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Deploying artificial nurseries in port areas: A complementary strategy to fisheries management for supporting coastal fish populations

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ABSTRACT

Conservation measures are essential for supporting biodiversity in areas impacted by human activities. Over the last decade, efforts to rehabilitate fish nursery habitats in ports through eco-engineering have gained attention. While these interventions show promise at a local level such as increased juvenile fish densities on artificial eco-engineered habitats compared to unmodified port environments there has been no comprehensive assessment of their contribution to coastal fish population recovery or their effectiveness relative to traditional conservation measures like fishing regulations. In this study, we employed the ISIS-Fish model, which integrates fish population dynamics with fisheries management, to examine the commercial coastal fish species, white seabream (*Diplodus sargus*), in the highly artificialized Bay of Toulon. By simulating different rehabilitation scenarios and fisheries management strategies, we provided the first quantitative evaluation of eco-engineered structure deployment in ports, covering 10% and 100% of the available port's linear extent. We compared these rehabilitation outcomes against the effects of enforcing strict minimum catch sizes.

Our findings indicate that while port nursery habitat rehabilitation can contribute to fish population renewal and increase catches, the benefits remain limited when project scales are small, especially when compared to the impacts of strict fishing regulations. However, a synergistic effect was observed when combining nursery rehabilitation with fishing control measures, leading to significant improvements in fish populations and catch yields. This study offers the first quantitative analysis of nursery habitat rehabilitation in ports, highlighting its potential as a supplementary strategy to fisheries management, though less effective on its own than robust regulatory measures.

1. Introduction

Human activities have led to a significant decline in marine biodiversity (De Vos et al., 2015; Pimm et al., 2014) and fish stocks (Yan et al., 2021). The two main drivers of this change are overfishing and habitat loss (Yan et al., 2021). This is especially true in coastal areas where sources of pressure accumulate. Coastal urbanization processes, and particularly the development of port areas (Meinesz et al., 1991), have led to the destruction and transformation of fish habitats (Mooser et al., 2021; Poursanidis et al., 2018). However, coastal habitats are critical assets for the sustainability of fish stocks, given their indispensable role as nursery grounds. Indeed, these areas can host high concentrations of juvenile fish, enhance juvenile growth with high food availability, decrease mortality due to predation, and contribute in renewing adult populations (Beck et al., 2001; Dahlgren et al., 2006). The survival of fish juveniles in nursery areas is influenced by density-dependent factors, such as the carrying capacity of the habitat, predation, and food availability (Le Pape et al., 2020; Planes et al., 1998) determining juvenile mortality and mainly conditioned by the structural complexity of the habitat (Connell and Jones, 1991; Scharf et al., 2006). Therefore, the quality and the surface area of nurseries are pivotal, determining the influx of new recruits into adult populations each year (Wilson et al., 2016). The increasing degradation of nursery habitats, combined with rising fishing pressure, amplifies the risk of population extinction, thereby posing significant ecological and food security issues (Yan et al., 2021). Considering this, it has become imperative for managers to proactively implement solutions to mitigate these detrimental effects.

To address the decline in fish stocks, European legislation has

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implemented regulations such as the establishment of a minimum catch size for both commercial and recreational fishing (Cardinale et al., 2017). Nevertheless, the complex socio-economic situation in the Mediterranean Sea sometimes hinders the efficacy of management governance and restrictions are seldom applied in practice (Cardinale et al., 2017), particularly by recreational fishing with high rates of fish caught below the legal size limit (Font and Lloret, 2014). More recently the European Commission implemented a law about nature restoration for the long-term recovery of nature including a specific part for marine ecosystems. It's aimed at giving a framework and fundings to support restoration projects already existing and promote new strategies (European Parliament and the Council of the European Union, 2024). In coastal ecosystems efforts to mitigate the impact of artificialization on fish populations have intensified, with the concept of 'greening' existing man-made 'grey' structures gaining momentum. Various eco-engineering projects of different scales have been implemented, focusing on enhancing the structural features of these artificial structures to attract colonizing communities and support coastal populations, while maintaining their primary function of coastal protection (Airoldi et al., 2021; O'Shaughnessy et al., 2020). Among these initiatives, small-scale artificial fish nurseries, ranging from 1 m^2 to 50 m^2, are increasingly being deployed in marine urban areas, in particular in Mediterranean ports, to rehabilitate their nursery functions (Bouchoucha et al., 2016; Joubert et al., 2023; Patranella et al., 2017). These projects are based on the idea that juvenile fish are subject to very high predation and mortality rates due to the lack of complexity of artificial habitats in ports areas. By enhancing the structural complexity of these habitats, eco-engineering projects aim to offer fish juveniles increased shelter and significantly reduce predation thus creating artificial nurseries. These artificial nurseries can be integrated during port construction or, more frequently, added later through the installation of artificial 3D designed microstructures (Bouchoucha et al., 2016; Joubert et al., 2023; Mercader et al., 2017; Patranella et al., 2017).

The surface area of nurseries is essential for the maintenance of nursery-dependent fish populations (Le Pape and Bonhommeau, 2015). The purpose of deploying artificial nurseries in ports is thus the conservation of fish populations on a larger scale than the port itself. In order to verify the ecological validity of this approach, numerous studies have evaluated whether artificial nurseries meet the key criteria of functional nursery habitats as defined by Beck et al. (2001); Dahlgren et al. (2006). However if monitoring these structures has revealed their effectiveness in increasing local juvenile fish abundance (Bouchoucha et al., 2016; Joubert et al., 2023; Patranella et al., 2017), existing studies are confined to small-scale projects, and surveys exclusively concentrate on the evaluation of fish abundance within ports. The connectivity between artificial fish nurseries and adult populations remains unexplored and the real capacity of these initiatives to support the renewal of adult fish populations with quantitative data has never been assessed (Macura et al., 2019). Currently, this lack of investigation hinders the determination of the effective contribution of these projects in truly rehabilitating the nursery function within ports. The recurring issue of insufficient insight into the true large-scale ecological benefits of marine environmental restoration projects is often inadequately addressed or entirely overlooked in many studies (Airoldi et al., 2021). In a world where financial resources are constrained and decisions regarding interventions must be prioritized, quantifying this contribution would not only aid stakeholders to compare the potential effectiveness of various measures more efficiently (Ward et al., 2022) but also to dimension projects. Achieving this requires anticipating the ecological outcomes and their impact on catches resulting from the management strategies employed (Airoldi et al., 2021). Here, our objective is to address a first quantitative assessment of the tangible impact of establishing artificial nurseries in ports on fish stocks and to provide a quantitative comparison between different restoration and fishing management measures.

Spatial models are widely used for prediction and decision-making in ecology (DeAngelis and Diaz, 2019), especially to predict intricate interactions within ecosystems, whether focusing on population dynamics, anthropogenic activities (Glaum et al., 2020; Plagányi et al., 2014) or conservation strategies (Bach et al., 2022; Gernez et al., 2023). They enable an assessment of the effectiveness of various scenarios representing adjustments to a reference state to model the actions implemented by management strategies (Refsgaard et al., 2007). Hence, spatial models are increasingly used to evaluate the effectiveness of restoration or rehabilitation measures, by comparing their impact with that of other management strategies (Possingham et al., 2015). In this study, we used the multi-fleet spatially explicit ISIS-fish model which is capable of accurately describing both the life cycle of the fish species studied and the fishing activity targeting them, while also being able to spatialize this information (Mahévas and Pelletier, 2004; Pelletier et al., 2009). To evaluate the impact of five management scenarios (S1, S2, S3, S4 and S5) on fish stock size, biomass and catches. In scenario 1 (S1), we tested the consequences of implementing artificial structures in ports, covering 10% of the port area, as a potentially attainable objective in the short term, and in scenario 2 (S2) the hypothetical case of 100% of the available port area equipped with rehabilitation solutions. Then, in scenario 3 (S3) we studied the impact of applying the strict application of existing regulations in terms of minimum catches. Finally, we evaluated maximal expected impact scenario with implementing both artificial structures in ports and a strict catch regulation in two scenario, scenario 4 (S4), resulting in the combination of scenarios 1 and 3 and scenario 5 (S5) resulting in the combination of implementing artificial structures in ports, covering 30% of the port area and scenario 3.

2. Material and methods

2.1. Case study

The study area encompasses the coastal zone near the city of Toulon (France) between Cape Sicié to the east (43.045975°E; 5.859140°N) and Cape Blanc to the west (43.091305°E; 6.371856°N) (Fig. 1), in the southeastern part of the Mediterranean coast. Spanning a surface area of 532 km^2, it covers all the coastal marine areas that are less than 50 m deep (Fig. 1). The Bay of Toulon has a mostly man-made coastline, making it suitable for nursery function rehabilitation measures. Anthropogenic activities mainly include tourism and local professional and recreational coastal fishing. The eastern part of the study area falls within the Port Cros National Park (MPA) (Fig. 1) that includes a controlled zone for marine activities and a reinforced protection zone where only professional fishing is allowed (Fig. 1). This study area therefore offers a number of opportunities for implementing management measures.

Some of these coastal areas possess physical characteristics of nurseries for various marine fish species: they feature shallow habitats (0–3m) protected from prevailing winds and waves, with gently sloping bottoms covered with sand, pebbles, cobbles, or algae-covered rocks (Harmelin-Vivien et al., 1995). Based on these characteristics, we estimate the linear length of natural nurseries at 55,820m, at a scale of 1:500 (see Section SI.1 in Supporting Information for further details). During benthic settlement, a proportion of juvenile fish enter port areas (Bouchoucha et al., 2016; Joubert et al., 2023) and can be hosted in infrastructures at less than 2m depth (docks). We estimate the total linear extent of port nurseries to be 24,771m (Fig. 2).

We focussed on the white seabream (*Diplodus sargus sargus*, Linnaeus, 1758, hereafter *D. sargus*). This coastal, nursery-dependent fish species inhabits areas at depths ranging from 0 to 50m (Harmelin-Vivien et al., 1995) and is of significant economic importance for artisanal and recreational fishers (Vigliola et al., 1998). Its lifecycle is well known (Belharet et al., 2020) and previous studies have already documented the presence of its juveniles in ports, on natural nurseries and on artificial fish nurseries in our study area (Bouchoucha et al., 2016). Current legislation sets the minimum catch size for *D. sargus* at 23 cm in the Mediterranean. Generally, this regulation is not respected, particularly

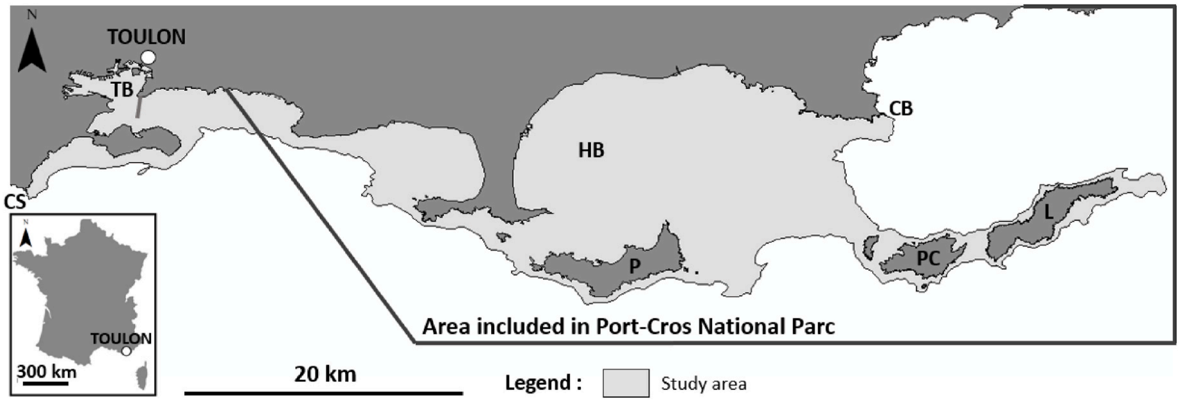

Fig. 1. Map of the study area, TB:Toulon Bay, HB: Hyères Bay, P: Porquerolles, PC: Port-Cros, L: Levant Island, CS: Cape Sicié, CB: Cape Blanc.

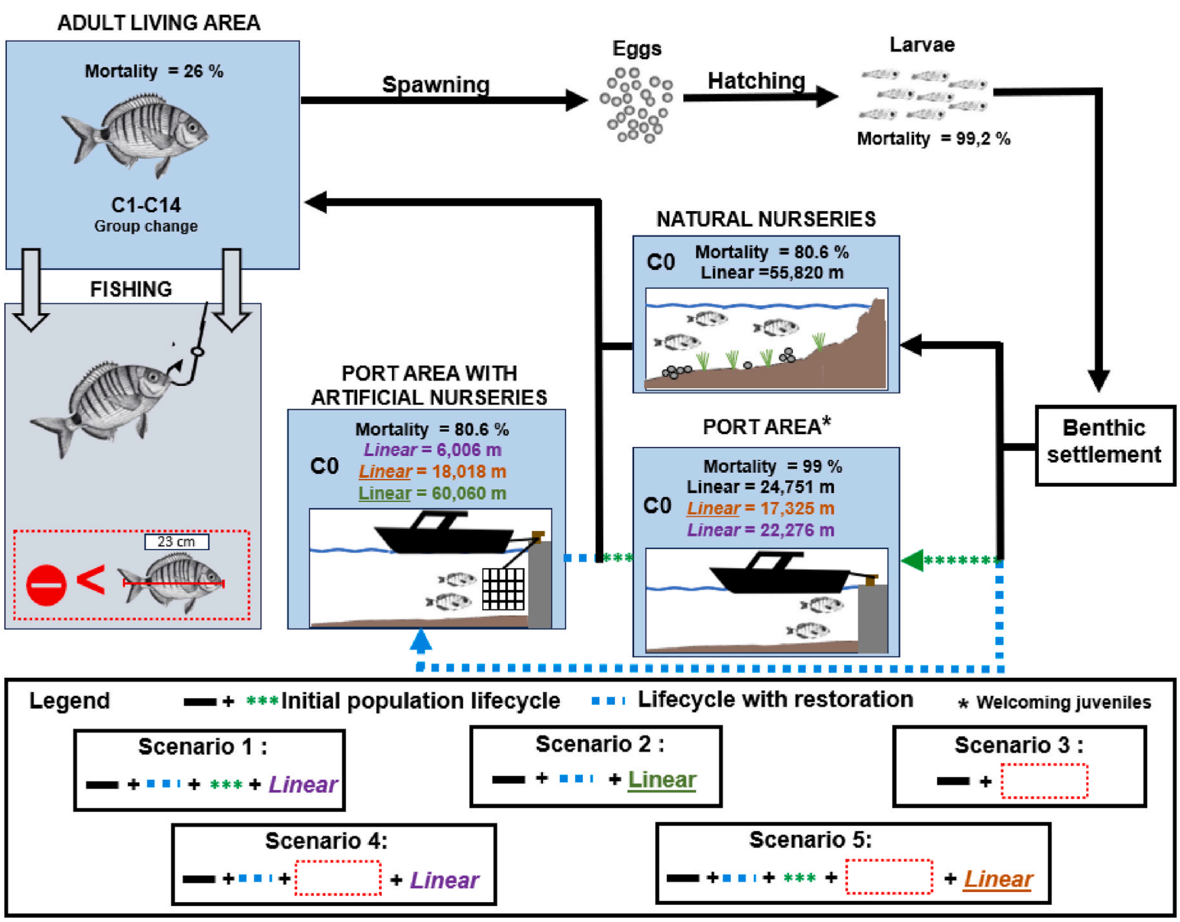

Fig. 2. Parameterization of the *D. sargus* lifecycle model and impacts on the lifecycle of *D. sargus* of conservation measures through scenarios. S1: rehabilitating a fish nursery function on 10% of the docks. S2: rehabilitating a fish nursery function on 100% of the docks. S3: banning fishing under 23 cm in length, S4:application of S1 and S3 together, S5: rehabilitating a fish nursery function on 30% of the docks and S3 together.

by recreational fishing (Font and Lloret, 2014).

2.2. Isis-fish model

The ISIS-Fish modelling platform (Mahévas and Pelletier, 2004) was used to simulate the lifecycle of *D. sargus* exploited by several fishing fleets and test conservation measures on the basis of scenarios. This spatially explicit simulation tool operates through three interconnected sub-models: (i) population dynamics, (ii) fleet dynamics, and (iii) fishery management. The sub models are coupled in space and time, exchanging information in a discrete space and over monthly steps. The first sub-model describes fish population dynamics, accounting for growth, reproduction, mortality, recruitment, and movements between different areas based on the age group of individuals. The second sub-model focuses on fishing activity and describes the spatial dynamics of vessel fishing time as a function of the gear used, the target species, the areas and the fleet to which it belongs. Every month the model simulates species abundance per group, and catches per fleets. Finally, the management sub-model describes the regulations governing the fishing activity based on technical restrictions, spatial limitations of access, catches limitations, etc. (see Mahévas and Pelletier (2004) and Pelletier et al. (2009) for details). Therefore, ISIS-Fish can describe a complex system with many species, many fishing activities and spatial interactions, as well as the population dynamics of a single species exploited by several fishing activities, as was the case here. This flexibility means that the complexity of the description of the system studied can be adapted to the question raised and the available data. Hereafter, we describe the parametrization of the case study following an extensive bibliographic review and experts consultation, the calibration process and the sensitivity analyses carried out to build an operational modelling tool accounting for uncertainties and test the effectiveness of several management scenarios.

2.3. Population dynamics

A description of the juvenile life stages of *D. sargus* and the movements of individuals from juvenile habitats to adult areas was established with a spatialised stage-structured model. The population was partitioned into 15 stages (C_0 to C_{14}) (Belharet et al., 2020). C_0 (the juveniles) includes individuals aged from 1 to 7 months, and stage 1 includes individuals aged from 7 months to 1.5 years. Subsequent stages (2–13) each represent a one-year age interval. Individuals in C_{14} are 14.5 years and older. C_0 individuals settle in both natural or port nurseries. To be able to compare natural, port and artificial nurseries we choose to express nursery areas in terms of linear meters of coastline or structure for more detail see S1.1.4. The settling capacity is fixed at 10 ind.m^{-1}, coupled with the length of each nursery (Doherty, 1991).

Each nursery was assigned with a juvenile mortality rate of 80.8% for natural nurseries (Belharet et al., 2020) and 99% for port ones (S1, Fig. 2). As a result, C0 stage experiment a mortality rate of 80.8% or 99% during their 4 first month after benthic settlement then an adult annual mortality of 26% (Belharet et al., 2020) see SI.1.1.4 for details. After a period of 6 months, the surviving C_0 juveniles leave the nurseries and migrate to the adult living zone as C_1. Each year, the survivors of the stages progress to the higher stages until reaching C_{14}. The adult population (C_1-C_{14}) and its recruitment (*i.e.* moving from C_0 to C_1) are thus limited by both the linear extent of the juvenile habitat and the annual juvenile mortality rate. In the model, the distribution of individuals in the different living zones (nurseries and adult areas) is uniform. All the parameters that shape the life of *D. sargus* in the model were sourced from the literature and are extensively described in SI.1.

2.4. Fishing activities

We distinguished two types of fishing activities: professional and recreational fishing both targeting fish from C_1 to C_{15}. Five professional fishing gears (long lining, trap, gillnet, trammel net and trawl) and two recreational fishing gears (angling and spearfishing) (Table 1) catch about 17.3 t year^{-1} (Système d'Information Halieutique, 2022) and 12.4 t year^{-1} of *D. sargus*, respectively (BVA, 2009; Cadiou et al., 2009). Fishing activity was homogeneously distributed throughout the adult life zone of *D. sargus*. Catches were calculated as a function of time, available *D. sargus* biomass and gear technical parameters describing their ability to catch fish (*i.e.* standardisation, selectivity and accessibility, see SI.1 for details).

Table 1
Annual catches of professional and recreational fishing activities described in the model. Professional catches are calculated from declarative data (REF) while recreational catches are estimates from BVA (2009); Cadiou et al. (2009).

Gears	Fishing activity	Mean annual catches 2019–2020 (kg.year^{-1})	Source of the data	Mean annual catches of the model after calibration (kg.year^{-1})
Long lining	Professional	14,280	Declarative data	14,272
Trap		25		33
Gillnet		780		778
Trammel net		1920		1423
Trawl		300		304
Angling	Recreational	6000	Estimations (Cadiou et al., 2009; BVA, 2009)	6019
Spearfishing		6400		6426

2.5. Calibration

A simulation consists of running ISIS-Fish over a defined period with a value for each parameter and the initial population abundance, resulting in monthly calculations of population abundance by age stages and catches. The period was set to 15 years to ensure the final population size reflects equilibrium. As the fishing parameters mentioned before lack literature values, they were calibrated to meet two objectives: (i) to align with observations or estimates of catches for each fishing gear (Table 1), and (ii) to correspond to the proportion of catches under the regulatory catch limit size of 23 cm for *D. sargus*. In France, professional and recreational fishers catch 19% and 81% of fish respectively under the regulatory catch limit size (Font and Lloret, 2014), despite the prohibition of capture.

Calibration involves running simulations with varied fishing parameter values, selecting the combination that best aligns with objectives (i) and (ii) (see SI.1 for details).

2.6. Management scenarios

The effectiveness of four management scenarios for the *D. sargus* population and catches was tested and compared to a reference scenario (S0) which simulates the current population of *D. sargus* (Fig. 2). S0 is used as an initial state from which the conservation scenarios were tested. Scenarios 1 and 2 (S1 and S2) involved eco-engineering 10% (6,006m including 2477 m of docks already hosting juveniles) and 100% of the docks in the port areas (60,063m including all the docks already hosting juveniles) of the study zone respectively (see SI.2 and Fig. 2). The model incorporates efforts to rehabilitate nursery functions by converting port nurseries and docks into natural nurseries. This involves a reduction in the juvenile mortality rate for already existing port nurseries and the creation of additional natural nurseries for the rest of the port (Fig. 2). These scenarios represent the potential effect of implementing artificial fish nurseries or integrating eco-design in port construction. Scenario 3 (S3) tested the strict application of the already existing regulations on the *D. sargus* catch size alone (strengthening of fisheries controls). Scenario 4 (S4) is a combination of S1 and S3. Scenario 5 (S5) is the combination of implementing artificial structures in ports, covering 30% of the port area and scenario 3 (see SI.2 and Fig. 2).

The effectiveness of each scenario was assessed based on the change in the *D. sargus* C_1-C_{14} population size (fish over 8 cm), as well as on catches, compared to those in S0.

2.7. Uncertainty around parameter values and sensitivity analysis

Numerous studies have investigated the life cycle of *D. sargus*, with a particular focus on its juvenile stages. However, the parameters examined, including the settlement capacity of nurseries (in ports and natural nurseries), the number of arrivals of larvae to coastal habitat per year, and the mortality rates of *D. sargus'* life stages are highly variable in time and space (Bouchoucha et al., 2016; Cheminée et al., 2011; Cuadros et al., 2018; Mercader et al., 2017; Pastor et al., 2013; Planes and Romans, 2004; Vigliola et al., 1998). Nevertheless, modeling the *D. sargus* population is constrained by these parameters. We selected a reference value of these parameters in the models (see above) combined a range of each parameter variation (see SI.3). An uncertainty analysis was then conducted using a simulation design employing random Latin

Hypercube Sampling (LHS). LHS is a stratified Monte Carlo sampling approach within the ranges of defined on each uncertain parameters, assuming equal probability for all values in the range. This approach provides a population abundance range for each scenario, offering insights into the potential variability in outcomes according to the variability in parameter values (see SI.3). Here, 5000 simulations were run for each scenario, each corresponding to a unique combination of values for the parameters. The mean gains or losses associated with a standard deviation for each scenario over the 5000 simulations was calculated compared with S0 so that the result is given in proportion to the result simulated by S0, for abundance N_a in January (equation (1)), mean weight change W_i per individual in January (equation (2)), and catches of professional L_p and recreational L_r fishing (equations (3) and (4)), respectively:

$$N_a = \frac{1}{5000}\sum_{k=1}^{5000}\left(\frac{\sum_{n=1}^{14} c_{n_0}}{\sum_{n=1}^{14} c_{n_s}} - 1\right)*100\ (eqn\ 1) \quad \text{(eqn 1)}$$

$$W_i = \frac{1}{5000}\sum_{k=1}^{5000}\left(\frac{\sum_{n=1}^{14} wc_{n_s} * \sum_{n=1}^{14} c_{n0}}{\sum_{n=1}^{14} c_{n_s} * \sum_{n=1}^{14} wc_{n0}} - 1\right)*100 \quad \text{(eqn 2)}$$

$$L_p = \frac{1}{5000}\sum_{k=1}^{5000}\left(\frac{\sum_{m_p=1}^{5} Ds_{m_p}}{\sum_{m_p=1}^{5} Do_{m_p}} - 1\right)*100 \quad \text{(eqn 3)}$$

$$L_r = \frac{1}{5000}\sum_{k=1}^{5000}\left(\frac{\sum_{m_r=1}^{5} Ds_{m_r}}{\sum_{m_r=1}^{5} Do_{m_r}} - 1\right)*100 \quad \text{(eqn 4)}$$

With c_{n_0} being the number of individuals in C_n of S0 in January, c_{n_s} the number of individuals in stage n and wc_{n_s} and wc_{n_0} the total weight of individuals in stage n, of scenario s or 0 (with $s \in \{1, 2, 3, 4\}$ in January. And for ii and iii, Ds_{m_p} and Ds_{m_r} the total annual catches of the gear m_p of simulated professional and recreational fishing respectively, Do_{m_p} and Do_{m_r} the total annual catches of gear m_p of professional and recreational fishing observed respectively.

3. Results

3.1. Reference scenario (S0)

The 5000 simulations for S0 of *D. sargus* gave an equilibrium population in January of $1.26 \times 10^6 \pm 0.66 \times 10^6$ individuals (mean ± SD). This population was renewed annually in September by $415.1 \times 10^3 \pm 204.1 \times 10^3$ recruits, including $352.6 \times 10^3 \pm 165.6 \times 10^3$ individuals from natural nurseries and $62.5 \times 10^3 \pm 44.5 \times 10^3$ individuals from port areas. Each year 9.4 ± 5.2 % of individuals over 8 cm were harvested by the fishing activities.

3.2. Management scenarios

The implementation of the scenarios led to a significant increase in the adult population of *D. sargus*, visible from the first years after eco-engineering rehabilitation operations and contrasted gains in catches between recreastional and profesionnal fleets.

The population approached equilibrium after 7 years and reached it by the 15th year, following a logarithmic pattern (Fig. 3a). Even with simulated uncertainty around the parameter values relating to settlement capacity, the annual volume of settlers arrived, and mortality rate, the ranking between scenarios was not modified. S1 led to an increase of 7.97 ± 1.35% in the adult population. This gain is 79.53 ± 13.48%, 16.83 ± 0.53%, 26.24 ± 1.20% and 37.32 ± 10.84% for S2, S3, S4 and S5 respectively (Fig. 3b). This gain is uniform for classes C_1 to C_{14} in S1 and S2. In contrast, for S3, S4 and S5, the abundances of classes C_5 to C_{14} increased by 34.84 ± 0.03%, 45.58 ± 1.82% and 59.47 ± 12.72%, respectively, compared with gains ranging from 2.46 ± 0.02%, 10.62 ± 2.40% and 21.30 ± 9.54 to 28.17 ± 0.02%, 38.38 ± 1.75% and 51.69 ± 11.98 for classes C_1 to C_4 (See SI.4). The ranking of gains remains consistent across classes, except for C_1, where the gains are greater following the application of S1 compared to S3 (See SI.4).

The average mass per individual of the populations resulting from S1 and S2 remains identical to that of the initial population. Conversely, S3, S4 and S5 lead to an increase in the average mass per individual of 7.79 ± 0.04%.

S1 results in an increase in catches by professional and recreational fishers of 7.97 ± 1.35%. It rises to 79.47 ± 13.48% for S2. While S3, S4 and S5 result in an increase in catches from professional fishing of 12.12 ± 1.8%, 21.03 ± 1.22% and 28.51 ± 11.19% respectively, they lead to a decrease in catches from recreational fishing of −70.42 ± 2.21%, −68.1 ± 2.1% and 69.13 ± 5.3% (Fig. 4). For both professional and

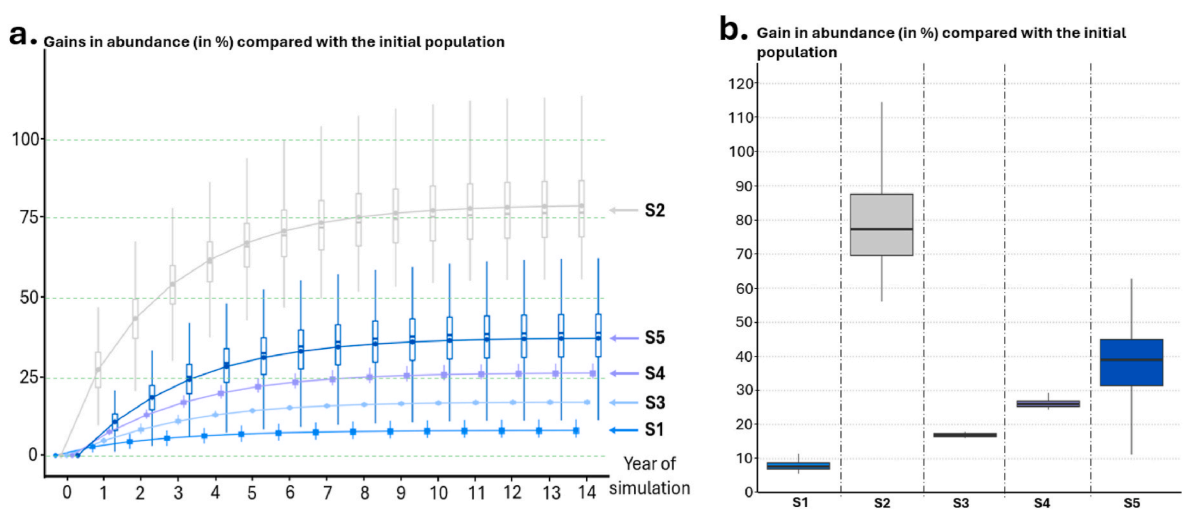

Fig. 3. Gains in abundance (in %) of adult *D. sargus* individuals (in January) as a function of the scenario implemented. A.) Boxplot of the yearly gain in abundance (the line link the mean of the gains for each boxplot), B.) Boxplot of the total abundance of the population after 15 years. Boxplots present the median at their centre surrounded by the first and third quantiles. The outliers are represented by black dots.

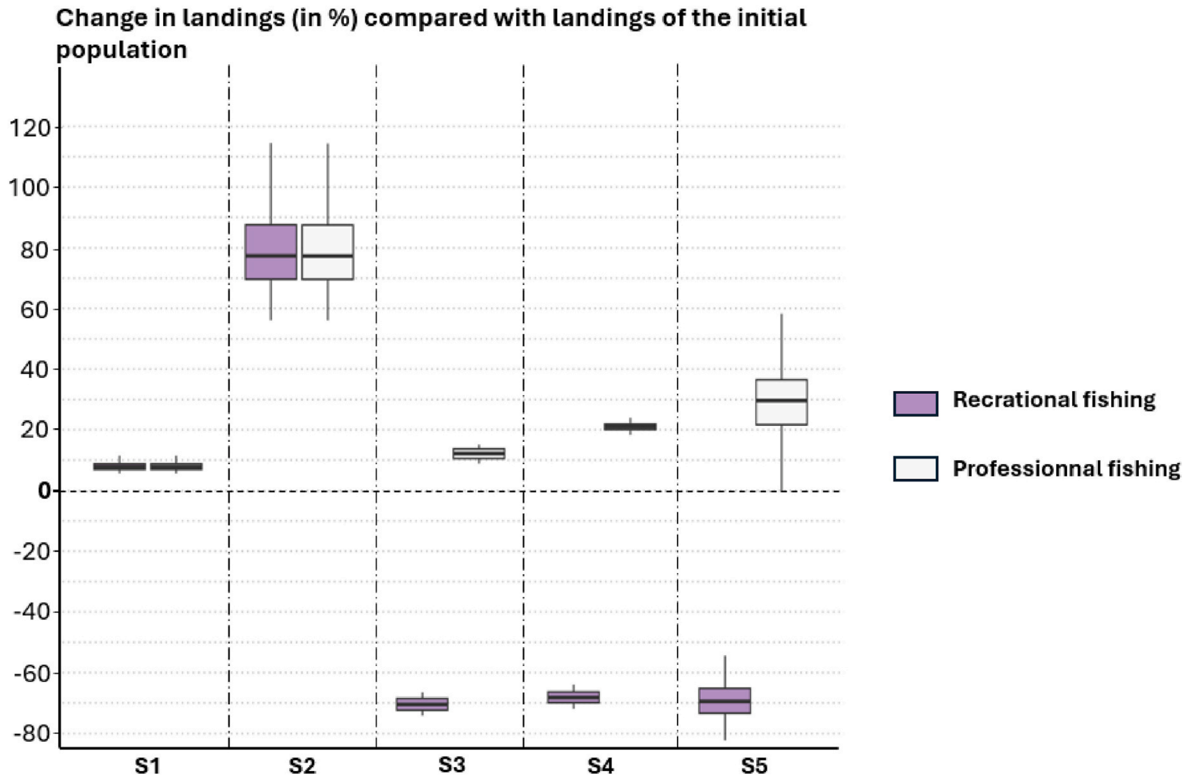

Fig. 4. Boxplot of the effect of the different scenarios on professional (grey) and recreational (violet) fishing annual catches at equilibrium, and expressed as a gain or loss (in %). Boxplots represent the median at their centre surrounded by the first and third quantiles. The outliers are represented by black dots. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

recreational fishing, these percentages are identical for all gears (See SI.4).

4. Discussion

To the best of our knowledge, this study represents the first modelled assessment of fish nursery rehabilitation projects' effectiveness in port areas, aimed at supporting coastal fish populations and fisheries. In addition, this work facilitated a comparison of the effectiveness between rehabilitation actions and a fishing control measure. Although small-scale eco-engineering rehabilitation projects demonstrate promise in supporting fish populations and fisheries, their effectiveness remains limited compared to fishing management measures. Moreover, our findings underscore the greater effectiveness of employing multiple conservation measures simultaneously rather than implementing them individually, providing valuable insights for environmental stakeholders in managing marine coastal areas.

Our findings reveal that the deployment of artificial fish nurseries in the Toulon port area has limited population level impact when 6 km of port are eco-engineered, and a significant restoration effect when 100% of the port is eco-engineered or when these measures are combined with complementary strategies, such as strict regulations on catch sizes.

These results suggest that current port nursery rehabilitation projects may be relatively small in scale, potentially limiting their real impact on fish populations. Indeed, existing studies on rehabilitation projects in port areas have reported rehabilitated linear extent of 15m (150 m^2) (Joubert et al., 2023), 20m (24 m^2) across five ports (Bouchoucha et al., 2016), 6m (4 m^3) (Patranella et al., 2017), and 50m (6.8 m^3) (Selfati et al., 2018). These figures fall significantly short of the 6 km of eco-engineered docks in S1 that leads to a 7.97% ± 1.35% increase in the adult *D. sargus* population. To significantly impact coastal fish populations and fisheries, it is therefore crucial to reconsider and potentially increase the spatial extent of rehabilitation projects. This critique aligns with common concern for restoration projects often very limited in scale particularly in the marine environment (Airoldi et al., 2021; Chapman et al., 2018). However, it is essential to note that, beyond financial considerations, project sizes cannot be expanded infinitely, and socio-ecological gains eventually reach a plateau. In our study, the gain between S1 and S2 should be regarded as an unattainable maximum benefit. In the model, the adult habitat have not been limited as the densities computed still lower than the one currently observed in certain protected area (Belharet et al., 2020) inducing in linear results the raise in percentage of the abundance of *D. sargus* when S1 and S2 are deployed. The model functions on the assumption that each linear meter of artificial fish nurseries in ports equals one additional meter of natural nursery. It implies that recruitment to the adult population is solely limited by the linear extent of the juvenile habitat while the number of settling larvae is never limiting. This hypothesis also assumes that the observed higher density of juvenile fish on artificial fish nurseries than on bare docks (Bouchoucha et al., 2016; Joubert et al., 2023) is exclusively linked to reduced juvenile mortality and not to the attraction of juveniles already present on neighbouring infrastructures. However, this aspect remains unclear and is a topic of debate concerning the local effectiveness of artificial structures in general (Bohnsack and Sutherland, 1985; Grossman et al., 1997). This also suggests that the excess mortality of juveniles in port areas compared to natural nurseries is solely due to the lack of habitat complexity. However although the growth and condition of juveniles are sometimes equivalent inside and outside a port for some *Sparidae* species (Bouchoucha et al., 2018), juvenile exposure to contaminants can have long-term effects and lead to a reduction in recruitment success (Kazour et al., 2020), and could lead to a drop in individual fitness during adult life (Bayley et al., 2002; Bouchoucha et al., 2018; Morán et al., 2018). These assumptions likely lead our model to overestimate the effectiveness of artificial fish nurseries in port areas. The gains in terms of fish population and catches for very small projects are almost certainly negligible. Adding artificial nurseries on port docks at the dimensions outlined in S1 and S4 correspond to a limited investment and deployment of artificial habitats and S2 might be deemed prohibitively expensive and unrealistic. However, a more feasible approach could involve designing docks to be eco-friendly during port construction and incorporating greater structural complexity. In this respect, scenario S5 presents a realistic and cost-effective option (Airoldi et al., 2021).

Our results suggest that rehabilitating nursery functions in port areas through eco-engineering is less effective compared to fishing management measures. This study confirms that while habitat loss significantly impacts coastal fish populations, for a commercial species such as *D. sargus*, fishing remains the main pressure constraining population growth (Jackson et al., 2001; Yan et al., 2021). Therefore, fishing pressure currently limits the effectiveness of rehabilitation projects. This pressure is particularly significant, as individuals below the minimum catch size (23 cm) are heavily targeted (Tsikliras and Stergiou, 2014), despite regulations in France prohibiting their capture. To support the renewal of fish populations, the foremost priority would be to regulate fishing activities (or apply existing regulations), especially recreational fishing for coastal species, before considering rehabilitation projects. This aligns with the Society for Ecological Restoration's recommendations to reduce the main pressures causing degradation before initiating restoration activities. (Gann et al., 2019). Nevertheless, the attractiveness of rehabilitation increases when combined with regulation measures. In our study, S4, combining reduced fishing pressure with artificial habitats in ports, provides a gain over 1.44% higher than the sum of gains in S1 and S3. The management measures in these scenarios target different segments of the population: S1 and S2 directly impact C_0, while S3 impacts classes C_1 to C_4. Gains from S1 and S2 uniformly affect classes C_1 to C_{14}, whereas gains from S3 increasingly affect classes C_1 to C_4 and then uniformly affect classes C_5 to C_{14}. This explains how S5 offers a substantial gain of over 28% in the *D. sargus* population. Therefore, rehabilitation projects should never be considered as a substitute for regulations or protection measures but can be regarded as a complementary measure, leading to a synergistic effect (Possingham et al., 2015). When no other viable options exist, they can also be regarded as mitigation projects. The gains are minimal, but they are still preferable to taking no action. A recent study highlighted the greater potential for restoring estuarine nurseries in the north of France than our study around Toulon (Gernez et al., 2023). The Mediterranean lacks stock assessment of coastal species like *D. sargus* and such intensive fisheries controls as the French Exclusive Economic Zones of the Atlantic or the Channel, particularly for inshore and recreational fishing (Bova et al., 2024; Cardinale et al., 2017). This comparison supports the fact that the implementation of conservation measures must be studied on a case-by-case basis, as regional context greatly influences their success.

The gains associated with each scenario's impact on *D. sargus* abundance are assessed after 15 years, representing a new demographic balance. This balance reflects the replacement of all individuals in the initial population with those born after the scenario's implementation. Introducing natural stochastic phenomena to the lifecycle of *D. sargus* would extend timescales and alter the logarithmic pattern of fish abundance (Hastings et al., 2021). For environmental managers, this implies that gains in population abundance during the initial years after implementing management measures may be lower than those observed in this study. Therefore, these solutions require long-term planning, with objectives spanning over a decade, regardless of the chosen conservation measure (Airoldi et al., 2021).

While models are valuable, they involve several approximations. Therefore, the results should not be seen as an exact reproduction of reality, and recommendations should be approached with caution. In particular, we did not account for changes in fishers' behavior when faced with increasing or decreasing resources. For example, catches by recreational fishers are strongly affected by scenarios 3, 4 and 5. In reality, fishers will likely adapt by targeting larger individuals, tempering the decrease in recreational fishing catches. This activity, important for the local economy, may be less impacted than predicted. In this case, additional data, regarding the spatialization of fishing activity and fish distribution, as well as testing conservation measures on different species and scales, can lead to more precise recommendations. Another important limit of the model is that it includes a stock-recruitment relationship constrained by the carrying capacity of nursery areas, making the recruitment less sensitive to the number of mature fish. Consequently, it doesn't accurately simulate the effects of overfishing mature fish on recruitment. The flexible nature of the ISIS-Fish model allows for refinement, such as considering fishers' behaviour and compliance with regulation or fishing activities setting improvement. These aspects can thus be addressed for future studies.

Finally, while our results indicate that large-scale effects of rehabilitation projects in ports may be limited, especially when these projects are small-scale, it is important not to undervalue their potential benefits. Our evaluation focused on metrics such as adult fish population abundance and fishery catches, which provide one perspective on effectiveness. Other studies have used different indicators, such as the local biodiversity or fish abundance in port areas (Bishop et al., 2022; Bouchoucha et al., 2016; Joubert et al., 2023), offering alternative views on project success and reaching different conclusions. Additionally, the societal impact of small-scale projects, including their role in communication and community engagement with environmental issues, should not be overlooked. International Standards of Ecological Restoration emphasize incorporating social objectives into restoration goals (Gann et al., 2019), highlighting the importance of stakeholder and citizen involvement. Although these projects primarily aim to conserve fish populations, they also foster increased public interest in marine conservation and restoration. This engagement not only raises awareness but also provides valuable educational and inspirational benefits, contributing positively to societal values (Díaz et al., 2018).

CRediT authorship contribution statement

Etienne Joubert: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Charlotte Sève:** Writing – original draft, Resources, Methodology. **Stéphanie Mahévas:** Writing – original draft, Resources, Methodology. **Adrian Bach:** Writing – review & editing, Conceptualization. **Marc Bouchoucha:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The Seaboost company, which financed Etienne Joubert work during the third year of this project, is specialized in building and selling artificial structures aiming to rehabilitate the fish nursery function in port areas. There are no other conflicts of interest to declare. All the authors have contributed to and approved the manuscript and **agree to its submission in *Marine Environmental Research* and to the publication policy and data publication policy**. **The manuscript has neither been submitted nor published elsewhere, the manuscript adheres to publisher's Ethical Guidelines. All sources of** funding **are acknowledged at the end of the manuscript**, **and no direct financial benefits could result from this publication**.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2025.106983.

Data availability

Data available via the Seanoe Repository: https://doi.org/10.17882/100531

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