Survival and growth of the Caribbean scallops, *Argopecten nucleus* and *Nodipecten nodosus*, in suspended systems at different culture depths and net replacement frequencies

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ABSTRACT: Survival of the Caribbean scallops *Argopecten nucleus* and *Nodipecten nodosus* in suspended culture is relatively low. The effects of culture depth and frequency of net replacement on survival and growth of both scallops were assessed, in addition to the effects on the amount of biofouling and presence of predators in the culture systems. Hatchery-produced juveniles were kept in pearl nets suspended at 3 different culture depths (6, 9 and 12 m) with 2 frequencies for net replacement (i.e. monthly and every second month, hereafter ‘bimonthly’). Survival of both scallop species was higher at 12 m depth. *A. nucleus* also showed higher growth rates at 12 m depth, while *N. nodosus* exhibited higher growth rates at 6 m depth. *A. nucleus* and *N. nodosus* performed best under monthly and bimonthly net replacement schemes, respectively. Frequency of presence and size of cymatid predators did not differ between treatments, but greater frequency and size of portunids occurred at bimonthly net replacement in *A. nucleus* culture nets. In most months, the biofouling dry biomass in the pearl nets was higher in those maintained at a depth of 6 m with bimonthly net replacement. The results indicate that the survival of both scallops could be improved by maintaining the culture systems suspended at a depth of 12 m, under lower temperature conditions, and applying a monthly net replacement scheme in *A. nucleus* in order to minimize the biofouling on the nets and a bimonthly scheme in *N. nodosus* in order to minimize scallop perturbation associated with net replacement.

KEY WORDS: Biofouling · Predators · Bivalves · Epibionts · Temperature · Portunids · Cymatids

1. INTRODUCTION

*Argopecten nucleus* (Born, 1780) and *Nodipecten nodosus* (Linnaeus, 1758) are pectinid species from the Caribbean, which are cultured at experimental and pilot scale (Velasco & Barros 2008, Velasco et al. 2011, Valderrama et al. 2016). Both species are epibenthic and live on sandy or calcareous bottom habitats. *A. nucleus* is a species of moderate size (~50 mm) occurring over the sea bottom until 50 m depth, while *N. nodosus* reaches larger sizes (~150 mm) and lives attached to hard substrates at depths between 10 and 120 m (Díaz & Puyana 1994, Lodeiros et al. 1999). Both exhibit strong growth in suspended culture systems at low densities (25 to 40% of bottom net coverage) at depths between 6 and 32 m, reaching the commercial size (40 mm in *A. nucleus* and 70 mm in *N. nodosus*) at 9 to 12 mo old (Lodeiros et al. 1998, 2001, Velasco et al. 2009, 2011, 2013, Barros et al. 2018). Their survival, however, is variable and can be rather low: between 7 and 68% for *A. nucleus* (Lodeiros et al. 1993, Velasco et al. 2009, Barros et al. 2018) and between 14 and 80% for *N. nodosus* (Lodeiros et al. 1998, 2000, Mendoza et al. 2003, Rupp 2007, Velasco et al. 2009, Gómez-León et al. 2010). The main factors related to the low survival of these species are predation, the presence of large amounts of biofouling and high temperatures (>28°C) (Freites & Núñez 2001, Rupp 2007, Velasco et al. 2009).

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Some of the main predator species for these scallops in suspended culture systems are portunid crabs (*Charybdis helleri* and *Cronius ruber*) and cymatid snails (*Cymatium pileare* and *C. cingulatum*) (Freites et al. 2000, Ciocco & Orensanz 2001, Velasco et al. 2009). Larval states of such organisms enter through the net into the culture systems and rapidly grow at the expense of predating the cultured scallops (Ventilla 1982, Freedman & Bell 1996). In the case of the biofouling, most of the species found are macroalgae and filtering invertebrates (especially *Balanus* sp.), which cover the culture systems and, to a lesser degree, the scallop shells (Uribe et al. 2001, Velasco 2008, Cortés-Useche et al. 2011, Carraro et al. 2012). These biofouling species usually compete for resources and restrict the water inflow into the culture systems, and they are also able to parasitize and deteriorate the scallop shells (Lesser et al. 1992, LeBlanc et al. 2002, Pacheco & Garate 2005, Fitridge et al. 2012). In addition, the presence of biofouling reduces the useful life of the culture systems, and the disposal of used systems in water or on land could impair the environmental quality of marine and terrestrial ecosystems (Uribe et al. 2001, Dürr and Watson 2010, Adams et al. 2011).

Among the mitigation measures used to control biofouling and the presence of predators in the culture systems, some of the most common are physical removal, coating shells and nets with anti fouling products, biocontrol and avoidance of natural recruitment (Fitridge et al. 2012). Removal monthly, or every 2 wk, of predators and biofouling, as well as the use of sea urchins inside the systems are practices that have been reported as helpful to control the settling of harmful organisms in culture systems of *A. nucleus* and *N. nodosus* at small scales (Velasco et al. 2009, Cortés-Useche et al. 2011). Nevertheless, the use of such practices at a larger scale is considered wasteful, expensive and inconsistent (Roma et al. 2009, Fitridge et al. 2012). Considering that the settling of predator larvae and biofouling is directly influenced by food availability (Pérez et al. 2016), the increase of culture depth could be a useful, cheaper and easier measure to limit the larval recruitment of harmful species, and possibly with less frequent net replacement.

With the goal of identifying operational practices that could improve the productivity of *A. nucleus* and *N. nodosus* cultured in suspended systems, the present study assessed the effects of culture depth and frequency of net replacement on the survival and growth of both species as well as on the degree of biofouling and presence of predators.

### 2. MATERIALS AND METHODS

A total of 7000 juveniles of *Argopecten nucleus* (mean ± SE shell length: 11.3 ± 0.14 mm) and 13 200 juveniles of *Nodipecten nodosus* (8.5 ± 0.08 mm shell length) were produced in the Laboratorio de Moluscos y Microalgas of the Universidad del Magdalena in Taganga, Santa Marta, Colombia (11° 16’ 03” N, 74° 11’ 24” W), following the protocols described by Velasco & Barros (2007, 2008, 2009) and Velasco et al. (2007).

In this study, a factorial experimental design was applied for both species using 3 different culture depths (6, 9 and 12 m) and 2 frequencies for net replacement (monthly and every 2 mo, hereafter ‘bi-monthly’), which resulted in 6 treatments with 3 replicates each. Juveniles of each species were randomly distributed in Netlon® pyramidal pearl nets (35 × 35 × 20 cm and 6 mm mesh size) at a stocking density of 30% of net bottom coverage. The number of scallops placed in each net was calculated on the basis of the area occupied in the bottom of each net (1225 cm²) and the surface area of each specimen assuming a circular shape (387 and 731 ind. net⁻¹ for *A. nucleus* and *N. nodosus*, respectively). The pearl nets were then individually suspended in a 100 m subsurface long-line at a depth of 5 m, leaving ~50 cm of separation between pearl nets. The long-line system was located in the aquaculture lease of the Universidad del Magdalena in Bahía Taganga (11° 16’ 04” N, 74° 11’ 36” W), where depths varied from 15 to 20 m.

Monthly or bimonthly, depending on the treatment, the pearl nets were taken out of the water and transported ashore for ~4 to 6 h in order to replace the nets as well as to estimate scallop growth and survival, the amount of biofouling and the abundance of predators in the nets. For this, the population of each net was transferred to containers (20 to 50 l) with seawater, and the living specimens were counted. Monthly survival for each replica was estimated as the proportion between the number of living bivalves at the end of the month or every second month and the initial number of animals placed in each net. The shell length of 30 randomly selected individuals was measured with calipers (0.01 mm). Potential predators (crabs and snails) that were present in culture nets were placed in plastic bags containing 4% seawater formalin for subsequent identification, enumeration and measurement of individual body size (shell length for cymatid snails and carapace width for portunid crabs). The biofouling dry biomass on the nets was also estimated based on the difference between the weight of the pearl net sun-dried for 7 d and the ini-
tial weight of the clean net. Finally, the scallops were placed in new pearl nets at their original densities with the number of animals readjusted in each net according to the method described above, and the culture systems were returned to the original depth. Every month, surplus animals extracted from each pearl net were distributed in extra replicates under the same conditions as those of the experimental juveniles in order to subsequently adjust the density in the case of high mortalities. The experiments lasted 6 mo for both species, between March and September 2011 for *A. nucleus* and between June and December of 2012 for *N. nodosus*.

Every 2 wk, 3 seawater samples (4 l) were collected using a Niskin bottle at the 3 culture depths. Seston concentration and organic content of each sample were determined following the methods of Strickland & Parsons (1972). Salinity was measured using a refractometer (Brixco, precision 1 ppt), and temperature was registered from glass maximum–minimum thermometers (Sper Scientific, precision 1°C) maintained at each depth. Due to administrative problems in the project, it was not possible to take water samples between June and July of 2012.

The existence of statistical differences in the growth and survival of scallops between culture depth and frequency of net replacement was analyzed using a 2-way ANCOVA, with time as the covariate variable. The frequency of presence and size of predators, as well as the biofouling dry biomass, were compared between treatments and different periods of time using a factorial ANOVA. Physical-chemical parameters (i.e. temperature, salinity, seston concentration and organic content) were compared between different culture depths and periods of time using a 2-way ANOVA. When differences among treatments and/or periods of time were detected, Bonferroni or Tukey multiple tests were performed to detect the specific intra-level differences. Before the analysis, data normality and homoscedasticity were confirmed in almost all cases, and transformations were applied when required. Thus, predator size data were log transformed, data for shell length in *N. nodosus* and biofouling dry biomass were ranked, and data for frequency of presence of predators were square-root transformed. Temperature data for *A. nucleus* culture did not comply with the normality and homoscedasticity requirements, so these data were analyzed using the Kruskal-Wallis test. Correlation analysis of the data (i.e. physical-chemical variables, monthly growth and survival rates of scallops, frequency of presence and size of predators, and biofouling dry biomass) was performed using Spearman’s correlation. The Statgraphics Centurion XVII X64 software was used for all statistical analysis, with significance level of $\alpha = 0.05$.

### 3. RESULTS

#### 3.1. *Argopecten nucleus*

Survival of *A. nucleus* after 6 mo in suspended culture varied between 29 and 48% (Fig. 1A), with the highest decrease (41–68%) registered in the first sampling, at 30 or 65 d culture time. Juveniles with
an initial shell length of 11.3 mm reached between 37.5 and 41.6 mm (Fig. 1B) at the end of the experiment, with growth rates between 0.14 and 0.16 mm d⁻¹. Highest survival and growth rates were found in animals cultured at a depth of 12 m and where net replacement was monthly (Table 1). The water temperature between March and September of 2011 varied between 23 and 29°C (Fig. 2A), with the lowest values at a depth of 12 m and the highest values at 6 and 9 m in July and August (K-W= 6.0, p < 0.0098). Salinity fluctuated between 34 and 37 ppt (Fig. 2B), with the highest values at depths of 9 and 12 m in March and the lowest values at 6 m in May (Table 2). Seston concentration fluctuated between 1.8 and 7.7 mg l⁻¹ (Fig. 2C), being highest at depths of 9 and 12 m in April and June and lowest at 6 m from April to June (Table 2). Seston organic content oscillated between 17 and 82% (Fig. 2D), registering highest values at a depth of 12 m in May with lowest at 9 m from June to August (Table 2). Significant neg-
ative correlations were found between the monthly growth rates of *A. nucleus* and water temperature (Table 3).

The frequency of presence of cymatid snails in the pearl nets oscillated between 0 and 16 ind. m$^{-2}$, their shell lengths fluctuated between 3 and 28 mm (Fig. 3A), and their growth rates ranged between 0 and 16 mm mo$^{-1}$. The frequency of presence of portunid crabs varied between 0 and 46 ind. m$^{-2}$, while their carapace widths were between 4 and 42 mm (Fig. 3B), and their growth rates were between 0 and 24 mm mo$^{-1}$. Significantly higher frequency and size of portunids were registered in April and/or June than in August (Table 1). No statistical differences

Table 2. ANOVAs of the physicochemical parameters of Taganga Bay (Santa Marta, Colombia) at different depths and months at which *Argopecten nucleus* and *Nodipecten nodosus* were cultured

| Species          | Variable        | Source of variation | SS    | df  | Square means | F     | p  |
|------------------|-----------------|---------------------|-------|-----|--------------|-------|----|
| *A. nucleus*     | Salinity        | A: Depth            | 2.78  | 2   | 1.39         | 20.55 | 0.0000 |
|                  |                 | B: Culture time     | 13.99 | 6   | 2.33         | 34.43 | 0.0000 |
|                  |                 | A × B Interaction   | 3.27  | 12  | 0.27         | 4.03  | 0.0008 |
|                  | Seston          | A: Depth            | 12.50 | 2   | 6.25         | 3.02  | 0.0631 |
|                  |                 | B: Culture time     | 43.57 | 6   | 7.26         | 3.50  | 0.0089 |
|                  |                 | A × B Interaction   | 63.03 | 12  | 5.25         | 2.53  | 0.0178 |
|                  | Seston organic  | A: Depth            | 1720.30 | 2  | 860.15       | 3.95  | 0.0293 |
|                  |                 | B: Culture time     | 7105.03 | 6  | 1184.17      | 5.44  | 0.0006 |
|                  |                 | A × B Interaction   | 1985.86 | 12 | 165.49       | 0.76  | 0.6844 |
| *N. nodosus*     | Temperature     | A: Depth            | 3.60  | 2   | 1.80         | 2.50  | 0.0000 |
|                  |                 | B: Net replacement  | 52.80 | 4   | 13.20        | 10.11 | 0.0000 |
|                  |                 | A × B Interaction   | 2.40  | 8   | 0.30         | 0.33  | 0.0000 |
|                  | Salinity        | A: Depth            | 0.96  | 2   | 0.48         | 2.48  | 0.0000 |
|                  |                 | B: Culture time     | 13.00 | 4   | 3.25         | 16.71 | 0.0000 |
|                  |                 | A × B Interaction   | 1.06  | 8   | 0.13         | 0.68  | 0.0000 |
|                  | Seston          | A: Depth            | 0.02  | 2   | 0.01         | 0.08  | 0.9206 |
|                  |                 | B: Culture time     | 0.13  | 4   | 0.03         | 0.34  | 0.8481 |
|                  |                 | A × B Interaction   | 0.95  | 8   | 0.12         | 1.28  | 0.2912 |
|                  | Seston organic  | A: Depth            | 2026.17 | 2  | 1013.08      | 4.38  | 0.5215 |
|                  |                 | B: Culture time     | 495.90 | 4  | 123.98       | 0.54  | 0.7107 |
|                  |                 | A × B Interaction   | 1568.18 | 8  | 196.02       | 0.85  | 0.5701 |

Fig. 2. Mean ± SE (A) temperature, (B) salinity, (C) seston concentration and (D) seston organic content in Taganga Bay during the experimental culture of *A. nucleus*. *p < 0.05
were found for the frequency of presence and size of cymatid predators found in the pearl nets at different culture depths or net replacement frequencies (Table 4). The biofouling dry biomass fluctuated between 215 and 1143 g m⁻² (Fig. 3C), with the higher values found under a bimonthly net replacement scheme, in the month of August, and in pearl nets kept at a depth of 6 m, except in April when higher biofouling values were verified at 12 m (Table 1). Significant positive correlations were found between the size of portunid crabs, the crab growth rate and the monthly growth of A. nucleus (Table 3).

### 3.2. *Nodipecten nodosus*

Survival of *N. nodosus* juveniles after 6 mo in suspended culture fluctuated between 0 and 44% (Fig. 4A), with marked declines (35–54%) registered in the first sampling at 30 or 65 d culture time. Survival values were significantly higher in animals maintained at a depth of 12 m and under a bimonthly net replacement scheme (Table 4). Juveniles with an initial shell length of 8.5 mm reached between 45.6 and 49.6 mm (Fig. 4B), exhibiting monthly growth rates between 0 and 15 mm mo⁻¹. No significant differences were found in the frequency of presence or size of portunid crabs oscillated between 0 and 16 ind. m⁻², and their carapace width presented values between 7 and 25 mm mo⁻¹ (Fig. 6B), and their growth rates were between 0 and 15 mm mo⁻¹. No significant differences were found in the frequency of presence or growth rate of predators between different months, culture depths or different net replacement frequencies (Table 4) during the experiment. Biofouling dry biomass fluctuated between 73.7 and 1083.3 g m⁻² (Fig. 6C). Significantly higher values were registered under bimonthly net replacement, especially in August and at 6 or 9 m of depth (Table 4). There was no significant correlation between predators or biofouling variables and the growth or survival of *N. nodosus* (Table 3).

### 4. DISCUSSION

The present study demonstrates how survival and growth of the 2 Caribbean pectinid species studied...
Fig. 3. Mean ± SE frequency of presence and size of the predators (A) Cymatiidae and (B) Portunidae inside the pearl nets with Argopecten nucleus and (C) biofouling dry biomass in the nets under different conditions (i.e. culture depths and net replacement frequencies). Numbers above bars represent the predator size means in mm (shell length for cymatid snails and carapace width for portunid crabs). *p < 0.05

Fig. 4. Mean ± SE (A) survival and (B) growth in shell length of Nodipecten nodosus maintained at different conditions (i.e. culture depths and net replacement frequencies). *p < 0.05
are affected by culture depth and net replacement frequency, in addition to environmental variables such as water temperature, bio fouling biomass and the size of portunid predators. These results facilitate a better understanding of the complex dynamics between environmental and operational variables inherent to scallop aquaculture in suspended systems and productive traits, which can support better management practices to improve productivity.

### 4.1. Effect of depth

The high survival of *Argopecten nucleus* and *Nodpecten nodosus* cultured at the greatest depth tested (12 m), as well as the highest growth of *A. nucleus* under such conditions, are similar to results previously reported for the survival of *N. nodosus* (Lodeiros et al. 1998), the growth and survival of *Euvola ziczac* (Lodeiros & Himmelman 2000), and the

| Variable                     | Source of variation       | SS       | df | Square means | F        | p     |
|------------------------------|---------------------------|----------|----|--------------|----------|-------|
| Survival                     | Covariable: Culture time  | 47 523.10| 1  | 47 523.10    | 172.36   | 0.0000|
| A: Depth                     |                           | 22 322.20| 2  | 11 161.10    | 4.05     | 0.0207|
| B: Net replacement           |                           | 11 450.90| 1  | 11 450.90    | 41.53    | 0.0000|
| A × B Interaction            |                           | 256.60   | 2  | 128.30       | 0.47     | 0.6294|
| Shell length                 | Covariable: Culture time  | 374 641 000.00 | 1 | 374 641 000.00 | 5467.62 | 0.0000|
| A: Depth                     |                           | 3 172 850.00 | 2 | 1 586 420.00 | 23.15    | 0.0000|
| B: Net replacement           |                           | 827 432.00 | 1 | 827 432.00   | 12.08    | 0.0005|
| A × B Interaction            |                           | 405 746.00 | 2 | 202 873.00   | 2.96     | 0.0520|
| Cymatid frequency            | A: Culture time           | 0.28     | 2  | 0.14         | 1.78     | 0.1835|
| B: Depth                     |                           | 0.07     | 2  | 0.04         | 0.44     | 0.6447|
| C: Net replacement           |                           | 0.14     | 1  | 0.14         | 1.78     | 0.1908|
| A × B Interaction            |                           | 0.06     | 2  | 0.03         | 0.24     | 0.7885|
| A × C Interaction            |                           | 0.36     | 4  | 0.09         | 1.11     | 0.3664|
| B × C Interaction            |                           | 0.07     | 2  | 0.04         | 0.44     | 0.6447|
| Cymatid size                 | A: Culture time           | 241.25   | 2  | 120.63       | 1.75     | 0.1875|
| B: Depth                     |                           | 102.98   | 2  | 51.49        | 0.75     | 0.4801|
| C: Net replacement           |                           | 63.74    | 1  | 63.74        | 0.93     | 0.3421|
| A × B Interaction            |                           | 96.04    | 4  | 24.01        | 0.35     | 0.8428|
| A × C Interaction            |                           | 70.58    | 2  | 35.29        | 0.51     | 0.6028|
| B × C Interaction            |                           | 82.24    | 2  | 41.12        | 0.6      | 0.5552|
| Portunid frequency           | A: Culture time           | 0.48     | 2  | 0.24         | 0.37     | 0.6924|
| B: Depth                     |                           | 2.48     | 2  | 1.24         | 1.91     | 0.1622|
| C: Net replacement           |                           | 1.19     | 1  | 1.19         | 1.83     | 0.1847|
| A × B Interaction            |                           | 0.19     | 2  | 0.09         | 0.48     | 0.6233|
| A × C Interaction            |                           | 4.74     | 4  | 1.19         | 1.83     | 0.1447|
| B × C Interaction            |                           | 1.37     | 2  | 0.69         | 1.06     | 0.358 |
| Portunid size                | A: Culture time           | 99.81    | 2  | 49.90        | 0.87     | 0.4256|
| B: Depth                     |                           | 457.25   | 2  | 228.62       | 4.01     | 0.0568|
| C: Net replacement           |                           | 346.39   | 1  | 346.39       | 6.07     | 0.0586|
| A × B Interaction            |                           | 723.30   | 4  | 180.82       | 3.17     | 0.0549|
| A × C Interaction            |                           | 90.39    | 2  | 45.19        | 0.79     | 0.4606|
| B × C Interaction            |                           | 114.75   | 2  | 57.37        | 1.01     | 0.3758|
| Portunid size                | A: Culture time           | 389.16   | 4  | 97.29        | 1.71     | 0.1721|
| A × B × C Interaction        |                           | 0.07     | 2  | 0.04         | 0.44     | 0.6447|
| Fouling                      | A: Culture time           | 1838.53  | 2  | 919.26       | 20.95    | 0.0000|
| B: Depth                     |                           | 2 139.53 | 2  | 10 259.76    | 47.16    | 0.0000|
| C: Net replacement           |                           | 210 260.00 | 1 | 210 260.00   | 458.6    | 0.0000|
| A × B Interaction            |                           | 7766.61  | 4  | 1942.15      | 44.25    | 0.0562|
| A × C Interaction            |                           | 1025.53  | 2  | 512.76       | 11.68    | 0.0001|
| B × C Interaction            |                           | 2861.08  | 2  | 1430.54      | 32.6     | 0.0698|
| A × B × C Interaction        |                           | 7970.39  | 4  | 1992.60      | 45.4     | 0.0745|

Table 4. ANCOVAs and ANOVAs of the survival and shell length of *Nodpecten nodosus* maintained at different suspended culture conditions (i.e. culture depths and net replacement frequencies)
Fig. 5. Mean ± SE (A) temperature, (B) salinity, (C) seston concentration and (D) seston organic content in Taganga Bay during the experimental culture of *Nodipecten nodosus* (August to December of 2012). *p < 0.05

Fig. 6. Mean ± SE frequency of presence and size of the predators (A) Cymatiidae and (B) Portunidae inside the pearl nets with *Nodipecten nodosus* and (C) biofouling dry biomass in the nets under different conditions (i.e. culture depths and net replacement frequencies). Numbers above bars represent the predator size means in mm (shell length for cymatid snails and carapace width for portunid crabs). *p < 0.05
growth of *Aequipecten opercularis* (Román et al. 1999) and *Pecten maximus* (Román et al. 2003). The lower temperatures as well as the lower values of biofouling dry biomass found in the pearl nets maintained at greater depths in most of the months suggest that these factors promoted survival in both pectinid species studied and the growth in *A. nucleus*. High temperatures (28°C) can cause a decrease in food intake and an increase in metabolic demands, resulting in less energy available for growth and reproduction of these 2 species (Velasco 2006). Similarly, the presence of a larger biofouling biomass in the pearl nets maintained in shallow waters most of the months probably exerted additional stress in the scallops, thus increasing their susceptibility to death. Some of the main causes of stress on scallops related to the presence of biofouling are (1) toxic nitrogenous waste products released to the water, (2) competition for resources such as food, oxygen and space, and (3) energetic costs related to repair of shell damage caused by shell-boring organisms (Lesser et al. 1992, LeBlanc et al. 2002, Fitridge et al. 2012). In contrast, the highest growth of *N. nodosus* cultured at 6 m suggests that this species had large energetic reserves to support its growth and/or that it had low energetic demands for shell reparation under high temperature and biofouling abundance conditions. It has been shown that *N. nodosus* is capable of storing, transferring and using nutrients from the muscle and digestive gland to support somatic and gonadic growth, respectively (Lodeiros et al. 2001), especially under suboptimal conditions (Velasco & Barros 2008). The suspension of the culture systems at greater depths, especially in August, was able to decrease the settlement of larval stages of biofouling species in the nets, thus promoting a positive effect on the survival of the 2 pectinid species studied and on the growth of *A. nucleus*.

### 4.2. Effect of net replacement frequency

The higher values of survival and growth in individuals of *A. nucleus* cultured under a monthly net replacement scheme, in comparison to those under a bimonthly scheme, are similar to those found for *E. ziczac* (Lodeiros & Himmelman 1996), *Placopecten magellanicus* (Claereboudt et al. 1994) and *Pinctada margaritifera* (Pit & Southgate 2003) cultured in systems with monthly and bimonthly net cleaning. These results are related to the higher values of biofouling biomass size and frequency of portunid crabs found in the pearl nets with bimonthly replacement. Indeed, crabs of larger size are able to predate on a greater number of cultured scallops, which has been previously reported for *Carcinus maenas* (Klein-Breteler 1975). Additionally, the positive correlation found between the size of portunid crabs and growth of *A. nucleus* suggests that portunids of larger size consumed a greater number of small scallops within the culture systems, which exhibited slower growth, therefore indirectly selecting larger scallops with a faster growth rate. Similar results have been reported in oysters *Crassostrea virginica* predated by crabs *Callinectes sapidus* (Eggleston 1990). It seems likely that a monthly net replacement contributes towards minimizing the settlement of larval stages of biofouling species in the nets as well as towards hindering the growth of portunid crabs, thus preventing them from reaching a critical body size within the pearl nets. These 2 aspects should explain the higher survival and growth of *A. nucleus* under a monthly net replacement scheme.

The high values of survival and growth observed in individuals of *N. nodosus* cultured under a bimonthly net replacement scheme suggest this species has low sensitivity to the deleterious effects of biofouling but high sensitivity to handling during net replacement. A lack of a significant relationship between the amount of biofouling and survival and growth has been previously documented for this species (Rupp 2007, Carrado et al. 2012) and other bivalves like *Mytilus galloprovincialis* and *Ostrea edulis* (Perera et al. 1999). The greater biofouling resistance of *N. nodosus* than of *A. nucleus* could be related to its higher shell thickness (1.5 mm vs. 1 mm in adults, respectively). Apparently, in *N. nodosus*, a monthly net replacement negatively affects survival and growth, which might be related to the stress inflicted by handling and manipulating the animals more frequently.

Higher mortality of *A. nucleus* and *N. nodosus* during the first period of experimental culture, immediately after seeding the scallops in the pearl nets (54 and 44% on average for *A. nucleus* and *N. nodosus*, respectively), suggest that the exposure to air, handling and manipulation during the detachment of juveniles from the artificial collectors, grading and seeding represent important stress factors that ultimately increase mortality rates. Usually these activities are performed for long periods of time (4 to 6 h) in the beach at high water temperatures (28 to 32°C) and in limited shade, where the scallops are placed in containers at high densities with small volumes of seawater (20 to 50 l) and low water renewal. To increase survival and growth in this species, it is highly recommended to reduce the duration of the
detachment, grading and seeding activities, in addition to implementing a system with flow-through tanks containing larger volumes of seawater.

### 4.3. Predation and biofouling

The maximum frequencies of presence of cymatid and portunid predators found in the pearl nets with *A. nucleus* and *N. nodosus* in Bahía Taganga (16 cymatids m\(^{-2}\) mo\(^{-1}\) and 24 portunids m\(^{-2}\) mo\(^{-1}\)) are similar to those reported for *A. nucleus* in the same geographical area (22 cymatids m\(^{-2}\) mo\(^{-1}\) and 11 portunids m\(^{-2}\) mo\(^{-1}\); Velasco et al. 2009) but lower than those found in the protected area Parque Natural Nacional Tayrona in other bivalve species like *Pinna carnea* (45 cymatids m\(^{-2}\) mo\(^{-1}\) and 33 portunids m\(^{-2}\) mo\(^{-1}\); Velasco & Borrero 2004), *Pteria colymbus* (41 cymatids m\(^{-2}\) and 6 portunids m\(^{-2}\) mo\(^{-1}\); Velasco & Borrero 1996) and *Pinctada imbricata* (33 cymatids m\(^{-2}\) mo\(^{-1}\) and 55 portunids m\(^{-2}\) mo\(^{-1}\); Velasco & Barros 2010). These results suggest that scallops are less appetizing or more difficult to predate than other Caribbean marine bivalves. This could also be indicative of a higher abundance of predators of bivalves inside protected areas. The growth rates of cymatids and portunids found in this study (40 and 42 mm mo\(^{-1}\), respectively) are high in relation to those estimated under suspended culture conditions of *P. colymbus* (12 to 26 mm mo\(^{-1}\), respectively; Velasco & Borrero 1996) and *P. imbricata* (23 to 25 mm mo\(^{-1}\), respectively; Velasco & Barros 2010). These differences could be related to temporal and spatial variations in water physicochemical conditions, changes in the species composition of the predator groups or differences in the nutritive value of the scallops and pearl oysters.

A decrease in the biofouling biomass in most culture systems at greater depths (12 m) is a suitable practice for reducing the settlement of larval stages of biofouling species and protecting the scallops from high temperatures, increasing survival in *N. nodosus* and *A. nucleus* as well as promoting growth in *A. nucleus*. A higher frequency of net replacement (i.e. monthly) reduces biofouling formation, thus increasing survival and growth in *A. nucleus* but not in *N. nodosus*, which seems to be affected to a greater degree by more frequent manipulation. However, considering that biofouling on the culture nets is one of the problems facing both scallop species studied, the use of cylindrical nets might be worthwhile as these may well have a lower surface area:volume ratio than pyramidal nets.

### 5. CONCLUSIONS

In summary, the suspension of culture systems at greater depths (12 m) is a suitable practice for reducing the settlement of larval stages of biofouling species and protecting the scallops from high temperatures, increasing survival in *N. nodosus* and *A. nucleus* as well as promoting growth in *A. nucleus*.

A higher frequency of net replacement (i.e. monthly) reduces biofouling formation, thus increasing survival and growth in *A. nucleus* but not in *N. nodosus*, which seems to be affected to a greater degree by more frequent manipulation. However, considering that the low survival values obtained in this study were not mainly due to the environmental factors studied (i.e. predators, biofouling and physicochemical parameters) but instead due to the high mortality of juveniles at the beginning of the culture, it is recommended to carry out additional research to optimize the practices related to the operations of seed detachment from the artificial collectors, grading and seeding.

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