

Nursery function rehabilitation projects in port areas can support fish populations but they remain less effective than ensuring compliance to fisheries management

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Supporting information

S1 Model description

S1.1. Population structure

In the model, the *D. sargus* population is divided into 15 age classes (C_0 to C_{14}), each one year apart except for C_0 and C_1 , in order to cover the different life stages of *D. sargus* (Belharet et al., 2020). The individuals in C_0 are between 1 and 6 months old. They are the young of the year (YOY) arriving in C_0 at *D. sargus*' cycle starting month: April (Lloret and Planes, 2003). Individuals in C_1 are between 7 months and one and a half years old, and those in C_{14} are 14 years old or older (Fig. 1). Each year, the transition from one age class to the next occurs in late September, aligning with the departure of

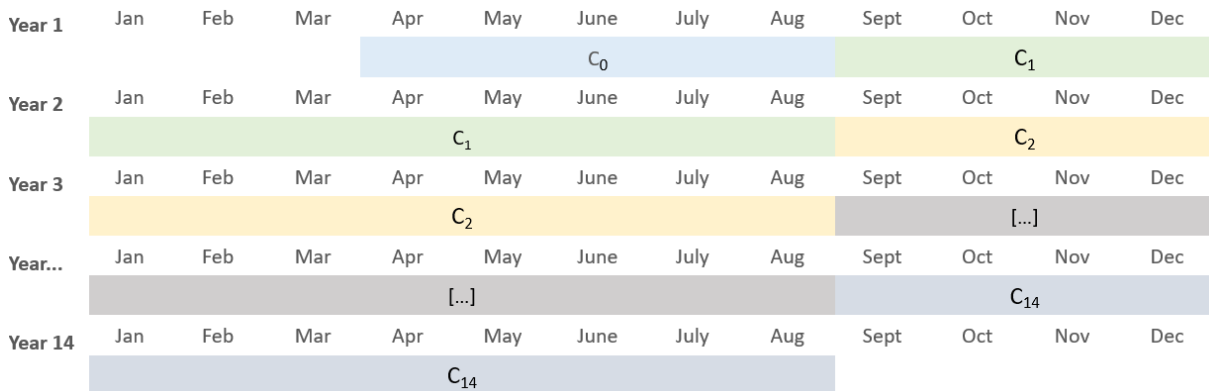


Figure 1: Age classes timetable in the model

juvenile nurseries from the study area. (Harmelin-Vivien et al., 1995; Planes and Romans, 2004).

S1.1.1. Growth

During the first year of *D. sargus*' development, the growth in length is considered linear (equation 1a, Planes et al., (1998). Older individuals' growth follows a Von Bertalanffy equation (equation 1b) (Belharet et al., 2020; Hussein et al., 2011):

$$L(a) = (a + m) * \frac{eq - 1}{eq} + 1 \quad (\text{eqn } 1a)$$

$$L(a) = l_{\infty} \left(1 - e^{-k \left(\frac{a+m}{12} - t_0 \right)} \right) \quad (\text{eqn } 1b)$$

with l_{∞} being *D. sargus* maximum length (cm), t_0 the hypothetical time at which the size of the individuals is zero, k the Brody's growth coefficient, a the age in months of the individuals, m the month in the cycle at which the calculation is performed and eq the succession point between the two equations (Table 1).

S1.1.2. Weight and maturity rate

The average weight $W(L)$ and maturity rate of individuals $M(L)$ are computed as a function of their size (L) according to the following equations (equation 2) (Le Cren, 1951) and (equation 3) (Gonçalves and Erzini, 2000):

$$W(L) = a_w * L^{b_w} \quad (\text{eqn 2})$$

$$M(L) = \frac{1}{1 + e^{-m_{50}(L-c_m)}} \quad (\text{eqn 3})$$

With a_p and b_p being two coefficients, m_{50} the size of *D. sargus* for which the maturity rate is 50 % and c_m the slope of the maturity curve (Table 1).

S1.1.3. Breeding and recruitment

The reproduction of *D. sargus* in our study area occurs between February and April, and the peak of juvenile settlement between April and June (Harmelin-Vivien et al., 1995; Lloret and Planes, 2003; Planes et al., 1998; Vigliola et al., 1998). *D. sargus* is a non-binding protandrous hermaphrodite fish. The proportion of females able to breed (s_r) in each class size (L) is determined by the following equation (Mouine et al., 2007):

$$s_r = 1 - 2e^{-0.15L} \quad (\text{eqn 4})$$

The reproduction rate (r_r) corresponds to the number of eggs that can be laid by individuals within each class according to their sex ratio (s_r), and their size L (equation 5). The coefficients af and bf were estimated by Belharet et al. (2020):

$$r_r = s_r * af * L^{bf} \quad (\text{eqn 5})$$

The breeding algorithm scans all classes living in the areas defined as "breeding area" during the breeding period (March). This algorithm takes in the reproductive rate r_r , maturity rate $M(L)$ and number of individuals in each group Nb_{ind} , and multiplies them (equation 6) by the estimated egg and larval survival rate (l_{sr}) (Belharet et al., 2020). The breeding matrix is browsed and filled with the number of eggs or future larvae within each zone, denoted N_L .

$$N_L = r_r * M(L) * Nb_{ind} * l_{sr} \quad (\text{eqn 6})$$

S1.1.4. Recruitment

Recruitment is limited by the nursery area capacity to host juveniles, which is different in natural areas (R_{max_nat}) and in port area (R_{max_port}) (Planes et al., 1998). This capacity represents the number of individuals able to settle in the recruitment area and to join C_0 equations 7a and 7b:

$$R_{max_nat} = L_n * d_m * S_w \text{ (eqn 7a)} \quad R_{max_port} = L_p * d_m * S_w \text{ (eqn 7b)}$$

Where L_n is the coastline length (meters) of the nursery area, d_m the maximum number of juveniles that can settle per meter of coastline, S_w the number of settlement waves and L_p the length of docks where *D. sargus* juveniles can settle (Table 1).

The number of recruits N_r in each area (C_0 in nurseries and ports) is defined by a Beverton-Holt equation (equation 8) (Belharet et al., 2020):

$$N_r = N_L \left(\frac{R_{max}}{N_L + R_{max} * g} \right) \quad \text{(eqn 8)}$$

With N_L being the initial number of larvae arriving in the area and $R_{max} * g$ the intensity of the density dependency (Table 1).

Determination of juvenile habitat coastal length

The length of the “natural” and ports’ benthic settlement zones (L_n and L_p) were measured on the basis of a map overlay according to criteria defined by previous studies (Cheminée et al., 2021, 2011; García-Rubies and Macpherson, 1995; Harmelin-Vivien et al., 1995; Ventura et al., 2014)) such as the bathymetry of the studied area (© Shom-IGN, 2021), benthic biocenosis (Andromède Océanologie, 2021) and exposure to winds and currents (Ifremer, 2021).

The coastal length of natural nurseries covers all sheltered areas within a depth of less than 3m, a slope of less than 23% and a biocenosis corresponding to either infralittoral rocks or loose infralittoral bottoms such as gravel and sand (García-Rubies and Macpherson, 1995; Harmelin-Vivien et al., 1995). This resulted in an estimation of 55,820 m of coastline (at a scale of 1:500). Using GIS we measured the linear length of port docks able to support the benthic settlement of juvenile fish from aerial photos (IGN and BRGM, 2022), resulting in an estimation of 24,751m (on a scale of 1:500). It corresponds to all the quays in the area with a depth of less than 2m. The total length of port docks was measured from aerial photos (IGN and BRGM, 2022) and estimated at 60 060m (comprising 24751m of docks already welcoming juvenile fish and 35 309m welcoming none, on a scale of 1:500) (Table 1).

S1.1.4. Natural mortality

The natural mortality rate (M_r) of *D. sargus* depends on the life stage (Belharet et al., 2020; Bouchoucha et al., 2016; Hussein et al., 2011; Planes et al., 1998) as well as the benthic settlement zone (natural nursery vs. ports). For natural nurseries, Planes and Romans, (2004) estimated 80.8% mortality of juveniles in the first four months after benthic settlement. In the port areas, the juvenile mortality rate during the first 4 months is very high due to the lack of refuge areas (Bouchoucha et al., 2016). In absence of data for this value, we set it to 99% (assumption not verified to date but on which most current nursery rehabilitation projects are based). We made the strong assumption that, for fish older than C_0 , there is no excess natural mortality of individuals having lived their first months in port areas compared to those from natural nurseries. For classes C_1 to C_{14} , the annual natural mortality rates were set to 26% (Belharet et al., 2020).

These mortality rates are first transformed into survival rates (t_s) with ($t_s = 1 - M_r$), expressed between 0 and 1, and then transformed in instantaneous mortalities (Table 2) according to the following equation (equation 9).

$$M_i = -\ln(t_s) \quad (\text{eqn 9})$$

	Parameter	Value	Reference
Growth			
	t_∞	Asymptotic body length (cm)	45 cm (Froese and Pauly, 2022)
	t_0	Age at length zero (yr)	- 0.99 (Belharet et al., 2020)
	k	Brody growth coefficient (yr^{-1})	0.17 (Belharet et al., 2020)
	eq	Continuity factor	11.93
Weight			
	a_w	Scale parameter ($g \text{ cm}^{-b}$)	0.016 (Belharet et al., 2020)
	b_w	Exponent	3.05 (Belharet et al., 2020)
Maturity			
	m_{50}	Length of 50% mature	20.06 cm (Mouine et al., 2012)
	c_m	Slope of the maturity curve	1.26 (Mouine et al., 2012)
Breeding			
	af	Coefficient	0.084 (Belharet et al., 2020)
	bf	Coefficient	4.51 (Belharet et al., 2020)
	l_{sr}	Larval survival rate	0.008 (Belharet et al., 2020)
		Breeding month	March (Lloret and Planes, 2003)
Recruitment			
	L_n	Coastal length of nursery area (m)	55 820 Measured on maps
	L_p	Length of quay were juveniles fish settle (m)	24 751 Measured on maps
	d_m	Max number of settlers (ind.m^{-1})	10 (Cuadros et al., 2018)
	S_w	Number of settlement waves	3 (Faillettaz et al., 2020)
		Recruitment month	April (4) (Lloret and Planes, 2003)
Mortality			

$M_{i.cop}$	Natural of class C_0 in ports areas (see table 1)	11.11263	Expert estimation
$M_{i.con}$	Natural mortality of class C_0 in nursery areas (see table 1)	4.020845	(Planes and Romans, 2004)
$M_{i.f}$	Natural mortality of class C_1 to C_{14} (see table 1)	0.3011051	(Belharet et al., 2020)

Annual mortalities for each group were therefore computed according to (equation 9) to both follow the literature data and fit our model (Table 2).

Table 1 : Summary table of the parameters governing the population dynamics sub-model in ISIS-Fish

Table 2: Mortality rates according to *D. sargus* life stages, calculation of natural mortality rates for ISIS-Fish

Class	Residence time	Survival	Formulae	Value in ISIS-Fish
C_0 port nursery	5 month	$t_{s.p} = 0,01$ $t_{s.f} = 0,74$	$t_{sa.cop} = \left(\sqrt[5]{t_{s.p} \times \sqrt[12]{t_{s.f}}} \right)^{12}$	$M_{i.cop} = 11.11263$
C_0 natural nursery	5 month	$t_{s.n} = 0,192$ $t_{s.f} = 0,74$	$t_{sa.con} = \left(\sqrt[5]{t_{s.n} \times \sqrt[12]{t_{s.f}}} \right)^{12}$	$M_{i.con} = 4.020845$
C_1 - C_{14}	12 month	$t_{s.f} = 0,74$	$t_{s.f}$	$M_{i.f} = 0,3011051$

S1.1.5. Abundance at equilibrium

The parameterisation of *D. sargus* population in ISIS-Fish is based on the parameter values of mortality, carrying capacity, number of benthic settlement waves and the length of natural nurseries (Table 2). Based on these parameters, ISIS-Fish was run to compute the equilibrium abundance per age class of *D. sargus* population. In this work, the assessment of the effectiveness of management measures involving rehabilitation or conservation methods is based on this equilibrium abundance.

S1.1.6 Accessibility

The accessibility is a biological parameter accounting for biological behaviour (e.g. hidden behaviour) affecting *D. sargus* technical catch probability according to different fishing gear (usually called catchability, as in (Mahévas and Pelletier, 2004)). Because of a lack of information in the literature, we calibrated this value with fishing parameters to reproduce the total annual catches.

S1.2. Fishing activities

Available data:

The fishing activities *D. sargus* populations were parameterised on the basis of information provided by Ifremer's Service d'Information Halieutique (SIH), corresponding to declarative data from commercial fisheries in 2019 and 2020 (Système d'Information Halieutique, 2022).

The declarative data from professional fisheries indicate an average annual catches of *D. sargus* in the fishing district of Toulon of 17.3 tons, spread over five fishing gears (Table 3). Recreational fishing catches of *D. sargus* represent 5% of total recreational catches in France (BVA, 2009). Thus, recreational fishers catches are estimated at 12.5 tons, according to an extrapolation of the data from Cadiou et al. (2009).

In addition to the value of total catches by gear, observations made during field inspections by agents of the Blue Coast Marine Park MPA (Parc Marin de la Côte Bleue) west of Marseilles, report that 19% and 81% of *D. sargus* catches by professional and recreational fishing respectively were individuals smaller than 23 cm (Font and Lloret, 2014). However, current regulations prohibit the fishing of *D.*

Table 3: Gear implemented in D. sargus fishing, associated with their catches.

Gear	Fishing activity	Mean annual catches 2019-2020 (kg.year⁻¹)	Fishing effort (hour.year⁻¹)
Long lining	Professional	14 280	757
Trap	Professional	25	4
Gillnet	Professional	780	494
Trammel net	Professional	1 920	1060
Gangui (Trawl)	Professional	300	88
Boat or shore line	Recreational	6 000	1216
Spearfishing	Recreational	6 400	1216

sargus individuals below this size.

Fishing parameters in ISIS-Fish:

ISIS-Fish describes the fishing activity using gears characterized by a gear and a fleet (i.e. group of vessels sharing same technical characteristics and gears). We divided fishing activities into two categories based on available knowledge and data: (1) professional fishing, composed with 5 gears (longline, gillnet, trammel net, gangui and trap) and grouped into 3 fleets, and (2) recreational fishing, composed of 2 gears (angling and spearfishing) and grouped into one fleet.

Each gear is characterized by (i) a standardisation factor that allows to compare fishing time between the different gears, and (ii) a selectivity curve of *D. sargus* depending on fish size that allows, in this case study, to distinguish a probability of capture below and above the minimum legal capture size of 23cm.

For each fleet, the proportion of time dedicated to the practise of a metier is set for each month (called strategy in ISIS-fish) using SIH data from 2019 and 2020. We defined the annual fishing effort per gear as a function of the fishing profile and the average annual effort. The fishing profile per fleet was identical for every month of the year. Annual fishing time was broken down into 8-hour fishing days, with the number of days per month varying according to the season. Vessel activity increases between winter and summer and then decreases between summer and winter. The number of fishing days per year was defined such that the sum of the hours corresponded to the total effort per trade reported by the SIH data.

S1.2.5 Calibration of the fishing parameters

The standardisation factor, the probability of selectivity for both professional and recreational fishing activity and the accessibility coefficient were estimated using a calibration procedure aiming at reproducing catches observations and expert knowledge described above (section available data and Table 4).

Calibration consisted in setting initial values for 12 unknown parameters (standardisation of each gear, selectivity for professional and recreational fishing and accessibility), running ISIS-Fish, comparing simulated catches to observations, and changing the initial values of the unknown parameters to reduce the discrepancy between observations and simulated values. To identify a good combination of parameters values, we select randomly 5 000 combinations using a random LHS (Latin Hypercube sampling).

The initial value of standardisation factor for the different gears was calculated by fitting a generalised linear lognormal model to the annual catches per unit of effort associated with fishing gear and by years (2019 and 2020) (Lehuta et al., 2010). The coefficients generated by the model and attributed for each gear were then exponentially transformed (Table 4). For recreational fishing, the coefficients were estimated in relation to the values calculated for professional fishing.

The calibration process was led following the ODDO method (Mahévas et al., 2019), (see table 5). The objective function (OF) used to select the best combinations of values minimising the difference between observed catches and simulated catches (Table 4). This function computes the sum of the comparisons between catches of *D. sargus* under 23cm from commercial and recreational fisheries from observations (D_{NMP_obs} & D_{NML_obs}) and simulations (D_{NMP_sim} & D_{NML_sim}) as well as total

observed (D_{PMm_obs}) and simulated (D_{PMm_sim}) catch by métiers, taken one by one. The aim is to minimise OF to get closer to observations.

$$OF = |D_{NMP_sim} - D_{NMP_obs}| + |D_{NML_sim} - D_{NML_obs}| + \sum_m |D_{PMm_sim} - D_{PMm_obs}|$$

Three successive calibrations were carried out with a fishing parameter variation capacity of respectively $\pm 20\%$, $\pm 2\%$ and $\pm 1\%$ around the established value in order to get closer to an optimal combination of parameter values. The values of the fishing parameters in the simulation minimising OF at the end of the last calibration process were selected and kept fixed for the rest of the study (Table 4).

Table 4: Initial and calibrated value of fishing parameters estimated in the model

	Gear	Standardization factor		Selectivity		Accessibility	
		Initial value	Calibrated value	Initial value	Calibrated value	Initial value	Calibrated value
Recreational fishing	Spearfishing	1.3	1.265361803	For Groups C₁ to C₄ : S = 0.8 For Groups C₅ to C₁₄ : S = 0.2	For Groups C₁ to C₄ : S = 0.770614002 For Groups C₅ to C₁₄ : S = 0.228198927	1×10^{-4}	9.8336×10^{-5}
	Boat or Shore line	1,22	1.185281584				
Professional fishing	Long lining	10,7	10.54983412	For Groups C₁ to C₄ : S = 0.8 For Groups C₅ to C₁₄ : S = 0.2	For Groups C₁ to C₄ : S = 0.15697549 For Groups C₅ to C₁₄ : S = 0.824428461		
	Trap	1.0	0.998235716				
	Gillnet	0,86	0.879663216				
	Trammel net	0,74	0.756877503				
	Gangui (Trawl)	0,24	0.240777458				

Table 5 : ODDO filling with the ISIS-Fish model, fishing parameters calibration (see Mahévas et al., 2019)

Model	Performance	Time per run	45 sec
		Parallelisation	10 runs in parallel
	Development	Language	Java
		Implementation of the optimisation algorithm	Recoding of the algorithm in Java
Pre-processing	Problem formulation	Model	ISIS-fish model of <i>D. sargus</i> fisheries
		Question	Estimating fishing parameters for <i>D. sargus</i>
		Data	Two years catches in kg associated with gear and effort
		Parameters bounds	Continuous values around 20% from the initial value
		Uncertainty (process and data)	Declarative and projected data for professional fisheries, estimation for recreational fisheries
		Initial objective function	Absolute value of differences: $OF = D_{NMP_sim} - D_{NMP_obs} + D_{NML_sim} - D_{NML_obs} + \sum_m D_{PMm_sim} - D_{PMm_obs} $
	Objective Function	Building	Other OF were tested: The standardised version: gives too much importance to the catches of gears that don't fish a lot of <i>D. sargus</i> and creates an imbalance. The squared version: Create an imbalance with large catches over-represented
		Final	Absolute value of differences: $OF = D_{NMP_sim} - D_{NMP_obs} + D_{NML_sim} - D_{NML_obs} + \sum_m D_{PMm_sim} - D_{PMm_obs} $
	Exploratory Analysis	data	No change
		reduction dimension	No
Algorithm	Family	Random LHS around the parameter values seed fixed	
	Description Justification	The aim is to explore parameter values within a broad spectrum, as the values established initially are uncertain.	
	Changes in the algorithm	No	

	Settings	<p>Test strategy: Number year of simulation = 15 Number of simulation = 5000 Number of parameters tested 12 comprising 4 groups (2 of 2 parameters and 2 of 5 parameters)</p>
Post-processing	Convergence	<p>Visual examination of FO, extraction of catches and parameters of the best simulation (minimising FO). Visual comparison with catch targets. Progressive targeting of parameters in 3 rounds of simulations:</p> <p>First run : 20% around the parameter values -> select parameters of the best simulation Second run : 2% around the new parameter values -> select parameters of the best simulation Third run : 1% around the new parameter values -> select parameters of the best simulation, visual validation with observations and set of the values for the rest of the study</p>
	Optimum properties including identifiability	FO
	Residual analysis	No
	Multicriteria	No
Optimisation process	Number of simulation required	15000
	Duration	21h
	Reached stopping criteria	Yes
Comments and failures	<p>Initially, the aim was to carry out a single analysis to select the simulation that minimised FO. However, the 20% variation around the values of the 13 (continuous) parameters was too large to find an ideal value for the parameters with this single design. 3 analyses were therefore carried out, progressively targeting the optimised values. This targeting concerns a single combination of parameters. It is very likely that there are other combinations of parameters that meet our objectives. Ideally, the simplex or bootstrap method should be applied to select the best of these combinations. However, given the uncertainty in our fishing data, the combination selected at the end of this calibration analysis is more than sufficient for our purposes.</p>	

S2: Management scenarios

Each scenario was established by modifying the value of specific parameters from the reference simulation in relation to the measure tested by the scenario. The values of these new parameters are described in Table 6.

		Parameter	New Value
Scenario 1	Recruitment	Coastal length of nursery area (m)	61 826
		Length of quay were juveniles fish settle (m)	22 276
Scenario 2	Recruitment	Coastal length of nursery area (m)	115 880
		Length of quay were juveniles fish settle (m)	0
Scenario 3	Accessibility	C ₀ - C ₄	0
		C ₅ - C ₁₄	9.8336x10 ⁻⁵
Scenario 4	Recruitment	Coastal length of nursery area (m)	61 826
		Length of quay were juveniles fish settle (m)	22 276
	Accessibility	C ₀ - C ₄	0
		C ₅ - C ₁₄	9.8336E-5

Table 6 : New parameter values introduced to test measures for the various scenarios

S3: Uncertainty analysis

In the literature, there is no consensus on the values attributed to these parameters (Cuadros et al., 2018; Planes et al., 1998). To account for this uncertainty, 5000 simulations were carried out for each scenario in the model, using a random LHS (Latin Hypercube scaling) analysis. Each simulation therefore corresponds to a combination of values, sampled within the range of variation of the ecological parameter uncertain values mentioned above (Table 7). This gives 5 000 equilibrium numbers of *D. sargus* for each scenario. All these equilibria were considered to constitute the population associated with each scenario. When the simulations were launched, the random LHS seed was kept fixed and identical for both the initial population and the scenarios. That way, each simulation has its identifiable counterpart in terms of the combination of ecological parameter values in the other scenarios. The comparison of the scenarios with each other consists of comparing all the 5 000 simulations with their counterpart.

Table 7 : Interval of variation for the parameters identified as sensitive in the reference model, associated with their initial value and the range of variation applied during the sensitivity analysis.

	Parameters	Initial value	Variation range
ΘMortality	Class C ₀ in nurseries (5 month)	80,80%	[64,06 ; 96,9]
	Class C ₀ in harbours (5 month)	99%	[79,2 ; 99]
	Class C ₁ -C ₁₄ (1 year)	26%	[20,8 ; 31,2]
ΘRecruitment	linear nurseries (m)	55 820	[44 656 ; 66 984]
	Carrying capacity (individuals.m ⁻¹)	10	[6 ; 13]
	Number of settling waves	3	[1 ; 4]

S4: Additional Figures

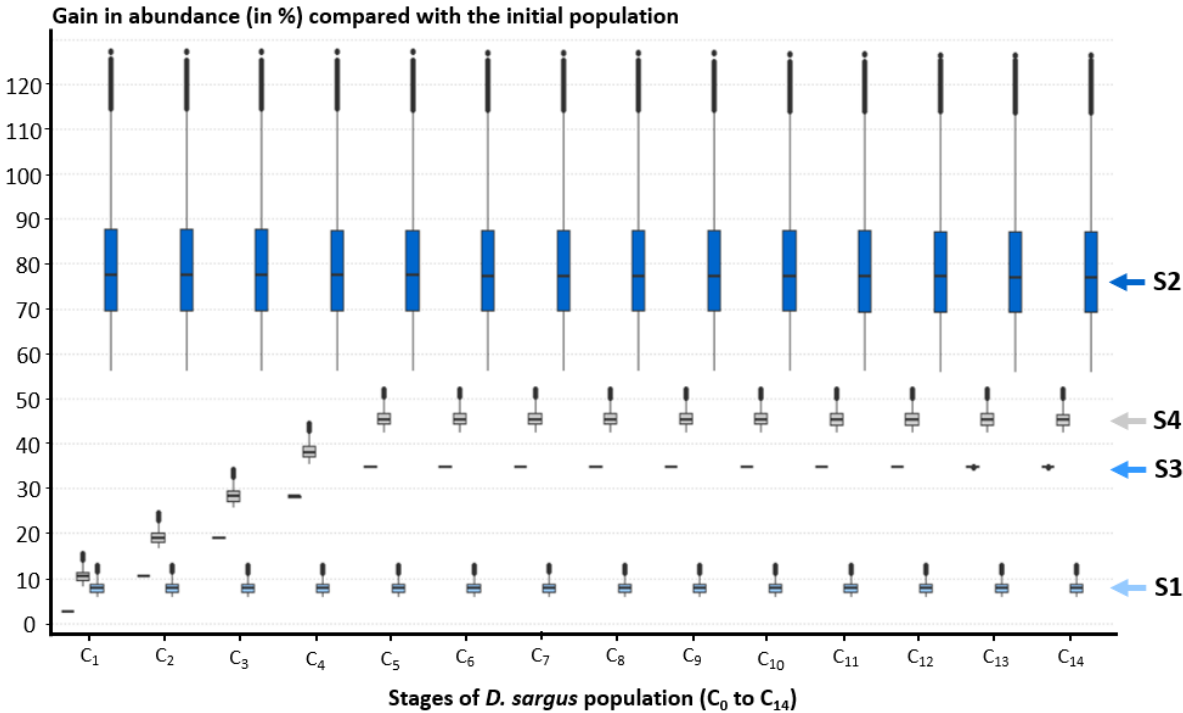


Figure 2 : Yearly gains in abundance (in %) of adult *D. sargus* individuals. Boxplots present the median at their centre surrounded by the first and third quartiles. The outliers are represented by black dots.

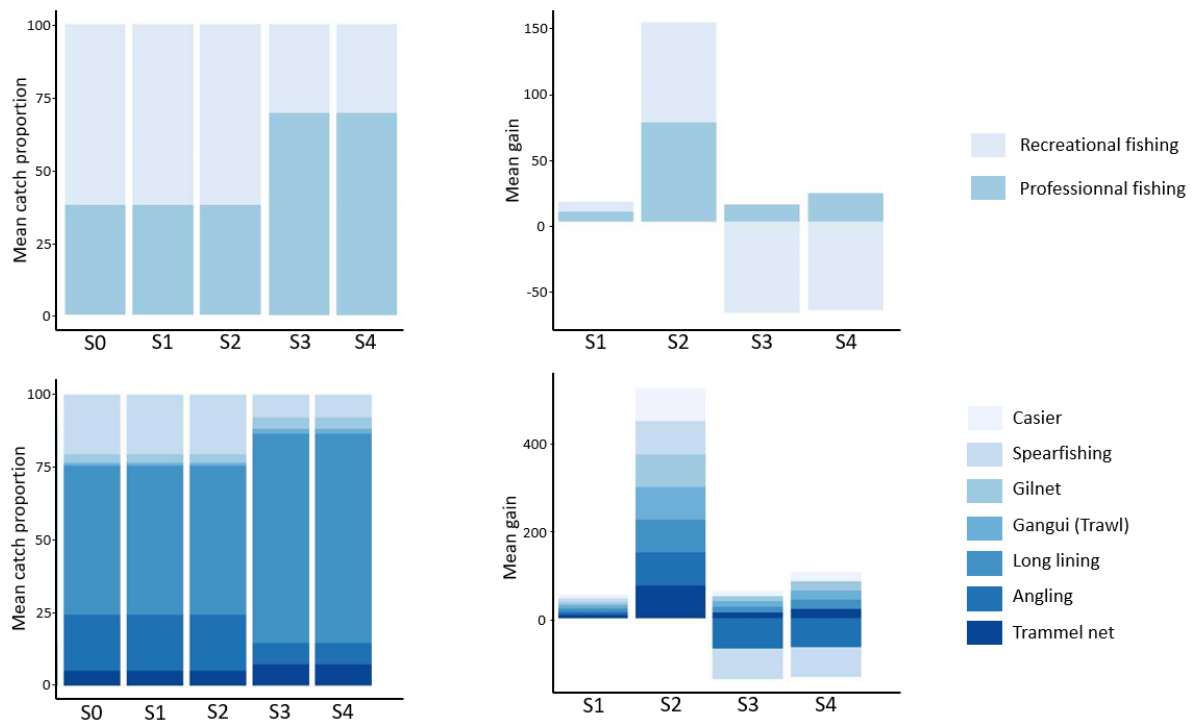


Figure 3 : Bar plot showing the proportion (in %) of catches by fishing gear in relation to total catches for each scenario and the mean gain per fishing type and per gear.

Differences in catches between gears can be explained by differences in catchability and effort:

$$C_s \approx q(s,g) * E(g) * N_s$$

$Q(s,g)$ is the product of the parameters in table 4. Scenarios S1 and S2 affect N_s while scenario S3 affects the parameter of selectivity of $q(s,g)$. This impact is different for the recreational and professional fleets but similar for the gears within each of these fleets. This assumption in the model is due to the fact that we did not have sufficient knowledge and data to parameterize differences. The only available data are catches (in weight) and the proportion of these catches under and over 23cm for professional and recreational fisheries. The consequences of this assumption are that the impacts of the scenarios on catches within each fleet do not differ between gears.

S5 - References

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