaculture. Another study also showed that a large proportion of the floating marine debris they studied in Chilean coastal zones came from sea-based aquaculture (Hinojosa and Thiel, 2009). Likewise, Feng et al. (2020) in China demonstrated that the macro-algae farming industry released 1037 tons of plastics in the ocean and that can be a source of microplastics.

In French Polynesia (FP), local communities, scientists and authorities have been concerned for several years by waste production, recorded as around 147 000 tons in 2012 (Murzilli et al., 2012). On islands, waste management is a sensitive issue because of the small land area available, the lack of capital and financing options, the significant operational costs of waste management (transportation, labour; *etc.*) and the vulnerability of the environment to extreme climatic events (Eckelman et al., 2014). This is particularly the case for atolls and remote islands in FP, where those problems are exacerbated. Thus, it is essential for islanders to reduce, or at least better control, their waste production and to optimize waste management systems. This issue is of particular concern for the pearl-farming industry operating in 23 remote islands mainly located in the Tuamotu-Gambier archipelago. In these islands, the waste management system is basic, limited to a collection system for household and green waste. No industrial waste treatment system exists. Yet, like most aquaculture industries, pearl-farming uses plastic materials to rear the oysters, such as plastic ropes, nylon, shade-mesh, buoys and plastic grating. However, there have been very few studies on waste production in the pearl industry in Polynesian lagoons (Andréfouët et al., 2014; Gaertner-Mazouni et al., 2018). A first estimate of the annual waste production of a farm of 15 ha using 15 collecting lines in Gambier islands evidenced that around 2 tons of waste can be produced annually (Gaertner-Mazouni and Rodriguez, 2016). These authors highlighted that some stages during pearl production, such as spat collection, contribute significantly to waste production.

Spat collection constitutes the first stage of production in the pearl industry in French Polynesia, representing 9464 collecting lines officially listed and deployed in lagoons (personal communication, DRM, 2019). A collecting line consists in a 200 m plastic rope (diameter > 16 mm) with 600 settlement supports (so-called 'spat collectors') on which larvae will attach. Spat collectors used in French Polynesia are made of black plastic shade-mesh strip sewn accordion-style on a plastic rope (Haws and Ellis, 2000), referred to as 'shade-mesh'. However, according to Gaertner-Mazouni et al. (2018), they are particularly brittle and fragile with a three-year life span. Moreover, inefficient collecting lines are sometimes abandoned due to the cost of retrieval compared to what they yield. Either way, in-use, broken or abandoned collectors will stay in the lagoon for years and eventually start to fragment or leach like every plastic, as suggested by Andréfouët et al. (2014), their brittleness probably reinforcing this phenomenon.

In order to investigate this emerging threat, Gardon et al. (2018) exposed *Pinctada margaritifera* to laboratory microbeads of polystyrene, in a preliminary study, and showed that its reproduction activity was affected. Furthermore, these authors recently assessed the toxicity of leachates of new and aged plastic pearl-farming materials (synthetic ropes and shade-mesh spat collectors) used in French Polynesia on the embryo-larval development of *Pinctada margaritifera*. Chemicals such as phthalates were found to leach from those plastic gears and toxicity was proven on embryos after a 48 h exposure at the smallest dose tested of 0.01 $g.L^{-1}$ (Gardon et al., 2020). Therefore, to ensure pearl-farming sustainability, there is an urgent need to replace these shade-mesh collectors by materials that are more resistant and environmentally-friendly.

In the literature, several settlement supports have been studied on bivalve species, either natural (*e.g.* coconut husks, bundles of various plants) or artificial such as tiles and plastic supports. However, none of the supports tested for *P. margaritifera* spat collection seemed to be more efficient than the shade-mesh collector (Haws and Ellis, 2000; Arini and Jaya, 2011; Ishengoma et al., 2011; Libini et al., 2013). According to the authors, numerous parameters have to be taken into account when choosing a collector for targeted species to stimulate its spat settlement. They showed that the shape, texture, color and position of the collector and its collecting surfaces could have an incidence on settlement efficiency, depending on the oyster species (Galtsoff, 1964; Taylor et al., 1998; Saucedo et al., 2005; Su et al., 2007; Arini and Jaya, 2011; Wang et al., 2017). It was reported that *Pinctada margaritifera* spat settle preferentially on rigid rough dark materials due to a negative phototaxy of larvae (Gervis and Sims, 1992; Friedman et al., 1998; Ehteshami et al., 2011; Ishengoma et al., 2011; Libini et al., 2013).

Among currently available collecting supports, grooved plastic plate collectors, referred to as 'plates', which are commonly used for *Crassostrea gigas* spat collection in France, seemed to be an interesting alternative to shade-mesh for various reasons. Firstly, they are made of rough semi-rigid plastic, reusable, that can be positioned either horizontally or vertically. Secondly, they are available in different colors, notably black, and are successfully used for the collection of bivalve spat (Ferra, 2008; Lescroart, 2017). Thirdly, these collectors are already available in French Polynesia for an average cost of 18.96 € (tax incl.) for a 50-plate collector.

Another point to highlight is that, even if it is still plastic, the plate collector could be a more environmental friendly alternative than shade-mesh collectors which have low longevity and release toxic chemicals and MP in the environment in the very short term (Gardon et al., 2020). With the shape of a round plate 1.7 mm thick and 150 mm wide, compared to the thin filament of 3 mm width of the shade-mesh, the plate collector is more resistant, notably to mechanical erosion and photo-degradation. These properties confer on plate collectors a life-span from 3 to 6 years (up to 10 years for the most durable ones) when they are used for collection of *Crassostrea gigas* spat *i.e.* subjected to the tide cycle and exposed to direct UV radiation (Ferra, 2008; Lescroart, 2017). Thus, they are reusable and their longevity could be even greater in French Polynesia as collection of *P. margaritifera* spat consists in continuous immersion of the collector at 5−6 m depth during 1–2 years. Moreover, no chemical toxicity of this material has been reported to our knowledge.

Therefore, the aim of this study was to determine whether plates could replace shade-mesh collectors and what would be the best conditions to do so. For this purpose, we designed a comparative study of the collecting efficiency of plate and shade-mesh collectors on *Pinctada margaritifera* spat settlement, by performing an *in situ* experiment. We assessed in particular the influence of the type of collector, collecting surface position, color and density of plates on spat settlement. To complete our study, a section discussing the cost and environmental impact of the best alternative is provided at the end of the study.

2. Material & methods

2.1. Experimental site

This study took place in the lagoon of Takapoto (145″20′W, 14′70′S) in French Polynesia between November 2018 and March 2019. This lagoon is defined as a closed environment characterized by poor water renewal due to the lack of shipping channels except narrow ones (Andréfouët et al., 2001). Water temperatures range from 26 to 30 °C (Ricard et al., 1979) and salinity from 38 to 41 PSU (Rougerie, 1979;

Pagès and Prasil, 2002).

2.2. Spat collectors

This experiment compared shade-mesh collectors and plate collectors. The shade-mesh collectors were composed of black plastic shade-mesh strip 8 cm in width, corresponding to a collecting surface of 1.28 m^2 (60 g of plastic/m^2), sewn accordion-style on a one meter plastic rope with a diameter of 6 mm, currently used by Polynesian pearl farmers. Plate collectors were made of grooved plastic plates 15 cm in width on a 1.2 m rigid PVC tube separated by a space of 2.5 or 5 cm with a collecting surface of 0.025 m^2/plate. Along with this comparison, the influence on settlement of the position of the collecting surface (*i.e.* horizontal *vs* vertical), plate color (*i.e.* black *vs* orange) and plate density for one tube was studied. Two densities were tested: 25 plates (half density plates, HDP) *vs* 50 plates (normal density plates, NDP), corresponding respectively to an average collecting surface area of 0.625 m^2 and 1.25 m^2.

In total, seven collecting devices were tested with 30 replicates each and attached alternately, every 40 cm, on a main rope with buoys to avoid a possible collecting zone effect (Fig. 1). The vertical orange plates device had only 12 replicates as it had been tested previously and did not yield consistent results (unpublished), only 42 orange plate collectors being available. They were placed at the beginning, middle and end of the line to avoid any zone effect.

2.3. Collector management and data collection

The main rope with the collectors was immersed in the lagoon, next to the collecting lines of pearl-farmers, at 6 m depth, which is the usual practice in French Polynesia. It was maintained at this depth and location by means of buoys and mooring posts. To follow the progression of the collectors during the experiment, the collecting line was checked every two to four weeks and depth was adjusted (adding buoys) if necessary. After four months (123 days), the collectors were retrieved. Monitoring was performed from photo and visual observations of each device. For each collector, *Pinctada margaritifera* and *Pinctada maculata* spat were removed and counted. Afterwards, the total weight of *P. margaritifera* and *P. maculata* spat.collector^{-1} was measured. For each species a mean weight per collector was calculated. Moreover, some *P. margaritifera* spat were randomly selected to be measured. Our sampling effort was adapted to spat number as a maximum of 349 individuals.collector^{-1} could be found: for collectors with less than 100 spat: all individuals were measured, between 100 and 200 spat: half of them, more than 200: a quarter of them. To do so, they were put on a millimeter paper, photographed and then length was measured by image analysis with Image J ® (Schindelin et al., 2012).

2.4. Statistical analysis

In this study, the efficiency of one collecting device was represented by the average density of spat of *P. margaritifera* and *P. maculata* settled on the structure, after four months of immersion. It was calculated by

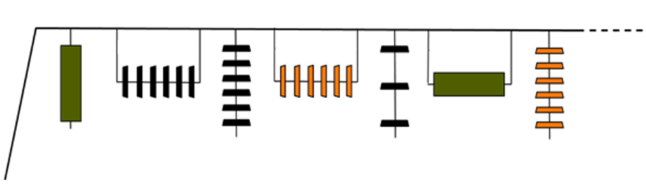

Fig. 1. Scheme of the first alternation of the seven devices on the main rope, from left to right : 1- vertical shade-mesh, 2- vertical black plates, 3- horizontal black plates, 4- vertical orange plates, 5- half density black plates, 6- horizontal shade-mesh, 7- horizontal orange plates. This pattern was repeated 30 times along the 200 m rope.

the following equation:

$$\overline{D_y}\ (unit.cm^{-2}) = \frac{1}{n_y \times S_y} \sum_{i=1}^{n_y} Ns_i$$

Where $\overline{D}$ = Average density of spat (unit. cm^{-2}); Ns = Number of spat, S_y = Surface area of collection (cm^2), y = *1, 2, 3, …* yth device, i = *1, 2, 3, …* *n*th replicate collector and n = number of collectors.

Spat density, average biometry traits and individual length were first analyzed using a one-way Anova testing the difference between devices. Prior to this analysis, normality of the model residuals was verified using Shapiro test and the homoscedasticity of variances was tested using Levene test. These analyses confirmed that the difference between the devices used in our experiment was significant (one-way Anova, $P < 0.0001$). Thus, a three-way Anova was performed testing incidence of the type, color and position and interactions between those factors. When interactions (Anova, $P > 0.05$) were found between different explanatory variables, those effects were tested independently with Student *t*-test; otherwise, for multiple comparisons, Tukey's Honestly Significant Differences test was used. Moreover, to assess plates density effect on those variables (*i.e.* Spat density, average biometry traits and individual length) a comparison was made between HDP (black and horizontal) and black horizontal NDP with *t*-test. HDP was compared to shade-mesh collector as well to see if it could be a potential alternative using *t*-test. Finally, Kendall's correlation was determined between mean length and weight of spat per device and was 0.7229 ($P < 0.0001$). Thus, we will present in this study only the results of mean spat length, as it was individual measures, *i.e.* statistics took into account individual variability, and the differences between devices were similar for the two variables. The results were considered as significant when the P-Value was lower than 0.05.

3. Results

A strong homogeneity was recorded in our observations, for each tested device. All spat (*P. margaritifera* and *P. maculata*) on shade-mesh were mainly located in the center of the mesh whatever its position. Conversely, for plate collectors, spat did not settle in the same place for each device. On normal density plates (NDP) collectors, *Pinctada maculata* spat were mainly located on the edges and *P. margaritifera* in the middle (Fig. 2A). Spat were mainly on the concave side. On half density plate (HDP) collectors, all spat on the convex side were located in the center, close to the PVC tube, and all over the concave side (Fig. 2B). Fig. 2C. represents a picture of a vertical plate as it was set in the sea. It shows that all spat were concentrated on the side less exposed to the sunlight compared to the horizontal plates (Fig. 2A).

Mean density of spat of *Pinctada margaritifera* is shown in Fig. 3. Shade-mesh collectors collected less than the others regardless of collecting surface position and plate color with a mean of 0.0012 (± 0.0006) to 0.0015 (± 0.0007) spat. cm^{-2} (T-test, $P < 0.001$). Black NDP also significantly recruited less in vertical position compared to orange NDP with 0.0030 (± 0.0014) and 0.0045 (± 0.0017) spat. cm^{-2} respectively (T-test, $P = 0.0049$). However, in horizontal position both NDP collectors recruited significantly more spat than in vertical position (Tukey, $P < 0.0001$), black NDP presenting the significantly highest mean of 0.0147 (± 0.0049) spat.cm^{-2} (T-test, $P = 0.0031$) (Fig. 3). Yet position did not significantly affect shade-mesh recruitment (T-test, $P = 0.0896$). For HDP, the recruitment was significantly lower than NDP with only 0.0033 (± 0.0014) spat.cm^{-2} (Kruskal Wallis, $P < 0.0001$) (Fig. 3, right). Nonetheless, HDP still collected significantly more spat than shade-mesh collectors (T-test, $P < 0.0001$).

No differences of density of *Pinctada maculata* were found when color or position were compared (Anova, $P > 0.05$). However, it was significantly lower for shade-mesh type (Anova, $P < 0.0001$), with 0.0182 (± 0.0115) spat.cm^{-2} than for plate collectors. Likewise, it was significantly lower for NDP than for HDP with 0.1283 (± 0.0288) and 0.2563

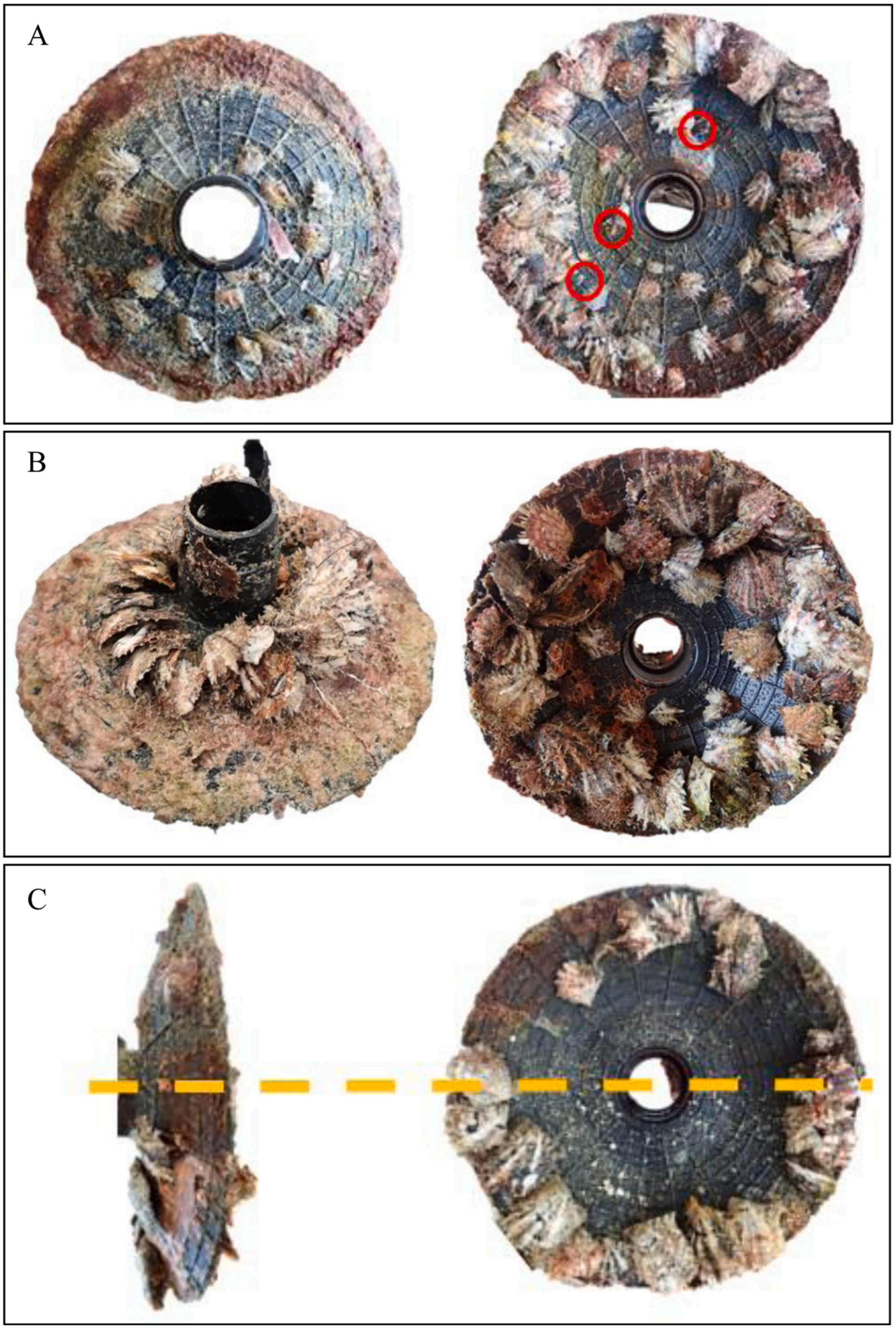

Fig. 2. From left to right pictures of (A) Convex (left) and concave horizontal black NDP, (B) Convex and concave horizontal black HDP and (C) Convex (left) and concave vertical black plates before retrieving spat. Spat circled in red are *Pinctada margaritifera* oysters, others are *P. maculata.* The part of the plate above the orange dashed line in C is the one closest to the surface (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

($\pm$ 0.062) spat. cm^{-2} respectively (Kruskal Wallis, $P < 0.0001$) (Fig. 4).

Furthermore, mean length of *Pinctada margaritifera* spat was significantly higher for shade-mesh collectors with 16.74 ($\pm$ 6.08) mm than the plates type with 10.54 ($\pm$ 3.49) mm (Anova, $P < 0.0001$) (Fig. 5). No other significant length differences were shown between the other devices (Anova, $P > 0.05$).

4. Discussion

In this study, despite the variability of *Pinctada margaritifera* spat density between collectors of the same device, our results showed that spats were collected more efficiently when using black horizontal plates. They also highlighted the influence of the type of collector, its position and its color. Many studies have demonstrated that spat of various oyster species such as *Ostrea edulis*, *Pinctada martensii* and *Pinctada maxima* preferentially settle on rigid support with a rough and textured surface (Galtsoff, 1964; Pearce and Bourget, 1996; Taylor et al., 1998; Filgueira et al., 2007; Su et al., 2007; Wang et al., 2017). Our results are also consistent with previous studies performed on *Pinctada margaritifera* spat settlement (Gervis and Sims, 1992; Ehteshami et al., 2011; Ishengoma et al., 2011; Libini et al., 2013). Even if both collectors have a rough or filamentous texture, plates are much more rigid than shade-mesh. It may have helped spat to get a firmer grip on the collectors as was suggested by Ehteshami et al. (2011), hypothesising that it

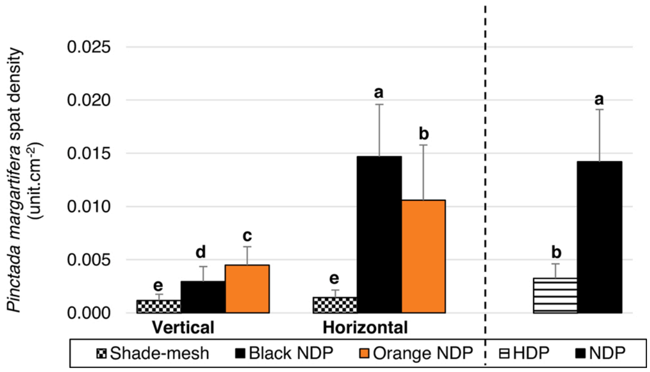

Fig. 3. Mean *Pinctada margaritifera* spat density (number of spats per cm^2) for shade-mesh, orange NDP and black NDP device in function of the position of the collecting surface (left of the dashed line) and for black NDP and HDP (right of the dashed line). Error bars denote standard deviations. Within one graphic, devices with different letters show significant differences (P < 0.05).

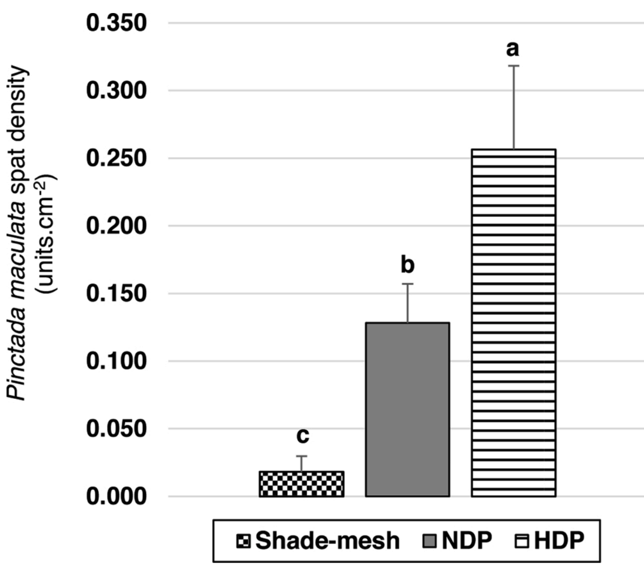

Fig. 4. Mean density of *Pinctada maculata* spat in function of type and density of collector. Error bars denote standard deviations. Devices with different letters show significant differences (P < 0.05).

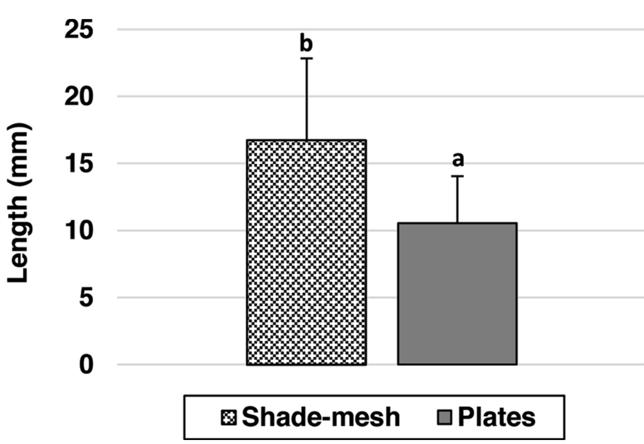

Fig. 5. Mean *Pinctada margaritifera* length in millimeters per type of collector at the end of the experiment. Error bars denote standard deviations. Devices with different letters show significant differences (P < 0.05, Anova).

would allow spat to place its byssal threads in a radial pattern providing a stronger attachment compared to filament. Furthermore, the improvement of collecting efficiency with the plate collector compared to shade-mesh could also be due to better protection against predation due to its rigidity and conic shape. Moreover, the incidence of a specific water flow on settlement has been underlined by various studies (Arakawa, 1990; Pearce and Bourget, 1996; Taylor et al., 1998; De La Roche et al., 2005). These two characteristics may have induced a water flow that facilitated the access of spat to settlement support, compared to filamentous shape, leading to better settlement efficiency as well.

In addition, our study supported the hypothesis of negative phototaxis of *Pinctada margaritifera* spat previously described by different authors for various oyster species (Gervis and Sims, 1992; Holliday, 1996; Taylor et al., 1998; Saucedo et al., 2005; Su et al., 2007; Ehteshami et al., 2011; Wang et al., 2017). These authors pointed out that spat preferred to settle on dark color collectors and on substrate less exposed to light. In our experiment, we observed a higher settlement rate with the horizontal position of plates which provides more shade than the vertical position. We also observed that, in this position, spat mainly colonized the convex underside of the plates which is less exposed to light than concave side. Similarly, spat on vertical plates were also mainly located on the part less exposed to light as shown in the photos of collectors. Moreover, spat were principally settled next to the PVC tube on the concave side. Thus, our results seem consistent with a high photo-sensitivity of *P. margaritifera* spat. On the other hand, as described by Galtsoff (1964) and Taylor et al. (1998), the two positions of plates induced a water flow dissimilarity that could also be responsible for the difference of spat recruitment between them. Conversely, position did not significantly affect collection efficiency of the shade-mesh collector. One assumption might be that space between plastic filaments of the shade-mesh does not significantly change water flow between positions and lets the light pass through so no part of it is more shaded than another.

Furthermore, different studies indicated that the color of collecting substrate has an influence on settlement of larvae of *Pinctada spp.* including *Pinctada margaritifera* (Taylor et al., 1998; Saucedo et al., 2005; Su et al., 2007; Arini and Jaya, 2011; Libini et al., 2013; Wang et al., 2017). They suggested that black or dark colored substrates seem to be preferred by larvae for settlement. In our case, we cannot draw any firm conclusions on color effect as it interacted directly with position presenting opposite results when comparing the number of spat on orange and black plates (*i.e.* light or dark color) for the two positions. In vertical position, orange plates had significantly higher density of settled *Pinctada margaritifera* spat than black ones and vice-versa when horizontal. Libini et al. (2013) also showed that black collectors collected more spat than others. However, yellow ones also collected more than green or brown collectors, which are darker. Moreover, Ompi et al. (2018) also studied settlement of *Pinctada maxima* spat on different substrates and did not find any effect of color. This demonstrates how important interactions between factors are, notably, depending on the type of collector, its position and color that should be considered with regard to the shade they will provide. In our study, for the plate collector, position seemed to be the most important factor to attract *P. margaritifera* spat compared to color, as it led to higher number of settled spat per collector when plates were horizontal, regardless of color.

Our experiment also demonstrated that increasing space between plates, by removing one out of two, significantly reduced the density of *Pinctada margaritifera* spat collected. The observed difference could be explained by a rise in predation activity due to the increased space. In these atolls, predators are various species of gastropods, crabs, worms and fishes (Coeroli et al., 1984; Gervis and Sims, 1992; Friedman et al., 1998; Humphrey, 2008; Kishore et al., 2018). However, in Takapoto lagoon, Coeroli et al. (1984) pointed out that fishes (Balistidae and Tetraodontidae) constitute the main pearl-oyster predators. We may assume that a 2.5 cm space was too small to leave them access to

P. margaritifera spat, particularly with *Pinctada maculata* on the edges of plates, as shown in the photos, but that a 5 cm space was sufficient. Moreover, increasing space may have also led to a stronger water flow that could have made it harder for *P. margaritifera* larvae to settle (Galtsoff, 1964; Arakawa, 1990; Taylor et al., 1998; De La Roche et al., 2005). However, our results showed that increasing space between plates also increased two-fold the density of *Pinctada maculata* spat collected compared to NDP. Thus, the difference of density of *P. margaritifera* could also be due to more intensive competition for space and food between species, *P. maculata* settling on nearly the whole surface area of HDP and not leaving any space for *P. margaritifera* to settle.

Furthermore, NDP also seemed to be more efficient for the collection of *Pinctada maculata* spat than the shade-mesh collector. There was 6 times more spat on them than on the shade-mesh collector, which means that this shape seems more suitable for their settlement. Friedman and Bell (1996) also studied the effect of different substrata on settlement of *P. margaritifera* and *P. maculata* in Solomon Islands. One of the collectors tested was the black shade-mesh collector and the other was black plastic sheeting (0.5 mm thick) threaded on a rope, and both were either 'bagged' or 'open'. As in our study, their results showed that spat of both species were collected together with a positive Pearson correlation of 0.62 between the number of spat of *P. margaritifera* and *P. maculata*. However, *P. margaritifera* preferred to settle on shade-mesh collectors without distinction of whether settlement supports were bagged or open whereas *P. maculata* spat preferred to settle on open collectors regardless of the collector material. Their hypothesis was that these spat seemed to search for maximum water exchange. They explained that the looser texture of the open plastic sheeting collector seemed to allow *P. maculata* spat to maintain a strong water exchange. Similarly, they indicated that those that settled on shade-mesh were usually found on the edges which also enabled them to have better water exchange. Likewise, in our case, plate shape may have offered *P. maculata* spat better water exchange than the shade-mesh filamentous shape with a different water flow. Moreover, increasing space between plates must have provided a better water exchange than NDP too. Interestingly, *P. maculata* were also usually found on the edges of plates which tends to confirm the hypothesis of Friedman and Bell (1996). In addition, unlike *P. margaritifera*, there was no incidence of position or color of plates. This could mean that *P. maculata* larvae are less photosensitive than black-lip pearl-oyster spat, less preyed on or too numerous in the lagoon for it to be shown. *P. maculata* oysters have long been considered as biofouling and were mainly thrown into the lagoons (Murzilli et al., 2012). This probably led to the development of *P. maculata* oyster beds and to the extensive spread of the population in the lagoons. The number of *P. maculata* collected on plate collectors raises the question of the suitability of this type of collector. The majority of pearl farmers usually consider *P. maculata* as a pest because this species is in direct competition for space and food with *P. margaritifera* (Addessi, 1999). However, if we compare the abundance of *P. margaritifera* and *P. maculata* measured during our study on shade mesh collectors to those obtained for the black horizontal plate collector, the conclusion is the opposite. On this plate collector, we found 9.2 times more *P. maculata* spat than *P. margaritifera* spat whereas on shade-mesh collector this ratio is 14. Likewise, when we compare the two devices, there are 9 times more *P. margaritifera* on plates than on the shade-mesh collector whereas there are only 6.1 times more *P. maculata*. All these findings clearly show that the shade-mesh collector tended to collect more *P. maculata* proportionally to *P. margaritifera* than black horizontal NDP.

Lastly, our results showed that mean length of *P. margaritifera* spat was lower on plates after four months of collection than on shade-mesh without showing any effect of color, density of plates or position. Thus, only the collector shape seemed to have an influence on this biometric trait. It is important to point out that the variable of mean length presented in this paper cannot be assimilated to the measurement of the growth of the collected spat. *Pinctada margaritifera* is known to spawn all year long (Gervis and Sims, 1992). This means that, in our study, there might have been several recruitment 'waves' (e.g cohort) leading to a high variability of age and size of oysters on one collector. It seems that plate shape was more suitable for successive settlements. In contrast, the settlement of oysters appears limited when biofouling covered the shade-mesh filamentous shape. However, this length difference is also likely due to the higher number of spat collected by the plate collectors. A negative relationship between growth and number of individuals per area has been described by Filgueira et al. (2007) on Galician mussel, which has been highlighted by other authors as well (Fréchette et al., 1996; De La Roche et al., 2005; Guiñez, 2005). They explained that it induces space competition and food limitation which could affect growth. In our case, space and food competition with *P. maculata* could also explain the difference recorded (Addessi, 1999). Biofouling development could also influence *Pinctada margaritifera* growth by reducing water flow and oxygen availability (Taylor et al., 1997; Pit and Southgate, 2003). Thus, further studies are needed to better understand the factors that control the spat recruitment and growth on the collectors. Moreover, longer tests over the current collection period (12–24 months) are needed to conclude on the eventual impact of spat length collected with plates on pearl-farming production and farmers' practices.

In conclusion, our study showed that black horizontal NDP could be a good alternative to shade-mesh collectors when focusing on short-term collection performance. However, many factors need to be taken in account before validation of this potential alternative. They concern environmental impact, practicality for pearl-farmers, and cost-benefit analysis. Plate collectors are made of plastic, so the quantity of plastic waste produced after several years of use is of importance. However, from our results on spat collection, initial calculations can be performed. Here, if we consider the longevity of a plate collector as around 6 years because they will be immersed practically continuously (Table 1), annual plastic waste production by shade-mesh collector expressed in relation to its efficiency (*P. margaritifera* spat collection) is 1.715 g.spat^{-1} while black horizontal NDP will produce only 1 g.spat^{-1}. But if we estimate the cost per spat collected, then black horizontal NDP appears more expensive, at 0.0172 €, compared to the shade-mesh collector (0.0123 €). These values represent only rough estimates, as other costs should be taken into account such as material costs (buoys to maintain the line afloat, the plate collector being heavier) and operating costs (transportation constraints of plate collectors, which are more voluminous, fuel, *etc.*). For these additional costs, the efficiency of the collectors in spat collection is also to be considered (*e.g.* twelve times fewer plate collectors needed to obtain the same amount of *P. margaritifera* spat), as it could counterbalance the final production cost per spat. So additional studies, involving economists, are needed to conclude on the affordability/feasibility of a change in practices for pearl farmers. This will be the next step of our approach.

Table 1
Comparison elements of black horizontal NDP collector and shade-mesh collector after 4 months of immersion.

	Black horizontal NDP	Shade-mesh
Collection surface (cm^2)	12,488	12,833
Cost tax included (€)	18.96	0.59
Plastic weight (g)	1100	77
Collector longevity (year)	6	3
Plastic waste produced per year (g)	183.3	25.67
P. margaritifera spat numbers per collector	183	16
P. margaritifera spat density (unit. cm^{-2})	0.0147	0.0012
Plastic waste per *P. margaritifera* spat collected per year (g)	**1**	**1.715**

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Author contribution

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N. Gaertner-Mazouni: Conceptualization, Methodology, Validation, Investigation, Resources, Writing – Original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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