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A cheap and efficient system for *Spongia anclotea* farming in the Bahamas

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Sponges are now requested for their commercial, industrial and pharmaceutical importance. This led to an increase in demand in the global markets with uncontrolled and excessive harvesting pressure that, together with diseases outbreaks, put wild populations at risk, with several habitats completely looted. Aquaculture of sponge fragments poses an alternative to wild collection since fragment regeneration is easy, cheap and efficient. We chose as subject of our study *Spongia anclotea*, common to the tropical Western Atlantic, due to its high request on the market for cosmetics, body care and pharmaceutical applications. We set a low-cost sponge farm made of cheap materials, thus affordable for local communities, which did not require significant maintenance. The growth and survival rate of 384 out of 2304 randomly chosen sponges have been investigated over a 4-year period. At the end of the study, sponges increased by an average rate of 380% ± 275% of their initial volume (with a maximum of 1480%) and 87.5% of sponges survived (death and detach during the whole period were considered as mortality). Farmed sponges from our structure resulted characterized by superior quality and shape compared to collected wild individuals from the area and, after six years of cultivation (4 years of the present study + 2 years of forecasted growth based on our findings), this improved quality could yield higher profits (618 USD vs. 547 USD, respectively, for a standard stock size). This experimental setup can be considered a good alternative to sponge harvesting and a good economic opportunity for developing countries.

KEYWORDS

***Spongia anclotea*, *Spongia pertusa*, sponge farming, aquaculture, growth, survival, Bahamas**

1 Introduction

Sponges (phylum Porifera) are a monophyletic (Wörheide et al., 2012) group which is estimated to include over 9000 species in 852 genera (de Voogd et al., 2024).

Historically, since the era of the Roman Empire, a small fraction of sponges, belonging to the order Dictyoceratida (family Spongiidae), characterized by a high quality spongin skeleton due to the almost total absence of spicules, great water retention, elasticity and resistance to usage overtime, were harvested for cosmetics in the Mediterranean Sea (Pronzato and Manconi, 2008; Ehrlich et al., 2018; Jesionowski et al., 2018). Recently, sponges have been demonstrated to be usable and profitable in various fields as biomedicine and pharmaceutical, due to the discovery and applications of their secondary metabolites (Faulkner et al., 1993; Amigó et al., 2008; Indraningrat et al., 2016; Abdelaleem et al., 2020; Pawlik and McMurray, 2020), biomonitoring and bioremediation, owing to their proficiency in filtering sea water, removing and accumulating different classes of pollutants (Patel et al., 1985; Olesen and Weeks, 1994; Hansen et al., 1995; Philp, 1999; Perez et al., 2002, 2003, 2005; Milanese et al., 2003; Cebrian et al., 2007; Santos-Gandelman et al., 2014; Orani et al., 2018), and aquaculture, as both farmed target species or as water filtration tool for bioremediation and reduction ecological impacts of farming in integrated multi-trophic aquaculture systems (IMTA) (Longo et al., 2016, 2020; Giangrande et al., 2020; Gökalp et al., 2021; Aguilo-Arce et al., 2023). This increase in demand made sponges a target organism in the global markets. While data before 1900 are not reliable for commercial sponges, a peak of 2 million collected sponges was reported in 1902 (Sella, 1912) and demand in the early 20th century was estimated at 30 tons/year. Wild sponges' gathering increased over time with over 100 tons/year in England and Germany in the 1930's (Arndt, 1938), 200 tons per year in 1985 up to around 2000 tons in 2003 (FAO Fishery Information and Unit (FAO-FIDI), 2005).

Since the end of the 20th century, new discoveries on applications of sponges put these organisms under excessive fishing pressure and, together with diseases outbreaks (Webster, 2007), wild populations become severely threatened and several areas faced significant reduction in both sponge abundance and species richness (Croft, 1990; Pronzato, 2003; Bertolino et al., 2017).

This situation led to an increase in sponge aquaculture efforts all over the world, from the Mediterranean Sea to the Atlantic and Pacific Ocean (Cahn, 1948; Storr, 1957, 1964; Croft, 1990; Handley et al., 2003). Researchers tried to develop new farming methods aimed at maximizing efficiency and reducing costs. Over time, the effects of new farming techniques (such as cages, fences, tendales, ropes, net pockets, spikes, and plastic pins (Duckworth et al., 2007; De Caralt et al., 2010; Osinga et al., 2010; Zea et al., 2010; Page et al., 2011; Betanzos-Vega et al., 2019)) on sponge growth, survival, and secondary metabolites production were evaluated, alongside other tests on integrated mariculture with the placement of sponges in association with fish and mussels' aquaculture systems (Gökalp et al., 2019, 2021; Giangrande et al., 2020; Li et al., 2023). To date, the accepted idea is that sponge aquaculture is species-specific, and each farming strategy must be calibrated to the needs of the target organism (Duckworth, 2009; Schippers et al., 2012). Currently, one of the most common farming techniques is growing fragments taken from natural individuals, taking advantage of the remarkable regenerative ability of these organisms. This practice was first adopted in the Mediterranean Sea (Cavolini, 1785, 1853), then it spread to America, Asia and Oceania (Duckworth et al., 1997, 2007; Louden et al., 2007). Aquaculture of sponge fragments gave new opportunities to developing countries which were facing ecological issues related to the past harvesting of natural individuals. In fact, this fragment regeneration method has been demonstrated to be simple, fast, inexpensive and efficient (Ayling, 1983; Duckworth, 2003). With proper protocols and conditions, a single individual may be a "source" for multiple generations (Osinga et al., 1999; Duckworth, 2001; Belarbi, 2003; Louden et al., 2007) thus shrinking the need of natural donors (Duckworth, 2009). This evidence made farming sponges a win-win choice for communities in developing nations, since it does not require expensive technologies and tools, it is easy to run, profitable and, ecologically speaking, it can decrease the anthropogenic pressure on natural stocks (Yi et al., 2005; Betanzos-Vega et al., 2019).

The genus *Spongia* is highly rated on the markets its specific features related to personal care, including fine texture and water absorption (Verdenal and Verdenal, 1987). The well-known *Spongia pertusa*, now accepted as *Spongia* (*Spongia*) *anclotea* de Laubenfels & Storr, 1958, is typical of the Atlantic Ocean coasts of America from Florida to Brazil. This species was chosen due to its high market value for cosmetics and body care and for the newly discovered pharmaceutical applications of its secondary metabolites as both antifungal agent against human pathogens and breast cancer CSC-like cell proliferation inhibitors (Osinga et al., 1999; Tang et al., 2018, 2022; Tian et al., 2023). Thus, improved understanding of its biology and physiology is fundamental for successful aquaculture farming. To our knowledge, only one study by Oronti et al. (2012) did a short-term preliminary investigation on growth and survival of *S. anclotea* in the Bahamas. Our study is the first long term investigation to address this species' adaptability to farming. In this work, we aimed to investigate *S. anclotea* regeneration and growth rates, together with survival and detachment, in an experimental site at Cape Eleuthera, Bahamas. Then, the productivity of the farm was estimated (in US $) and the revenue made by selling farmed sponges was compared to the profits made by selling similar size natural sponges collected from the study area. This allowed us to evaluate the actual applicability and the benefits of this farming system to help the economy of local communities and alleviate the stress on natural sponges' populations.

2 Materials and methods

2.1 Study site

The study took place in Cape Eleuthera Bay (Bahamas), near the Cape Eleuthera Island School and Institute (Figure 1). The farm was set in a dredged channel (3 m depth) 15 m far from the shore. The area was chosen basing on a past pilot study (Oronti et al., 2012) in

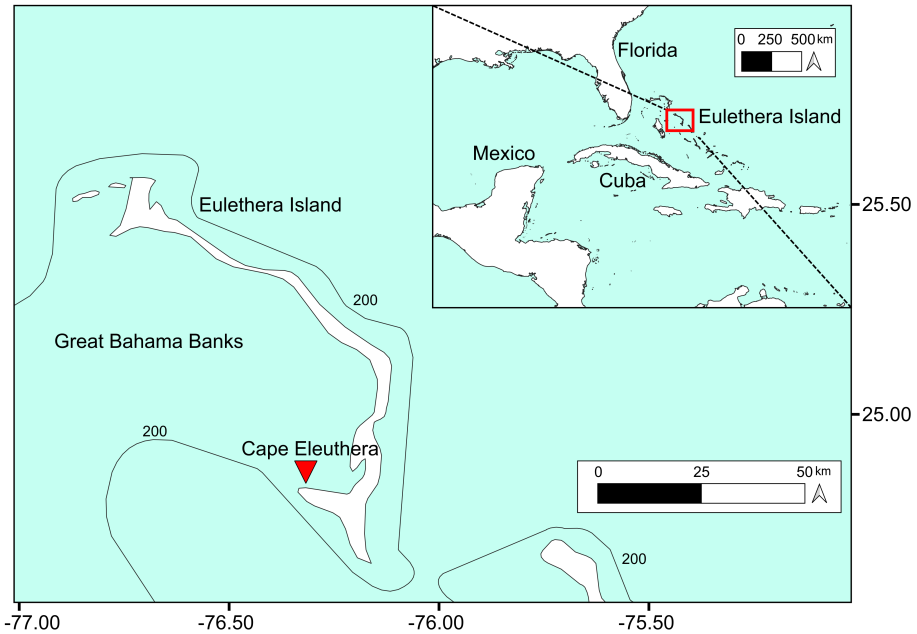

FIGURE 1
Study area. Red triangle indicates *Spongia anclotea* farm setup location at Cape Eleuthera, Eleuthera Island, Bahamas.

which Spongia anclotea farming at this location resulted in higher growth rates and lower mortality compared to other sites in the area, probably due to higher nutrient terrestrial runoff and weaker wave energy and water turbulence. Furthermore, the vicinity to the shore made setup, sampling and analyses much easier compared to offshore areas.

2.2 Study setup

A total of 8 farming cells (A-B-C-D-E-F-G-H) were built in November 2010 following the scheme reported in Figure 2, at a depth of 3 m. Cell X was already present from the previous pilot study (Oronti et al., 2012) and filled with older sponges, so it was not considered in this study. Every cell involved 6 strands made of 5 modules 105 cm far from each other. To do so, 240 concrete blocks (15 kg each) were deposited on the bottom, each presenting a vertical iron bar (1 meters long, 19 mm diameter) where two bitumen coated nylon twines were fixed at different heights (15 cm and 45 cm from the top of the bar) and pulled between bars of the same strand.

The upper portions (2/3 of total volume) of donor sponges from the area (estimated between 576 and 768 native individuals, explant volume ranging between 450-600 cm3 per donor sponge) were cut with a knife to obtain fragments, the remaining 1/3 were left sticked to the substrate for recovery as suggested by Duckworth and Battershill (2003). Sponge portions where then divided, ensuring that at least a side had undamaged pinacoderm, into multiple smaller sub-spherical fragments (usually 3-4 fragments per donor sponge). During every processing step, sponges were always kept underwater to avoid air exposition and minimize stress. Fragments were then tied with zip ties 15 cm apart from each other for a total of 48 individuals per strand numbered as 1-24 up for the upper thread and 1-24 down for the lower one. Strands orientation was set parallel to the local water current to minimize hydrodynamic stress.

For growth analysis, due to the large number of samples, only one randomly chosen strand per cell was processed for a total of 2304 samples (6 strands x 2 rows x 24 samples x 8 cells).

The experiment ran from 2010 to 2014. It began in November 2010 (setup and first measures) with subsequent measurements in July 2011, January 2012, July 2012, February 2013 and September 2014. Dimensions were measured underwater with precision calipers assessing the length of the three main axis of the sponges (length, width, height: x, y, z). Volumes were calculated using the ellipsoid as a reference shape (Formula 1), due to its similarity to samples shapes.

$$Sponge\ (ellipsoid)\quad volume = \frac{4}{3}\pi xyz$$

Formula 1. Ellipsoid volume.

Growth rate expressed as a percentage was calculated as in Formula 2.

$$Sponge\ \ volume\ \ growth\ \ rate\ \ \% \ = \frac{Volume\ \ tx - Volume\ \ t0}{Volume\ \ t0} * 100$$

Formula 2. Sponge growth rate. Volume at tx indicates the volume of a sample measured at one of the five sampling times (t1-t5), while volume at t0 represents the initial measurement of that sample's volume.

The survival rate was assessed considered death or detachment of sponges as one, since both fates resulted as an individual lost for final sale.

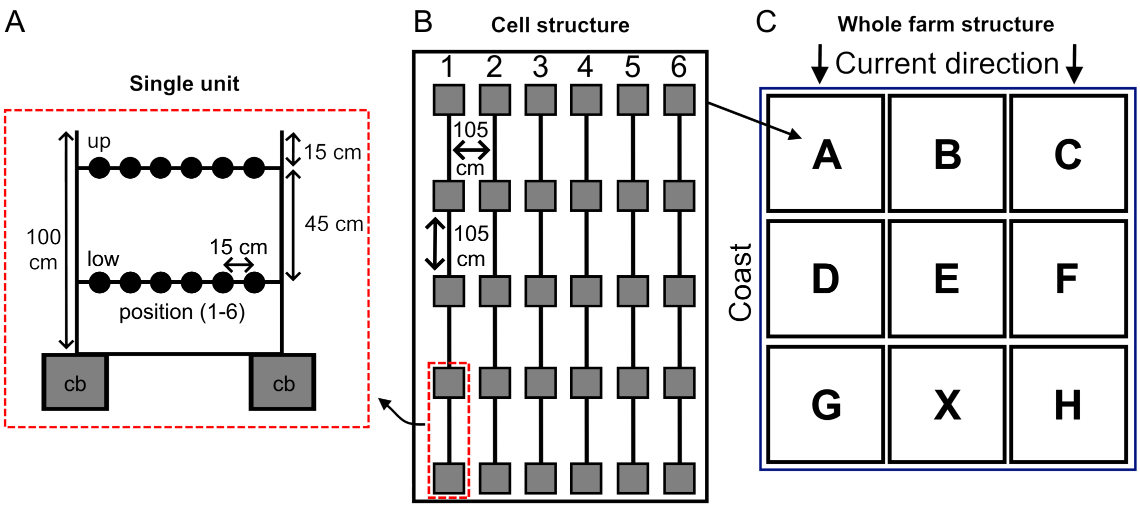

FIGURE 2
Scheme of the sponge farm. **(A)** details of a single unit of a strand (a full strand is made by 4 units). Two concrete blocks (cb) support two iron bars, between which two nylon twines are pulled; 6 sponges (black circles) per twine at the two depths, up-low, are placed (24 on the complete strand). **(B)** structure of a single cell made of six strands (1-6) viewed from above: dimensions approximately 4 x 5 meters in length and width, respectively. **(C)** comprehensive map of the farm viewed from above, all cells **(A–H)** are shown. The left side is near the coastline while the right side is exposed to open sea. The main water current in the area flows downwards.

2.3 Economic analysis

The total costs of initial setup and annual maintenance comprising materials (concrete blocks, iron bars, bitumen coated nylon twine, zip ties) and manpower (scuba diving preparation of the structures, monitoring and sponge measuring) have been assessed. At the end of the study, the quality and the market value (wholesale price) of farmed sponges has been explored by experts in the field from the Spugnificio Rosenfield sponge farm of Muggia, Italy, which professional activities consist in importing wholesale farmed or harvested sponges, processing and modelling sponges to obtain highly requested spherical shapes and final resale. The quality of sponges primarily depends on their skeleton shape and texture. Wild sponges, which grow attached to the substrate, develop irregular morphologies and textures that are less commercially desirable. In contrast, sponges cultivated on suspended lines, experiencing no spatial constraints, grow freely in all directions resulting in more spherical shapes and homogeneous texture, which are likely to be defined as 1st quality and highly requested on the market. Last, potential profits for the farmers (revenues minus costs) were estimated and compared with mean profits made by selling collected wild sponges of similar size. Two estimations were made, at t4 (3 years), where sponges reached the commercial size and a forecasted t6 (4 years of the current study, plus 2 years of forecasted growth based on our findings, assuming a constant growth and the absence of potential stressful events), when the farm productivity would be stable and settled. The number of marketable sponges was estimated based on survived individuals at t4. At t6, no difference in numbers was assumed, based on the premise that in an operational farm (unlike our study, where dead/ detached sponges were intentionally not replaced) blank spaces are constantly refilled, thereby minimizing the loss of individuals. We considered as revenue only the wholesale price of sponges, excluding additional costs for buyers, as these were not relevant to the study's focus on the farm's economic feasibility. Similarly, for collected sponges, we decided to consider as profit the wholesale price for buyers. We excluded the presence of significant additional expenses for sponge fishers, since most of sponge collection in the Caribbean is performed by "staff and hook" or apnea diving in shallow waters with small artisanal boats as support, with almost absent expenses and equipment. In the Bahamas, sponge collection in rural local communities is a sporadic activity carried out by fishermen. For this reason, the cost of the boat has not been considered, as it is already covered by their main fishing operations and does not represent an additional expense. Since the study ended in 2014, prices were updated not by a simple conversion of the past vs current global value of the dollar. We investigated the current local value at the Bahamas of each component for both costs and revenues and reported in American dollars (USD).

2.4 Environmental variables from satellite data and anomalies analysis

To provide a general overview of the physical conditions during the experiment, we reported the seasonal variations and anomalies of several environmental variables during the study period. Satellite data of seawater temperature, chlorophyll-a, oxygen, salinity, nitrates, phosphates, silicates and biomass for the experimental site and timeframe were obtained from the product Global Ocean Physics Reanalysis (doi.org/10.48670/moi-00021), dataset "cmems_mod_glo_phy_my_0.083deg_P1D-m", and the product Global Ocean Biogeochemistry Hindcast (https://doi.org/

10.48670/moi-00019), dataset "cmems_mod_glo_bgc_my_0.25deg_P1D-m", on Copernicus Marine Service. Details are described in Supplementary Data 1.

Temperature data (from 1987 to 2021) were analyzed using the R package "heatwaveR" to assess Heatwaves "MHW" and Colds Spells "MCS" during the study period, details of the protocol are reported in Supplementary Data 2. Following the same procedure, anomalies over 90^{th} and under 10^{th} percentile were also detected for each other variable (in this case the climatology was calculated over the 1993-2021 period due to limited extent of the available datasets).

2.5 Statistical analysis

Generalized Linear Mixed Models (GLMM) were run to investigate statistical differences in growth rate among different (1) rows (upper-lower), (2) position (1-24), (3) cells (A-H) and their interaction with time (Supplementary Table 1). For (1), we set a GLMM with growth rate as dependent variable, the interaction of row and time as fixed factors, and sample id as random factor. For (2), a GLMM was set with growth rate as dependent variable, the interaction of position and time as fixed factors, and sample id as random factor. For (3), a GLMM was set with growth rate as dependent variable, the interaction of cell and time as fixed factors, and sample id as random factor. To assess differences in survival (death + detach) of sponges among rows, position, cells, three binomial GLMM has been set with alive/dead organisms (as 0/1) as dependent variable (Supplementary Table 1). As for growth rate, the first model included the interaction of row and time as fixed factors, and sample id as random factor. The second model included the interaction of position and time as fixed factors, and sample id as random factor. The third model included the interaction of cells and time as fixed factors, and sample id as random factor. For all models, pairwise comparisons (Tukey test) were run when significant differences were found. The statistical models were developed under the R statistical environment v.3.6.2 (R Core Team, 2021) using package stats (R Core Team, 2021), lme4 (Bates et al., 2015) and emmeans (Lenth, 2023).

3 Results

A total of 384 sponges were analyzed 6 times during a 4 years period for a total of 2304 measurements (1152 up and 1152 down) (Figures 3B–F). Sampling intervals were November 2010, July 2011, January 2012, July 2012, February 2013, and September 2014.

3.1 Growth and mortality analysis

The average sponge volumes increase rate at t5 measured 380% ± 275%, with the minimum individual value recorded in cell C (-80%) and the highest record in cell D (1480%) (Table 1).

Analyzing the different part of our farming structure, no differences in growth were observed between up and down rows of cells at every time interval and no differences were found between the positions 1-24 on the two rows (Supplementary Table 1). Considering the whole period t0-t5, no differences in growth rate were observed between cells. At t5, differences were observed only between cells C-D and C-G (Figure 4; Supplementary Table 1).

A total of 54 out of 384 sponges (14%) were lost to death or detachment during the study, with no statistical differences between rows, position, and cells (Figure 5; Supplementary Table 1).

As a personal observation of the authors, since t0, the sandy-orange cut surfaces of the fragments were covered with regenerated pinacoderm within a couple of weeks. We observed that the self-cleaning capacity of the sponges, so evident in wild specimens (Figure 3A), was initially weakened in the transplanted fragments, which tended to be covered by both sediments and epibionts, and it was recovered only one or two years after the start of culturing. Interestingly, this restoration corresponded with the recovery of the initially lost, probably due to cutting and transplantation, endobiont organisms as worms, shrimps, etc. To date, the role of organisms living inside sponges and the nature of their associations are still under debate; if benefits for endobionts (food, shelter) are easier to assess, the benefit for the sponge have not been determined (Westinga and Hoetjes, 1981; Wulff, 2006; Martin and Britayev, 2018; Goren et al., 2021; Lira et al., 2024). Here, we could roughly suggest, as a personal reflection based on qualitative observations, a potential role of these organisms in cleaning the surface of sponges.

3.2 Environmental variables and anomalies

Heatwaves and Cold spells, together with Chl-a, oxygen, salinity, nitrates, phosphates, silicates, biomass anomalies calculated for the study period are reported in Figure 6 and Supplementary Figure 1. The climatic conditions of the area have been rather stable for each variable during the study without co-occurring anomalies, with the exception of October/November 2012, during t3-t4, where an intense drop of temperature from the 90th percentile down to a cold spell event (below 10th percentile) took place. Concomitantly, a salinity anomaly below the 10th percentile and anomalous peaks over the 90th percentile of primary productivity and biomass in the area were observed. These anomalies co-occurred with Hurricane Sandy, hitting the Bahamas around the end of October 2012. Nitrates, phosphates and silicates did not show any associated anomaly.

3.3 Economic analysis

Experts from the Spugnificio Rosenfield sponge farm of Muggia, in the person of Elena Pesle, stated that sponges reached selling size at t4 and defined their quality as first quality for the 80% of sponges, the remaining 20% as second quality. Under their supervision, we assessed the costs (all values reported were updated at 2023) for the initial setup to $387 plus $15 for the annual maintenance activities for a total of $432 at t4. Maintenance consisted mainly in checking the structure integrity and the cleaning of ropes from fouling,

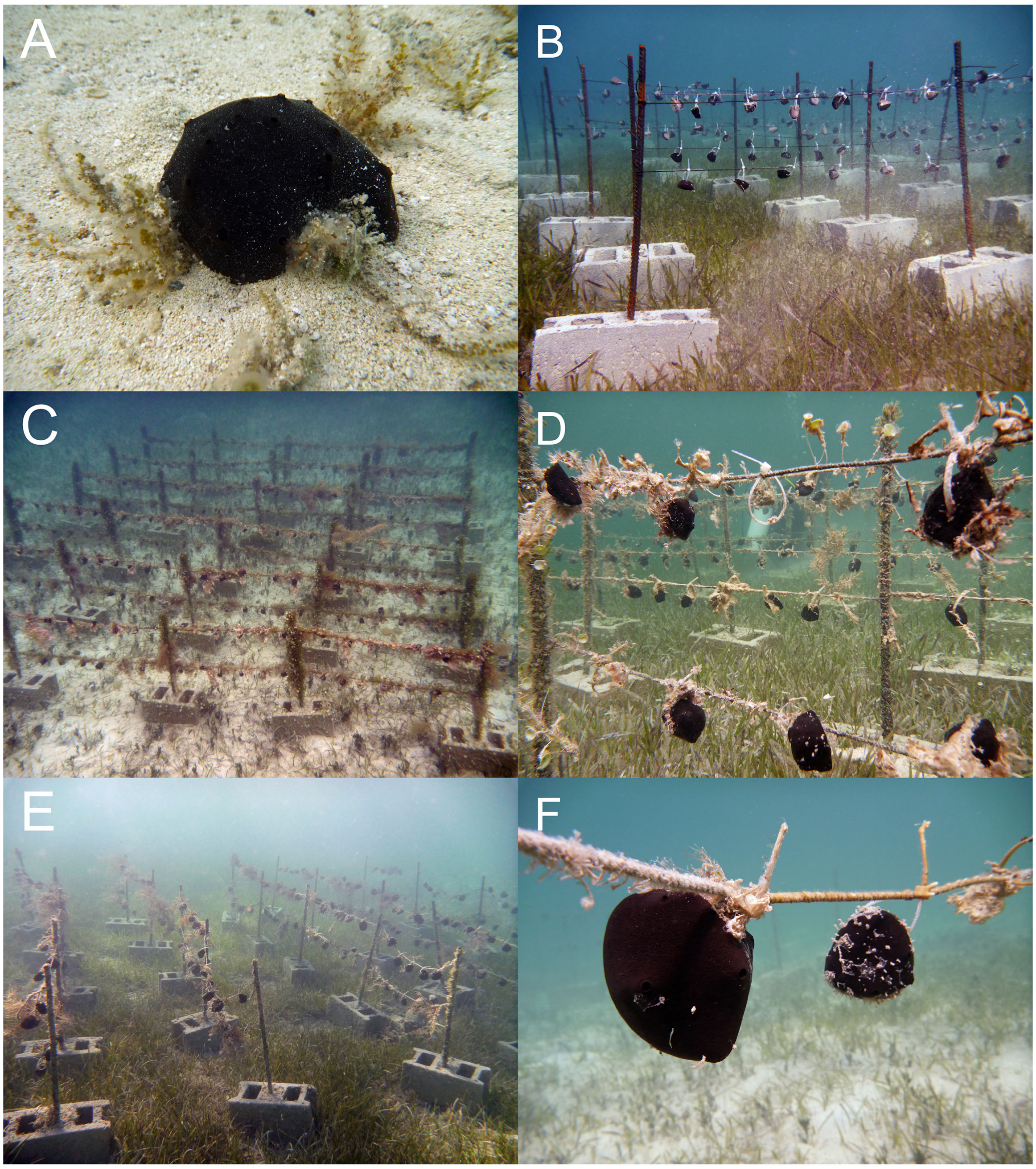

FIGURE 3
Experimental setup. **(A)** wild Spongia anclotea specimen, **(B)** t0, orange color indicates the fresh cutting surfaces, **(C, D)** overview of farming area and a zoom on a detached individual at t1, **(E)** t4, **(F)** individuals at final sampling time t5.

activities that can be performed by farm operators on a monthly basis, without the need of external experts and extra costs (Table 2). A common stock of collected wild sponges at entry-level commercial size, usually made by 50% first quality, 50% second quality, is worth $1 per sponge, while a same size farmed high-quality stock is worth about $2/2.5 per sponge. At t4, 348 out of 384 sponges survived and this number was used for the analysis. Based on our results about growth and survival rate of farmed sponges, at a hypothetical forecasted t6 (assuming a constant growth and the absence of potential stressful events), profits made by *Spongia anclotea* farmed individuals would exceed wild sponges' collection profits ($618 vs $547) (Table 3).

4 Discussion

Marine sponges are a fundamental component of the benthic ecosystem due to their abundance, function and services like shelter provision (Herrnkind et al., 1997; Coppock et al., 2022), bioremediation (Amato et al., 2024) and water filtration (Dayton et al., 1974; Ayling, 1981; Costello and Myers, 1987; Maldonado et al., 2012, 2017; De Goeij et al., 2013; Pawlik and McMurray, 2020). Commercially, sponges request is constantly increasing for cosmetic, industrial, pharmaceutic applications and the supply from natural populations, which are mainly located in developing countries and put under excessive stress, is becoming increasingly

TABLE 1 Sponge growth summary.

time	Mean volume	sd. Volume	Mean % increase	sd. %
t0	149.40	56.09	0	0
t1	205.28	83.58	38%	35%
t2	321.15	145.71	119%	77%
t3	388.82	174.513	167%	99%
t4	442.96	230.20	209%	150%
t5	668.57	355.94	380%	275%

Comparison of mean and standard deviation of Volume and Growth rate at each time interval.

unable to support the demand. At the current state of the art, farming sponges requires simple setups and cheap tools (Verdenal, 1990; Duckworth and Battershill, 2003; Page et al., 2005), which could benefit local communities in developing countries who lack large capitals to invest. For these reasons, in our study, we decided to adopt a structure of sponge farming which potentially meets these needs and can be assembled with simple materials (concrete blocks, iron bars and nylon twines), involving low-cost processing and maintenance while guaranteeing efficient sponge growth, as already observed in multiple studies (Corriero et al., 2004; Friday, 2011; Çelik et al., 2011; Maslin et al., 2021; Bierwirth et al., 2022).

The two most important parameters in sponge farming are growth and survival rates (Duckworth, 2009; Santiago et al., 2019; Mohite et al., 2020; Ou et al., 2020). Looking at our results, no significant differences in both growth and mortality were found for the two depths, the position on the row, and cell. From a structural point of view, these homogeneous results indicate our farm setup as a strong and efficient farming environment where, at least for this species, the different depths of farming do not affect sponges' growth and so does the position on the twine or the position of the cell. According to Duckworth et al. (2007) farmed sponges' volume should increase by 100% per year in order to be considered profitable. In our study, at t5 (4 years), the mean rate of volume increase accounted for 380% (individual values ranged from a minimum of -80% to a maximum of 1480%). This wide range of results may be related to the variability in terms of state of health, resistance, and resilience among the numerous donor individuals. Within donor sponges, some individuals could have been already in suffering health condition, or they could be less genetically gifted, leading to a shrinkage in volume over time, while others, more suited for growth, exhibited the highest values. However, compared to other taxa, records about sponge growth and shrinkage rates in literature are scarce and limited to a few species (Ayling, 1983; Barthel, 1986; Hoppe, 1988; Garrabou and Zabala, 2001; Duckworth et al., 2007; De Caralt et al., 2010; Osinga et al., 2010; Zea et al., 2010; Page et al., 2011; Padiglia et al., 2018; Gökalp et al., 2019; Li et al., 2023). Moreover, within this deficiency of data, farmed sponge growth has been demonstrated to be species specific, highly variable [from negative growth (Hoppe, 1988; De Caralt et al., 2008; Page et al., 2011; Di Camillo et al., 2012), to 2000% increase per year (Pronzato and Manconi, 2008; Page et al., 2011; Schippers et al., 2012)] and easily influenced by several factors like seasonality, water temperature, water transparency and currents (Barthel and Theede, 1986). Thus, a clear picture of growth performance in relation with different farming techniques is not available (Corriero et al., 2004). The only study on *Spongia anclotea* was carried out by Oronti et al. (2012), which reported a growth rate of 6.2 cm^3/month over a three year period. We recorded a better growth rate (11.28 cm^3/month), but it should be considered that the smaller initial size of sponge fragments in Oronti et al. (2012) may have influenced the velocity of growth. Within the genus *Spongia*, Çelik et al. (2011) investigated line-farmed *Spongia officinalis* specimens and registered growth rates of 5-17% in two years. Our farming system of *S. anclotea* from Cape Eleuthera resulted in better performance. Environmental factors, like seasonal variations of water temperature, were demonstrated to potentially influence sponge growth. In locations with marked seasonality like temperate areas, growth is higher during the warmer season (Handley et al., 2003; Kelly et al., 2004; Page et al., 2005). Similarly, studies in Australia found a positive relationship between growth rates and temperature (Duckworth et al., 2007). Other research works, on the contrary, found no effect of seasonality on sponges' growth (Ayling, 1983; Hoppe, 1988; Costa et al., 2015). Being the Bahamas in a semi-tropical area, the temperature range in our study area may be too limited to affect sponge growth rate significantly or *S. anclotea* may be one of those species which are not particularly affected by the variations of water conditions. However, during t3 - t4, a drop in growth was observed in some farm cells. At that time, a long cold spell took place at Cape Eleuthera, caused by the impact of Hurricane Sandy on the area, potentially slowing down the growth of sponges. Considering the scarcity of studies on sponge growth, our results could help to fill this gap in sponge science.

In aquaculture, another important issue is mortality of organisms since it means a complete loss of time and money invested. In our study, mortality was limited, only 54 out of 384 sponges died (or have been lost) during the study. Verdenal (1990) stated that a good farm should yield about 90% of survival of organisms per year. Our farming system accounted for a final 86% in a 3-year span, thus being in line with the standard. This result is noticeable if compared with survival rates reported in literature, which ranged from 0 to 100% of survival across different farming methodologies and species (Osinga, 2010; Gökalp et al., 2019, 2020; Bierwirth et al., 2022). Oronti et al. (2012) recorded a 12.5% mortality rate for *S. anclotea* in three years of farming. The higher mortality (14%) we observed may be due to the longer duration of our study. For *S. officinalis*, Çelik et al. (2011) reported a survival rate of 82-85% of specimen farmed with a similar line technique to the one we adopted. Due to the absence of existing literature data on *S. anclotea*, we were unable to determine if our results on growth and survival represent just the intrinsic growth rate of this species or if they are influenced by the farming methodology and location. In our farm, most of lost sponges were due to detach. Sponge death was observed only during the first 12-18 months after transplantation. We decided for scientific purposes to not add new sponges on blank spaces but, in a context of economic

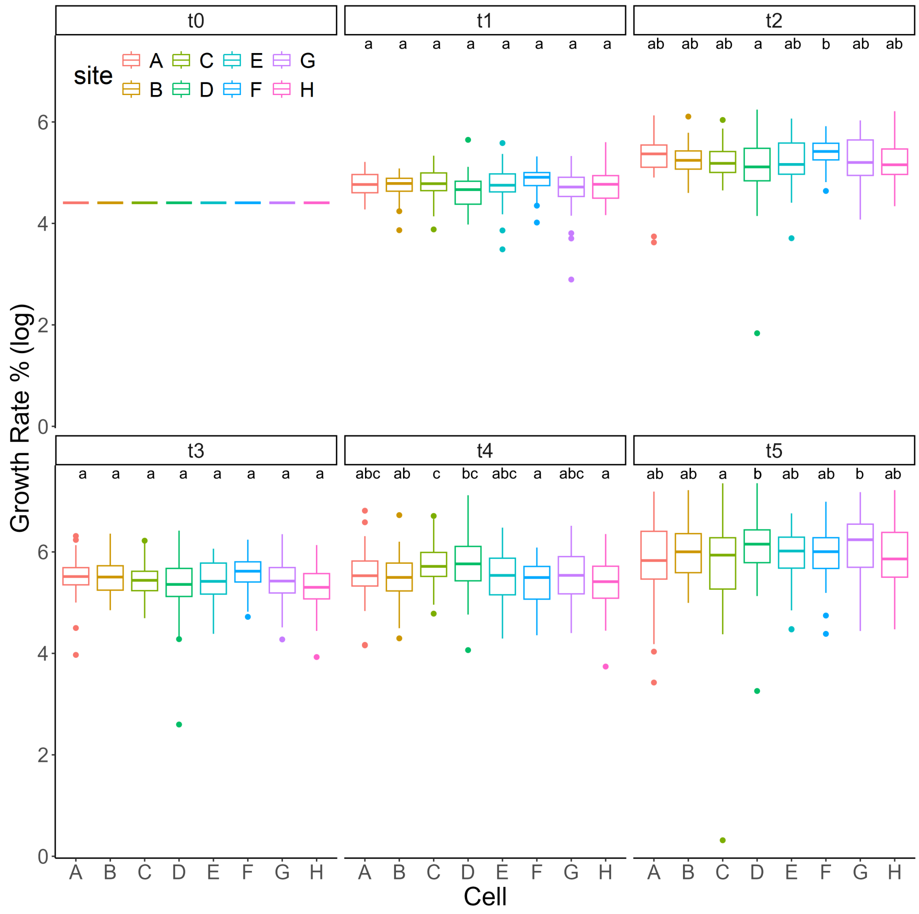

FIGURE 4
Growth analysis. Growth (log scale) of S. anclotea for each farming cell **(A–H)** at different time intervals (t0-t5).

activities, it would be quite easy to fill the holes with new sponges collected in the area (sometimes detached sponges are still in the vicinity of the cells) and maintain the farm fully operational.

Another key factor for both growth and survival rates is the hydrodynamics of the area. Growth rates of farmed sponges were shown to increase with current flow (Wilkinson and Vacelet, 1979), which provides more food particles, until it becomes strong enough to cause physical damage to sponge tissues (Duckworth et al., 1997; Bannister et al., 2007). Duckworth (2003) found that individuals of Latrunculia wellingtonensis farmed in areas with strong water motion grew three times bigger compared to areas with weak currents. Conversely, in area where strong currents cause excessive suspension or where weak currents deposit large amounts of particles, sponges may be buried, with detrimental effects on their ability to filter water and, consequently, on their survival (Reiswig, 1971; Osinga et al., 2001; Gökalp et al., 2020). During our study, damage by strong currents and increased suspension caused by Hurricane Sandy could justify the weak growth observed during t3 – t4. Plus, the registered peak of Chl-a (most probably an algal bloom), may have additionally impaired the filtering capacity of sponges leading to an even stronger state of stress. Except for the potential acute impact of the hurricane, no other evidence of the effect of hydrodynamics were observed since sponge growth and mortality in different cell positions, and consequent different exposure to currents, did not show clear picture of potential interactions. This suggest, on one hand, that S. anclotea may be tolerant to average currents and suspension, and, at the same time, that the choice of the area (nearshore and not affected by strong currents and waves) and the design of the sponge farm were proficient for this species. Thus, this confirm that finding a proper location and plan a smart farm design is a key factor to maximize the overall efficiency and productivity.

The following step of this study was assessing the commercial quality of the farmed sponges. Experts from the Spugnificio Rosenfeld sponge farm of Muggia stated that most of the sponges were over the minimal commercial size already at time t4 and that about 80% of them were defined as first quality sponges, the remaining 20% as second quality. At t4, the overall estimated profit for farmers for 348 sponges was $264, while a standard stock of natural harvested sponges (usually made by 50-50 of 1st and 2nd quality sponges) is usually worth $348. On a longer time scale, 6 years, the profitability of our farm exceeded the standard stock at same sponge volume ($618 vs $547). It must be considered that the time needed to reach commercial size and the consequent t6 could be easily reduced by using initial fragments of larger size. Here, being a pilot study, we chose to obtain 3-4 small fragments for donor sponge. Just starting from fragments of double the size would

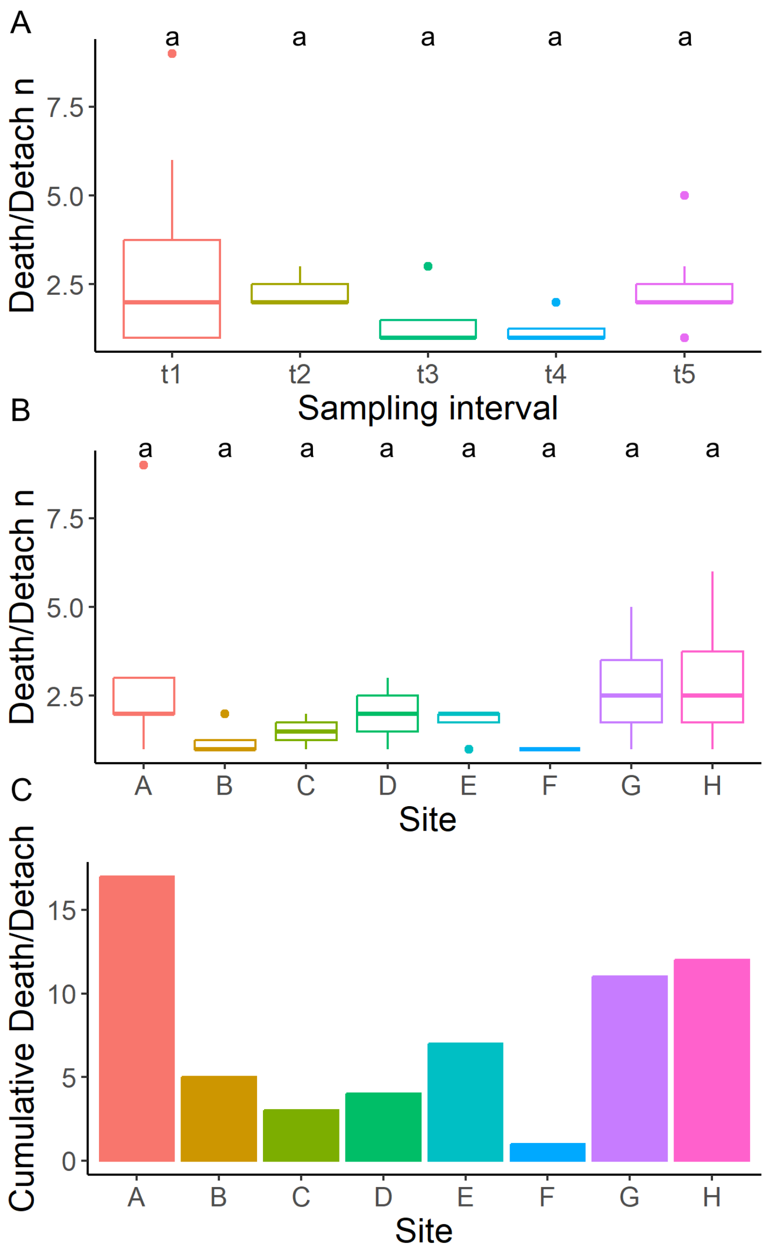

FIGURE 5
Mortality analysis. **(A)** boxplot of detached/dead individuals for each time interval, **(B)** boxplot of detached/dead individuals for each farming Cell, **(C)** total number of detached/dead individuals for each farming Cell.

cut the farming time in half with consequent economic benefits for producers and avoiding issues with mortality at smaller sizes.

As a conclusion, our results suggest this farming system as a valid alternative to harvested sponges since its profitability in the short/mid-term is higher. In addition to the economic and commercial aspects, our results are also significant from an ecological perspective since finding new sources of sponges, like aquaculture, could be a key tool to reduce stress on their populations. Furthermore, the presence of open-sea sponge farms, acting as high-density reproduction areas, could provide a significant amount of fragments, propagules and larvae for the surrounding regions, thus favoring the restocking of wild populations affected by fishing pressure and natural mortality events (Leong and Pawlik, 2010; Pawlik, 2011). On the other hand, long-term farming could increase the risk of confined in-situ reproduction with consequent genetic degradation over time impairing their fitness and survival (Pérez-Portela et al., 2014). Plus, the high density of individuals could favor the outbreak of sponge diseases, predators and parasites, as observed worldwide in different species and locations (Webster, 2007; Maldonado et al., 2010; Page et al., 2011; Wulff, 2012; Choudhury et al., 2015), that could then spread and harm wild populations.

Further studies are needed to test the efficiency of this farming technique in the long term both on S. anclotea and other

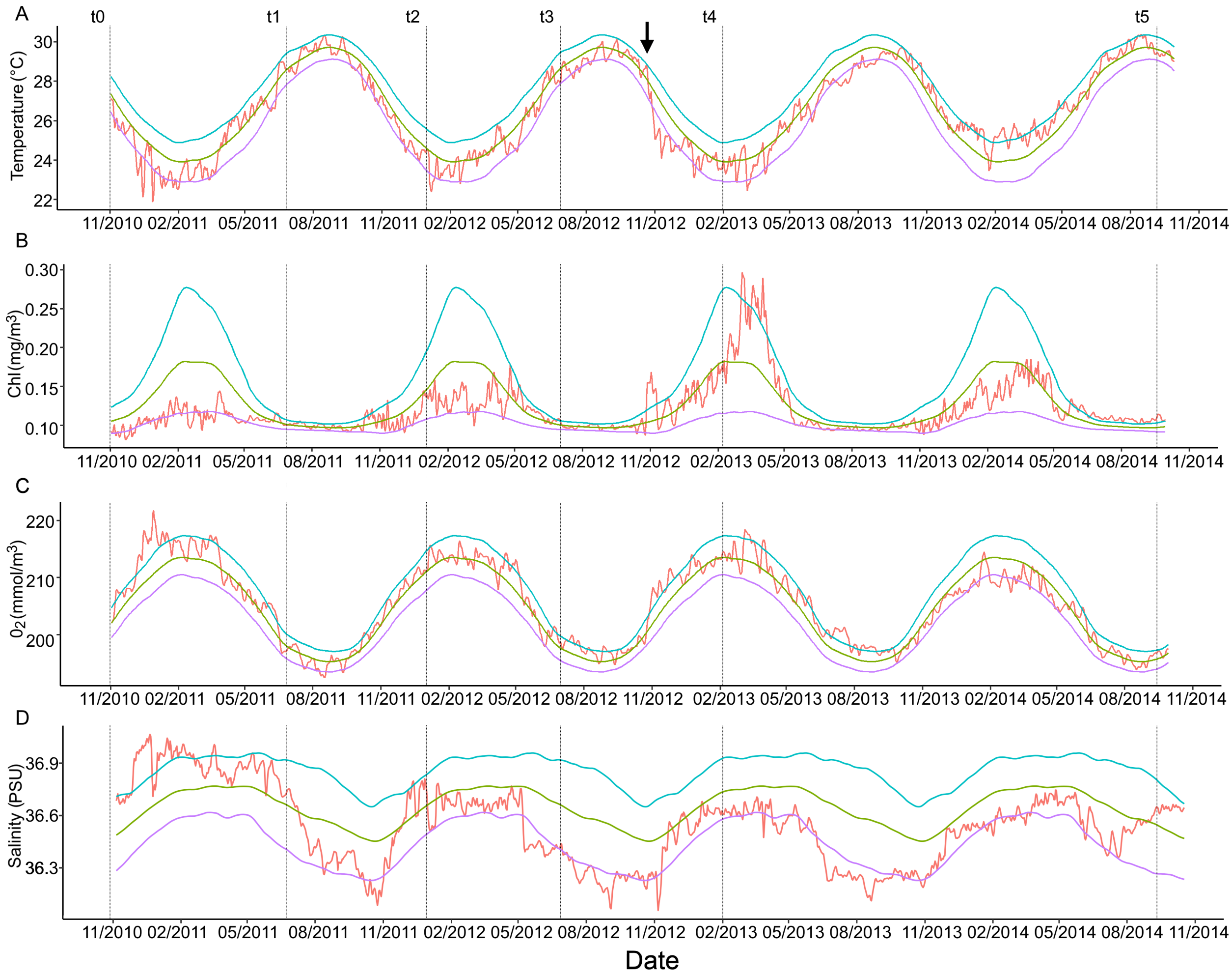

FIGURE 6
Environmental factors anomalies. Red line is the observed value of the variable, green indicates the climatology, blue and purple line indicates the 90th and 10th percentile for each variable. **(A)** Temperature, **(B)** Chlorophyll-a, **(C)** Oxygen and **(D)** Salinity. Dotted lines are time intervals t1-t5. Black arrow indicates the arrival of Hurricane Sandy at the study site.

TABLE 2 Economic assessment.

Cell setup costs		
Building materials		
	Number	Cost tot. US $
Blocks	30	79.2
Iron bars	30	88
Nylon twine	1	8.8
Ziptie	300	11
Manpower	1 person 2 days	200
Total costs ($)		387
Annual maintenance		15

Building and maintenance costs for the whole farm setup (expressed in US Dollars).

TABLE 3 Economic analysis.

Profit Farmed vs Harvested Sponges		
	T4 (3 years)	T6 (6 years)
Cost of farmed stock	432	477
Price paid by buyers for farmed sponges	696	1095
Price paid by buyers for harvested sponges	348	547
Profit farmed	264	618
Profit harvested	348	547

Cost, sell value and profit (Sell value – Cost) for 348 farmed and harvested sponges at t4 (time where legal size of farmed sponges is reached) and forecasted t6 (time where profits of farmed sponges overtake harvested sponges profit).

commercially important sponge species. This would allow to obtain a clearer picture of all the potential benefits, both economic and ecological, or unexpected detrimental effects, on the ecosystems and economy of local communities all over the world.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

GM: Data curation, Formal Analysis, Writing – original draft, Writing – review & editing. RA: Conceptualization, Investigation, Writing – review & editing. AB: Conceptualization, Investigation, Writing – review & editing. MN: Writing – review & editing, Formal Analysis. EP: Writing – review & editing, Funding acquisition, Project administration, Supervision. AT: Writing – review & editing. MA: Conceptualization, Funding acquisition, Investigation, Project administration, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1519832/full#supplementary-material

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