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ORIGINAL RESEARCH

When non-target wildlife species and alien species both affect negatively to an artisanal fishery: the case of trammel net in the Alboran Sea

José C. Báez · Juan A. Camiñas · Raquel Aguilera · Jairo Castro-Gutiérrez · Raimundo Real

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Abstract In the Northern Alboran Sea, artisanal small-scale fisheries using trammel nets suffer economic losses, and local fishermen see their way-of-life endangered, due to interactions with wildlife species such as alien species and dolphins. On the one hand, the alien seaweed *Rugulopteryx okamurae*, which was first recorded in the Alboran Sea in 2015, has undergone an intensive expansion in the sub-region, monopolizing the available seabed, causing radical changes in the underwater seascape and clogging the trammel nets. On the other hand, the damage caused to the fishing nets by dolphin fish predation is an ancient problem worldwide, but it is intensifying in the last years. The main objective of this study is to understand the main environmental and technical conditions that favor damages of fishing trammel nets in the Alboran Sea, which entails an important loss of catchability, due to (i) the clogging of the artisanal fishing trammel nets by invasive seaweed, and (ii) the breaking of the nets by dolphin predation. Through close monitoring of fishermen in port, we obtained direct information of 548 sets. Our results indicate that approximately 30% of trammel sets suffered a damage due to unwanted interaction with alien seaweeds and dolphins. As seaweeds invasion is a global problem while dolphin-fishing gear interaction is more local, we concluded that only a large-scale management of exotic algae, together with the involvement of local fishermen, could solve the economic problems of this activity.

Keywords Alien species · Brown tides · Dolphin · Mediterranean Sea · Net damage

J. C. Báez (✉)
Centro Oceanográfico de Málaga, Instituto Español de Oceanografía (IEO, CSIC), Puerto Pesquero S/N, 29640 Fuengirola, Spain
e-mail: josecarlos.baez@csic.ieo.es

J. C. Báez
Instituto Iberoamericano de Desarrollo Sostenible, Universidad Autónoma de Chile, Av. Alemania 1090, 4810101 Temuco, Región de La Araucanía, Chile

J. A. Camiñas · R. Aguilera · J. Castro-Gutiérrez
Asociación Herpetológica Española, José Gutiérrez Abascal, 2, 28006 Madrid, Spain

R. Aguilera
Centro Oceanográfico de Murcia, Instituto Español de Oceanografía (IEO, CSIC), Varadero nº 1 Aptdo 22, 30740 (Murcia), San Pedro del Pinatar, Spain

J. Castro-Gutiérrez
Departamento de Ciencias Agroforestales, Escuela Técnica Superior de Ingeniería, Universidad de Huelva, Campus El Carmen, 21007 Huelva, Spain

R. Real
Departamento de Biología Animal, Facultad de Ciencias, Universidad de Málaga, Málaga, Spain

Introduction

Local and small-scale fisheries are an important source of marine resources that contribute to food security in coastal communities, including the Mediterranean Sea (Griffith et al. 2007; Teh and Pauly 2018; Loring et al. 2019). They are also a relevant local economic engine in developed countries (Lloret et al. 2018). In the Alboran Sea subregion, small-scale fisheries are associated with artisanal fishing gear alternation and with high diversity of used gears, being trammel nets the main gear (Camiñas 1990; FAO ArtFiMed 2011). In addition to being local and small-scale, these trammel net fisheries are artisanal and traditional (Baro et al. 2021). According to Baro et al. (2021), the importance of the artisanal fisheries is remarkable in the fishing sector of the Northern Alboran Sea, both in terms of the total landed captures and economic profit. Thus, artisanal fisheries represent 10% of the total weight landed by all the fishing fleets operating in the north Alboran subregional area. Moreover, its economic profit represents around 21% of the total fish sold in the first-sale fish markets involved. This economic profit is due to the high value of sales achieved by the fresh products obtained, because of their high quality and the reduced time required to reach from capture to final consumers. However, fishermen suffer economic losses, and thus see their way-of-life endangered, due to interactions with wildlife species. These disturbances involve problems provoked by newly arrived alien species (Haubrock et al. 2022) and other traditional conflicts such as those caused by different protected dolphin species (Snape et al. 2018; Pardalou and Tsikliras 2020).

There are many examples of invasive species that reduce biodiversity and for which there are no fisheries, such as, for example, the rabbitfish (*Siganus luridus*) involved in some cases of Ciguatera poisoning (Chinain et al. 2021). The ongoing warming of the world's oceans is facilitating the movement of species towards the poles, causing a "tropicalization" of temperate ecosystems throughout the world (Horta e Costa et al. 2014; Báez et al. 2019). Such an increase in the abundance of tropical species is changing the taxonomic structure of temperate areas, which could accelerate the deterioration of local habitat with devastating consequences for species, ecosystems and fishing activities dependent on them. On this basis, many authors predicted a tropicalization of commercial fishing catches (Cheung et al. 2013). In addition, human activities are facilitating the encroachment of alien species, which become major stressors of invaded marine environments (Boudouresque et al. 2017). Current tropicalization and the introduction of alien species are producing important impacts on the marine ecosystems in the Mediterranean Sea, and particularly in Alboran. These changes are affecting local fisheries by modifying the availability of local fish and by affecting the usefulness of fishing gears. It is important to know in detail how those recent modifications affect local ecosystems, endemic species and the species exploited by artisanal fisheries.

Canopy-forming seaweeds are the main bioengineers in the shallow environments of temperate and cold seas (Navarro-Barranco et al. 2019). Currently, temperate seaweed diversity is experiencing strong changes due to multiple stressors such as climate change and alien species that tend to homogenize the communities where they settle (Harley et al. 2012; Blanco et al. 2020). Since 2015, when the Northwest Pacific alien *Rugulopteryx okamurae* was first recorded in the Alboran Sea (Ceuta, at the western end of the Mediterranean), it has undergone an intensive expansion in the sub-region, monopolizing the available seabed and causing radical changes in the underwater seascape (Ocaña et al. 2016; García-Gómez et al. 2018; 2021). It has replaced native canopy-forming seaweed and triggered significant changes on native fauna (Navarro-Barranco et al. 2019). In addition, the rapid growth of *R. okamurae* produces strong so-called "golden tides" clogging the artisanal trammel nets, which entails an important loss of catchability (García-Gómez et al. 2018). Moreover, fishermen need to expend extra time to make the net operational again (Fig. 1) and subsidies have been necessary to alleviate the economic losses of local fishermen (Junta de Andalucía 2021).

Due to its varied diet and adaptive behavior, dolphins, and especially the bottlenose dolphin (*Tursiops truncatus*), have been involved in the predation of fish caught in different fishing gear, especially gillnets and trammel nets, in different countries throughout the world and particularly in the Mediterranean Sea (for example, Zollet and Read 2006; Revuelta et al. 2018; Snape et al. 2018; Miliou et al. 2018; Monaco et al. 2019; Pardalou and Tsikliras 2020; Pardalis et al. 2021). Preys species of bottlenose dolphin include

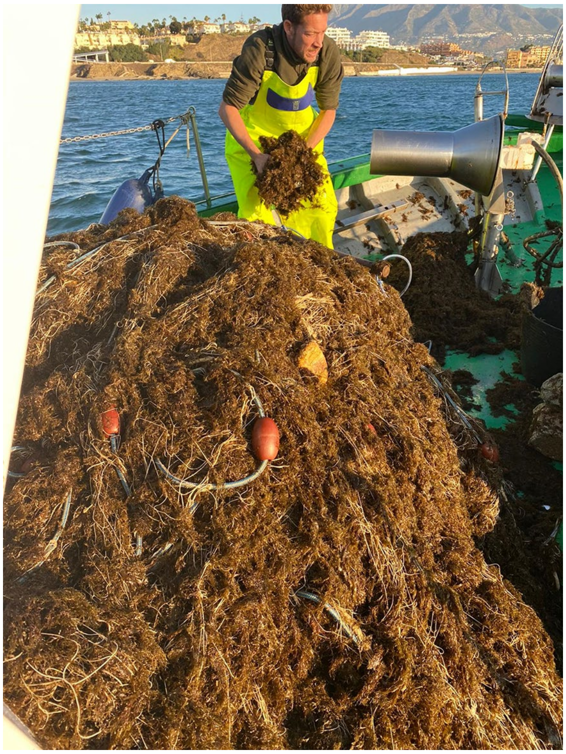

Fig. 1 A Spanish fisherman cleaning his trammel nets of the alien species *Rugulopteryx okamurae* in the Alboran Sea

fishes and cephalopods although the feeding behaviour shows ontogenic and sex differences (Blanco et al. 2001). Its diet is composed of some species with commercial value for fishery, such as the hake (*Merluccius merluccius*), European pilchard (*Sardina pilchardus*) and anchovies (*Engraulis enccrasicholus*) (Blanco et al. 2001).

Predation on catches causes serious damage to fishing gear together with catch losses (Fig. 2). These damages are highly variable and difficult to quantify, but lead to economic losses for artisanal fishing vessel owners that can reach up to 30% of a year's profits (Monaco et al. 2019; Pardalou and Tsikliras 2020). Gear damage reduces the catchability of the gear until the holes produced by dolphins during depredation events are repaired or the damaged units are replaced and, therefore, modifies the fishing effort. In addition, fishermen are forced to modify their strategy, quitting known profitable fishing ground, alternating to other fishing gear or reducing the time the net gear is set, in order to avoid or reduce such interactions (Goetz et al. 2014). Previous studies on gear predation by dolphins

Fig. 2 A Spanish fisherman showed the damage to fishing gear cause by dolphin predation in the Alboran Sea

in the Mediterranean region of Andalusia (Southern Spain) indicate that these predation events have increased in the last years, due to an increase in the abundance of bottlenose dolphins in the area according the surveyed fishermen (Aguilera et al. 2020). Up to 88% of active artisanal fishermen surveyed by Aguilera et al. (2020) at the landing ports reported negative interactions with bottlenose dolphins.

The main objective of this study is to understand the main environmental and technical conditions that favor damage on fishing trammel nets in the Alboran Sea, which entails an important loss of catchability, due both to the clogging of the net by the alien seaweed *R. okamurae*, or to the breaking of the nets by dolphin predation.

Material and methods

Study area

The Alboran Sea is a marine bridge that connects the Mediterranean and Atlantic areas. It is the westernmost sub-basin of the Mediterranean, being connected with the Atlantic Ocean through the Strait of Gibraltar. Therefore, it is the first region of the Mediterranean Sea receiving the surface Atlantic water flowing eastward from the Gulf of Cadiz, and the last basin that the Mediterranean waters cross before exiting to the Atlantic Ocean. As a consequence of its location, the Alboran Sea is filled by a large number of water masses (Vargas Yañez et al. 2021). The main circulation of the Surface Atlantic Water in the Alboran Sea is characterized by two mesoscale anticyclonic gyres, involving the shedding of submesoscale eddies and filaments. In this context, the Alboran Sea shows rich biodiversity, and biological productivity which has favored the development of an important fishing activity in both shores (Báez et al. 2021). Also important to the sub-region small-scale fisheries activity, the climate of the Alboran Sea is mostly characterized by mild wet "winters" (from October to April); warm to hot and very dry summers (from June to August) and overall semiarid conditions. It is a Mediterranean-type climate, which is loosely defined as a subtropical to midlatitude climate (Sánchez-Laulhé et al. 2021).

Fisheries data origin

The operative fishing fleet registered in recent years under the modality of artisanal gears on the Spanish coasts of the Alboran Sea amounts to 318 vessels distributed in a total of 11 ports (Baro et al. 2021). The coast of the province of Malaga is where the largest number of artisanal vessels are concentrated (52%). Two ports, Caleta de Vélez (Velez-Málaga) and Fuengirola, concentrate approximately half of the small-scale fisheries fleet registered in Málaga province (Fig. 3). The small-scale fisheries fleet is very similar in its characteristics, it has an average length overall (LOA) around 8 m, and gross tonnage (GT) around 2.73. On the other hand, the fleet is highly adaptive and dynamic, using a wide variety of fishing gears as described by Camiñas (1990) and Baro et al. (2021). In this paper, we have focused on the fishery using trammel nets exclusively, as trammel nets are the ones that can suffer the most damage from being clogged with seaweeds and broken by dolphin predation.

A total of 548 sets performed by 10 different boats based in Fuengirola (3 boats) and Caleta de Vélez (7 boats) along the coast of Málaga province within the continental shelf, were monitored between March and July 2021. This period is the most active for the Andalusian artisanal trammel fleet. Outside this period, due to bad weather conditions and the low demand for species such as red mullet, the artisanal fleet operates with other gears. For monitoring, and given that it was not possible to board additional scientific personnel on many vessels due to the scarce habitability of the boat, daily monitoring was carried out in port with the skippers and crew. We obtained from each vessel information about the number of sets, place of the fishing operation, duration of the set, target species, depth and characteristics of the net.

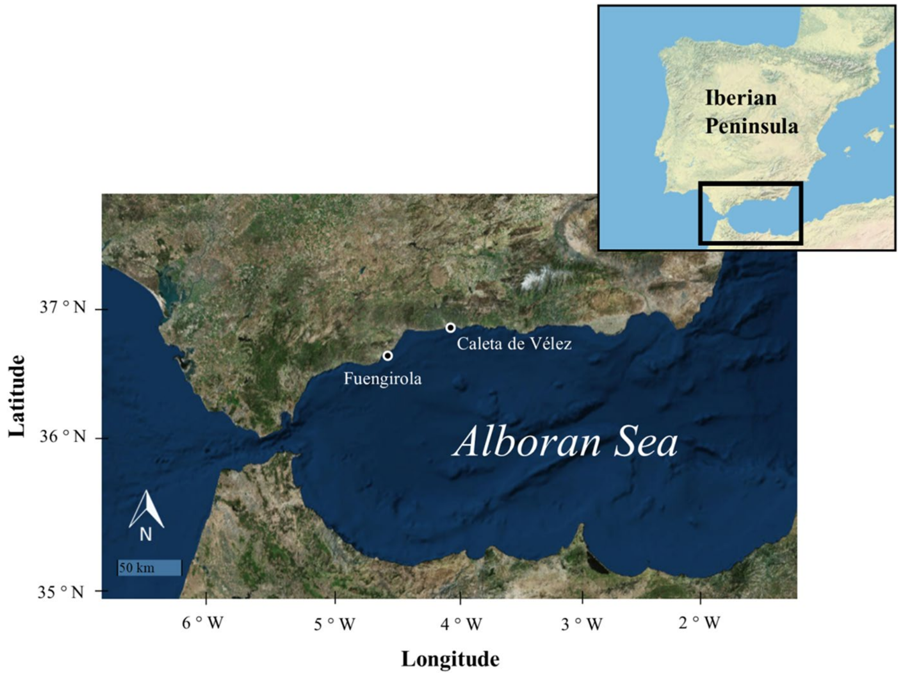

Fig. 3 Map of the study area, we highlight the fisheries harbor of Caleta de Vélez and Fuengirola

In previous studies (i.e. Aguilera et al. 2020), interviews were conducted in the 14 fishing ports of the Mediterranean provinces of the Andalusian region. A total 33 interviews were carried out to active skippers. The fishing gears most affected by bottlenose dolphins were the stripped red mullet trammel net (37%) and the common cuttlefish trammel net (26%). The remaining thirty-seven percent of the fishing gears concerned were: trammel net, bullet tuna gillnet, sardine gillnet, set gillnet, Mediterranean flyingfish gillnet, Atlantic bonito gillnet and hake gillnet. Regarding the economic losses, the fishermen reported a mean of 582 € (SD = 341) per event of negative interaction; the cost was estimated considering both gear damage and catch loss. The total cost declared by the fishermen of a failed fishing trip (including indirect costs such as the number of operators paid, fuel consumed, missing catch, etc.) was 871€ (SD = 1130). It has been calculated that a single predation event could lead to 59% (Andalusia), 76% (Malta), or 78% (Sicily) reduction of the catch, and that 33–76% of the gear could be damaged, involving is some cases its total destruction (Monaco et al. 2020).

We compiled declarations by some Cofradias (fishers brotherhoods) to assess the economic losses in other ports. At Barbate, in the Atlantic part of the Strait of Gibraltar, the species that was caught the most in 2015, the year in which *R. okamurae* was detected for the first time, was the sablefish (*Lepidopus caudatus*) with 137.66 tons. In 2016, it went to 110.46 tons; in 2017, to 174.88; in 2018, it dropped to 51.57. Another fish whose sharp decrease has been noted is the blackspot seabream (*Pagellus bogaraveo*), of which 21.88 tons were obtained in 2017. In 2019 the landings dropped to 2.5 tons.

Factors and explanatory variables

Two different target variables were studied: (i) the damage to gear due the clogging of the artisanal fishing trammel nets by seaweed (abbreviated as CNS, thereafter), and (ii) the breaking of the nets by dolphin predation (abbreviated as BND, thereafter). CNS was assessed when the skipper, after hauling the trammel net onboard, returned to port for cleaning. This could mean the hasty end of the fishing day and the loss of net capture during that set. On the other hand, a BND event was considered when a net break occurred. As possible explanatory factors affecting the local incidence of CNS or BND we analysed both environmental and technical variables. The values of environmental variables were obtained by direct sampling beside the base port.

We grouped the explanatory variables into three different factors: A) Spatio-temporal, B) Oceanographic-Environmental and C) Technical features of the fishing. Thus, each factor is represented by a set of variables, in total 14 predictor variables (Table 1).

Table 1 List of factors and explanatory variables checked to perform the logistic model. The type of variables and units are included

Factor	Variables	Acronym	Type	Units
Spatio-temporal	Month	MO	Ordinal	Dimensionless
	Longitudinal gradient	LG	Ordinal	Dimensionless
Oceanographic-environment	Sea Surface Temperature	SST	Quantitative	ºC
	Air temperature	AT	Quantitative	ºC
	Wind direction	WD	Qualitative	Dimensionless
	Moon phase	MP	Qualitative	Dimensionless
	Cloudiness*	CL	Qualitative	Dimensionless
Technical of the fishing operation	Soak time	ST	Quantitative	h
	Number of net units	NNU	Quantitative	Dimensionless
	Mesh size	MS	Qualitative	Dimensionless
	Fishing ground depth	FGD	Quantitative	m
	Target species	TS	Qualitative	Dimensionless
	Gross register tonnage	GT	Quantitative	Dimensionless
	Length overall	LOA	Quantitative	m

*denoted variable only used in the BND (Breaking of the Nets by Dolphin predation) model

(A) The spatio-temporal factor included the variables month, and longitudinal gradient. Both variables are ordinary and dimensionless. The month variable refers to the month when the fishing was done, in the interval between the value 3 (March) and 7 (July). The longitudinal gradient refers to the order of the location in the West–East gradient following the coast, and the range of the variable goes from 1 (further west) to 23 (further east).

(B) The Oceanographic-environmental factor included the variables: air temperature, cloudiness, moon phase, Sea Surface Temperature, and wind direction. Air temperature ranged between 11 °C and 25 °C, and was taken directly in the port at 09:00 a.m. Cloudiness is a qualitative variable with four states: (i) sky covered with clouds, (ii) sky without clouds, (iii) cloudy intervals, and (iv) slightly cloudy. Moon phase also is a qualitative variable with six states: (i) New Moon, (ii) First Quarter, (iii) Full Moon, (iv) Last Quarter, (v) Growing Moon, and (vi) Waning Moon. Sea Surface Temperature range was 11 °C to 25 °C, and was taken directly in the port at 09:00 a.m. Wind direction is a qualitative variable with six states: (i) North, (ii) South, (iii) Northeast, (iv) Northwest, (v) Southeast, (vi) Southwest, and (vii) East and West.

(C) The Technical features of the fishing operation included the variables: soak time, number of net units, mesh size, fishing ground depth, target species, Gross register tonnage, and Length overall. Soak time is the time the net remains in the water, with 1 h soak time being the most frequent, involving 148 sets. Number of net units is the number of net setting pieces, and is an estimation of the total length of the trammel nets, ranging between 6 and 34 net units, being the sets with 15 net units the most frequent with 191 sets. For the Mesh size, we used the commercial categories with which the fishermen make the nets. Fishing ground depth, varied between 1 and 60 fathoms. Target species is a qualitative variable with 8 different states (see the groups of species of each state in Table 2), each different state (i.e. group of target species) representing a different fishery strategy. Gross register tonnage was ranked between 0.71 and 4.79, and Length overall ranged between 6 and 10.5 m.

Statistical analysis

Two different statistical models were performed for each target variable (CNS and BND). We used logistic binary stepwise forward/backward regression to obtain the probability of occurrence of at least one local CNS and BND event in a particular set in function of the three explanatory factors (Spatio-temporal, Oceanographic-Environment, and Technical) together (final model) and separately for individual factors or pairs of factors (partial models). The partial models were performed using the variables related to each factor that were included in the final model. Model coefficients were assessed by means of an Omnibus

Table 2 Checklist of the target species (TS), with 8 different states, each states represent a different fishery strategy

Fishery strategy	Species-common name	Scientific name
TS 1	Common cuttlefish	*Sepia officinalis* Linnaeus, 1758
TS 2	Striped red mullet	*Mullus surmuletus* Linnaeus, 1758
TS 3	Red mullet	*Mullus barbatus* Linnaeus 1758
TS 4	Tiger prawn	*Penaeus kerathurus* (Forskål, 1775)
TS 5	Common sole	*Solea solea* (Linnaeus, 1758)
TS 6	Atlantic bonito	*Sarda sarda* (Bloch, 1793)
TS 7	Slender rockfish; Greater forkbeard; European lobster; Common spiny lobster	*Scorpaena elongata* Cadenat, 1943; *Phycis blennoides* (Brünnich, 1768); *Homarus gammarus* (Linnaeus, 1758); *Palinurus elephas* (Fabricius, 1787)
TS 8	Common seabream; Common pandora; Common dentex; Redbanded seabream; Greater amberjack; Shellfish	*Pagrus pagrus* (Linnaeus, 1758); *Pagellus erythrinus* (Linnaeus, 1758); *Dentex dentex* (Linnaeus, 1758); *Pagrus auriga* Valenciennes, 1843; *Seriola dumerili* (Risso, 1810);–-

test and the goodness-of-fit between expected and observed proportions of positive events along ten classes of probability values was evaluated using the Hosmer & Lemeshow test (which also follows a Chi-square distribution; low p values would indicate lack of fit of the model) (Hosmer and Lemeshow 2000).

In addition, the discrimination capacity of the model (trade-off between sensitivity and specificity) was evaluated with the receiving operating characteristic (ROC) curve. The area under the ROC curve (AUC) provides a scalar value representing the discrimination capacity of the model (Lobo et al. 2008).

In a similar way to Muñoz et al. (2005) we performed a variation partitioning to assess as percentages the relative contribution in the explanatory model of each factor included to explain the damage to the trammel nets by seaweeds (CNS) or dolphin predation (BND). The main aim of this analysis is to assess the pure effects of each factor (Borcard et al. 1992; Muñoz et al. 2005). Therefore, the part of the variation in each final model explained by each factor was obtained by correlating the values obtained from the final model and the partial models, using Spearman rank correlation coefficient and the squared correlation values. Then, the pure independent effect of each factor was assessed by subtracting from 1 (the whole variation) the variation explained by the partial model of the other factors combined (for example: R^2(Spatio-temporal pure) = 1-R^2f(Oceanographic-Environment + Technical of the fishing).

Favourability function (F)

Regardless of the goodness-of-fit of the model, logistic regression is sensitive to the presence/absence ratio (Hosmer and Lemeshow 2000). The favorability function (Real et al. 2006; Acevedo and Real 2012) adjusts the model to inform about the degree to which the Spatio-temporal, Oceanographic-Environmental and Technical factors favor the event, regardless of the presence/absence ratio of CNS or BND. The threshold 0.5 from the favorability model is easier to interpret, as it indicates neutral explanatory conditions, i.e., neither favourable or unfavourable for CNS or BND.

Favorability was easily calculated from the probability obtained by the logistic regression according to the expression:

$$F = \frac{\frac{P}{(1-P)}}{\frac{n_1}{n_0} + \frac{P}{(1-P)}}$$

where P is the probability of a CNS or BND event occurring, n1 is the number of observed events of net damage for each CNS or BND, and n0 is the number of observed sets with no net damage.

Because the Favorability function removes the effect due to the ratio of presences/absences, the CNS and BND models can be directly compared (Real et al. 2006; Acevedo and Real 2012). Thus, we plotted the Favorability function of CNS and BND in the same range of the explanatory variables. These plots help us to interpret the response of each Favorability function to the same variables.

Results

Approximately 30% of sets suffered a net damage due to unwanted interaction with non-target wildlife species (alien seaweeds or dolphins). This obviously leads to economic losses of the small-scale fisheries fleet due to a reduction in captures, the cost of repairing/substituting the whole net or damaged units, and the time in hours of repairing or mounting a new net on land. Moreover, the percentage of total sets with traces of seaweeds in the nets regardless of damage was 33.8%, while the percentage of sets with damage by seaweeds was 12.4% (CNS). In relation to the damage caused by dolphin predation (BND), 17.9% of the sets suffered damage. Only 4 sets suffered both CNS and BND at the same time (0.73%), and only 3.65% of total sets showed damage from BND and traces of seaweeds (Fig. 4).

Two statistically significant logistic models were obtained for the target variables CNS (clogging trammel nets by seaweeds), and BND (breaking of the nets by dolphin predation), respectively. The models were significant according to the Omnibus test, and their discrimination capacities were good (Table 3), although the breaking of the nets by dolphin predation (BND) model showed poor goodness of fit, according to the Hosmer and Lemeshow test.

We performed 12 different partial models (Table 4 and 5). In the CNS model, the partial model with highest Spearman correlation with the final model involved the factors

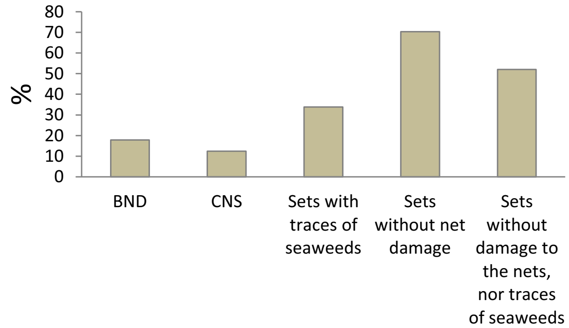

Fig. 4 Percentage of sets by CNS (clogging trammel nets by seaweeds), BND (breaking of the nets by dolphin predation), Sets without traces of seaweeds, Sets without net dame, and sets without damage to the nets, nor traces of seaweeds

Oceanographic-Environmental + Spatio-temporal (Table 6), but in the BND model, the partial model with highest correlation with the final model involved the factors Technical features of the fishing + Oceanographic-Environmental (Table 7). The percentage of relative contribution in the explanatory model of each factor included to explain the clogging of trammel nets by seaweeds (CNS), or breaking of the nets by dolphin predation (BND) can be seen in Table 8.

The variables target species, month and longitudinal gradient were significant in both CNS and BDN models. Thus, we plotted the average value of favorability, for each state of these variables for both CNS and BNS (Figs. 5, 6, 7).

Discussion

In the particular case of the CNS, this study is the first approach to its damage on the trammel net. The main variables and factors that explain the damage to the net are fundamentally related to the oceanographic-environmental and spatio-temporal factors that, on the one hand, determine the marine currents (as is also the case of lunar phases and wind direction) and, on the other, reflect the distribution and abundance of the alien seaweed *Rugulopteryx okamurae*.

Table 3 Explanatory factors and variables included in both final models CNS (clogging trammel nets by seaweeds) and BND (breaking of the nets by dolphin predation), and goodness-of-fit. Key: R^2_N, Pseudo-R-squared Nagelkerke; 2LL, less than twice the natural logarithm of the likelihood; AUC area under the ROC (receiving operating characteristic) curve. Variables in CNS model: LG, longitudinal gradient; WD, wind direction; MP, moon phase; MO, month; TS, target species. Variables in BND model: NNU, number of net units; TS, target species; GTR, gross register tonnage; CL, cloudiness; MP, moon phase; LG, longitudinal gradient

	CNS	BND
Omnibus test	175,145 ($p < 0.0001$)	115 ($p < 0.0001$)
Hosmer and lemeshow Test	5.879 ($p = 0.661$)	22.014 ($p = 0.005$)
-2LL	201.860	384.698
AUC	0.922	0.809
Factors	Spatio-temporal, oceanographic-environment and technical of the fishing	Spatio-temporal, oceanographic-environment and technical of the fishing
Variables	LG; WD; MP; MO; TS	NNU; TS; GTR; CL; MP; LG

Table 4 Goodness-of-fit of CNS (clogging trammel nets by seaweeds) partial models. Key: -2LL, minus twice the natural logarithm of the likelihood; AUC area under the ROC (receiving operating characteristic) curve

Partial model	-2LL	AUC
Technical of the fishing + oceanographic-environment	294.229	0.854
Oceanographic-environment + spatio-temporal	261.207	0.898
Technical of the fishing + spatio-temporal	273.630	0.892
Technical of the fishing	340.820	0.781
Oceanographic-environment	365.263	0.736
Spatio-temporal	294.817	0.867

Table 5 Goodness-of-fit of BND (breaking of the nets by dolphin predation) partial models. Key: -2LL, minus twice the natural logarithm of the likelihood; AUC area under the ROC (receiving operating characteristic) curve

Partial model	-2LL	AUC
Technical of the fishing + oceanographic-Environment	410.017	0.790
Oceanographic-environment + spatio-temporal	472.509	0.703
Technical of the fishing + spatio-temporal	420.855	0.784
Technical of the fishing	431.013	0.773
Oceanographic-environment	485.559	0.657
Spatio-temporal	507.768	0.578

Table 6 Spearman correlation coefficient (Rho-Spearman) between the probability CNS model (clogging trammel nets by seaweeds), and partial models

Partial model	Rho-Spearman
Technical of the fishing + oceanographic-environment	0.873
Oceanographic-environment + spatio-temporal	0.914
Technical of the fishing + spatio-temporal	0.231

Table 7 Spearman correlation coefficient (Rho-Spearman) between the probability BND (breaking of the nets by dolphin predation), and partial models

Partial model	Rho-Spearman
Technical of the fishing + oceanographic-environment	0.958
Oceanographic-environment + spatio-temporal	0.537
Technical of the fishing + spatio-temporal	0.774

Table 8 Percentage of relative contribution in the explicative model of each factor included to explain the damage to gear due or clogging trammel nets by seaweeds (CNS), or breaking of the nets by dolphin predation (BND)

Factor	% Relative contribution CNS	% Relative contribution BND
Technical of the fishing	16.5%	70%
Oceanographic-Environment	30.9%	20%
Spatio-temporal	23.8%	8%

In the case of the BNS, the technical features of the fishing operation are the most important (up to 70% in the present study) as was also the case in previous studies (Pennino et al. 2015; Snape et al. 2018; Pardalou and Tsikliras 2020).

Target species, month, and longitudinal gradient were important variables for both clogging trammel nets by seaweeds (CNS), or breaking of the nets by dolphin predation (BND), but due to the fishing

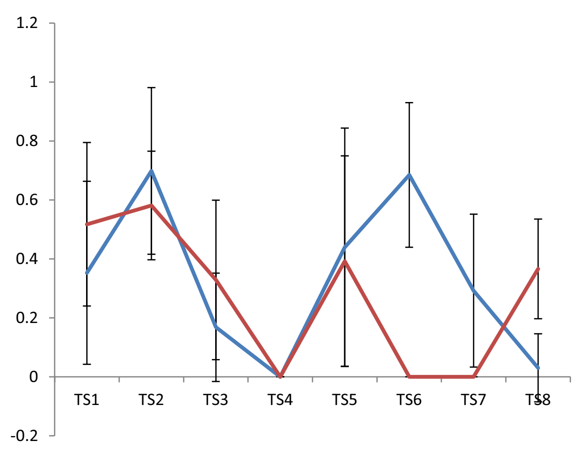

Fig. 5 Average value of favorability, for each state of the target species (TS) variable for both CNS and BNS. The confidence interval of the standard deviation is shown. Key: Blue, CNS (clogging trammel nets by seaweeds); and Red, BND (breaking of the nets by dolphin predation). Key as in Table 2

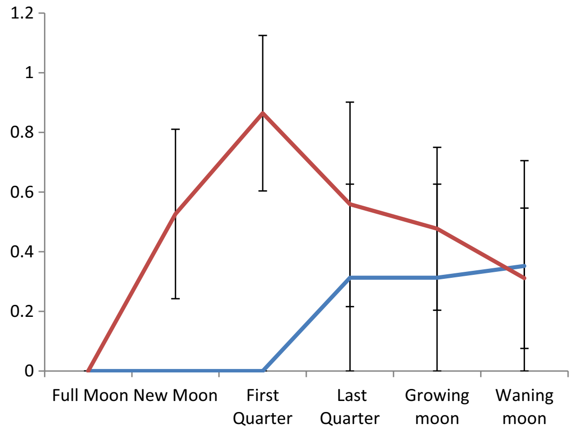

Fig. 6 Average value of favorability, for each state of the month (MO) variable, for both CNS and BNS. The confidence interval of the standard deviation is shown. Key: Blue, CNS (clogging trammel nets by seaweeds); and Red, BND (breaking of the nets by dolphin predation)

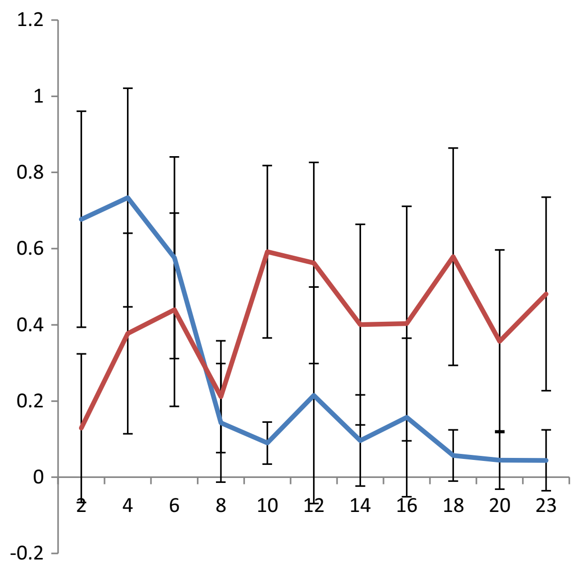

Fig. 7 Average value of favorability, for each state of the longitudinal gradient variable (LG) for both CNS and BNS. The confidence interval of the standard deviation is shown. Key: Blue, CNS (clogging trammel nets by seaweeds); and Red, BND (breaking of the nets by dolphin predation)

strategy they had different effects, and in some cases opposite, for the two types of damage. For example, in the case of longitudinal gradient, the interaction with dolphins increased from west to east, while the presence of algae increased in the opposite direction.

The different fishing strategies used, depending on the target species, also had a differential effect in both cases, although when the fishermen went in search of the tiger prawn (*Penaeus kerathurus*) they did not suffer damage to their nets in either case. This could be due to the fact that the trammel net in these cases is set in deeper waters. We can also assume that fishers using higher GT boats targeting tiger prawn have better revenues from the fishery compared to fishers who fish in near-shore areas targeting red mullet and cuttlefish. Depending on the target species, in the case of CNS, the nets suffered more damage when the target was striped red mullet and Atlantic bonito, while in the case of BNS higher damage was associated to common cuttlefish (*Sepia officinalis*) and striped red mullet (*Mullus surmuletus*). In fact, of 40 observed sets targeting striped red mullet, 62.5% suffered serious net damage. During the red striped mullet fishery season from Sardinia, Díaz López (2005; 2006) observed net damage for 68.7% of fishing days in trammel fishery, which is very similar to the damage observed in our study. Moreover, many studies (for example, Gazo et al. 2008; Pardalou and Tsikliras 2020) reported highest net damage in trammel fisheries targeting striped red mullet, in a similar way of our findings. However, other studies also observed that the cuttlefish nets were less predated by dolphins (Lauriano et al. 2004; Pardalou and Tsikliras 2020), in opposition to our findings. This is a point to highlight, because perhaps the fishermen of the south of Spain use some technical peculiarity for the trammel net targeting cuttlefish, different from other parts of the Mediterranean, or simply that culturally the dolphins of the Alboran Sea have become familiar with the taste of the cuttlefish.

The fishing strategy during trammel fisheries targeting striped red mullet, imply setting the net in shallow water, and near stones, which coincides with the area where *R. okamurae* is concentrated, and also attracts the dolphins. Moreover, it is the most exposed area to the effect of tidal currents towards the coast. On the other hand, dolphins could feel a special attraction for stripped red mullet perhaps for three different reasons: (i) its taste, because this species contains some component that dolphins need to complement the daily diet, or because red mullet could be a delicatessen for dolphins, (ii) lower energy cost to prey on these specific nets, and (iii) due to the better visibility of shallower depth, where they find the entangled fish more easily. In the case of the predation on cuttlefish captures the reasons could be similar.

Other differential effect between CNS and BND was that of the different lunar phases. Here we must bear in mind that the moon will determine the tidal regime, and therefore the current that occurs with the rise and fall of the sea.

In the case of the CNS model, other variables analysed were wind direction and month. In general, the North components of the wind direction tend to increase the probability of CNS, versus the South components, which decrease the probability. This may be due to the fact that the direction of the flow takes the opposite direction to that which it had on the surface when reaching a certain depth (Pond and Pickard 1983). The months of summer, generally with higher productivity, and better conditions for the growth of seaweeds, were the months with the highest probability of CNS.

In the BND model other significant variables were the number of net units, and gross tonnage (GT) of the ship, both with a negative effect in the probability. A priori, the higher the number of net units, and therefore the larger the net, the more likely it is that dolphins will prey on these nets. In a similar way, higher GT implies larger ships with higher fishing effort, so they could be more likely to be affected. However, the observed effect was the opposite. This may be explained because the fishermen set near the coast fewer parts of the net, and similarly, ships with higher GT tend to set in areas further away from the coast (because they have more autonomy). Therefore, we hypothesize that the set most depredated by dolphins are near the coast, at shallow depths and in clear waters, areas where bottlenose dolphin are commonly found. After surveying the skippers who have collaborated in this study about this possibility, they all agreed with this hypothesis.

According to Pardalou and Tsikliras (2020), the mesh size of the net had a negative relationship with the increase in predations, because the mesh size of the net could increase its selectivity, and possibly the dolphins are attracted to nets with greater variety of preys. In our study, the mesh size was not significant, and had no effect neither in the CNS nor in the BND events. Therefore, there are other technical variables that are more important in both cases. The effect of the GT or fishing power could also be important, because depredation decreases in vessels targeting species of high value in deeper waters, such as the tiger prawn; conversely, fishermen working close to the harbor face a double impact due to low-value catches and because they are most affected by bottlenose dolphin predation.

Economic survey results

A total of twelve fishermen were surveyed about the economic impact dolphins have on their economic activity. These fishermen were based in five ports, four in Malaga province (Caleta de Vélez, Fuengirola, Nerja and Málaga) and one in Granada province (Motril).

The nets, composed of several units, are always exposed to natural wear and tear due to their frequent use and time passed under the sea, where the greatest damage is caused by rubbing against rocks or deterioration by snags. According to surveys, nets may have a lifespan of between 2 and 20 years. Currently, interaction with dolphins results in nets lasting between 1 day and one fishing season (2–7 months depending on the target species and the number of interactions).

The extent of the damage depends on the number of dolphins feeding and breaking the net. When there are few dolphins (2–5 individuals), their behavior related to the capture in the nets and their feeding behavior is selective and the damage is minor. However, groups of more than 5–10 individuals interact more aggressively with the nets causing more damage that can result in the loss of the total capture and put the gear out of use.

Eighty-three per cent of respondents repaired nets when damage was minor (50 cm in diameter). These holes require between half an hour and an hour to repair. Approximately, repairing a net with minor damage requires between 8 and 9 h. Given the minimum wage in Spain (1000 €/month), each hour of work in Spain is equivalent to 6.25 €. Therefore, the economic value of the repair time of a net is between €50 and €60 per net plus the equivalent value of the fish not caught by that damaged area of net.

All the fishermen reported that the damage is severe when dolphins go in groups of several individuals. When this happens, they would rather buy a new piece to replace the damaged unit than repair it because of the length of time it would take to repair. Major damage is not treated until the piece is unusable, then it is replaced by a new one. Each new piece costs between 100 € and 300 € already assembled. An unassembled part costs around €50, but requires several hours of work to assemble. Replacing a complete net with a new one costs around 6000 €.

Half of the fishermen reported suffering more damage when the target species is the red mullet (*Mullus surmuletus*). Questions about the economic impact of these interactions showed that fishermen in the last 3 years have suffered a 30–50% reduction in profits. In some cases, the destruction of nets has meant that profits have not exceeded losses due to the purchase of new gear, leading to the fishermen having to stop fishing for the remainder of the season. The few profits made are now being reinvested in new nets. The situation has led some respondents to declare that they are considering selling the boat and changing their trade.

Possible solutions

Our results show that even within artisanal fisheries there is a disparity in who gets affected more by wildlife species; in this case the fishers who set nets in near-shore areas are more affected than higher gross tonnage (GT) boats that set nets in deeper waters. We can assume fishers using higher GT boats are socioeconomically better as compared to fishers who fish in near-shore areas. One possible solution is to allow the exploitation and mass removal of *R. okamurae* seaweed by this lower GT stratum. *Rugulopteryx okamurae* seaweed could be put to industrial use in the extraction of agar–agar and other products of interest. These nets would not be attacked by dolphins. Moreover, it would favor tourism, which perceives seaweed as a disturbance. However, due to current legislation, the Spanish government denied permits for commercial exploitation of the invasive algae (source: El PAIS 10/06/2022, available from website https://sevilla.abc.es/andalucia/cadiz/sevi-gobierno-deniega-comercializacion-alga-asiatica-invasora-estrecho-202206101942_noticia.html).

There are many examples of invasive species that have become the target of a new type of fishery performed by local fishermen in newly colonized habitats. Some cases are, for example, the Nile perch (*Lates niloticus*) (Aloo et al. 2017), the blue swimming crab *Portunus segnis* from Gulf of Gabès (Shaiek et al. 2021), or the lionfish (*Pterois volitans*) from Venezuela (Báez and Gutiérrez 2018), for which extractive fishing is the only option to control the invasion. All these fisheries are artisanal and operate in the framework of a subsistence economy. A well-known alien species that today is the target of several professional fisheries in the Mediterranean Sea is the blue crab (*Callinectes sapidus*) (Mancinelli et al. 2017). Nevertheless, there are many invasive species that reduce biodiversity and for which there are no fisheries, such as the rabbitfish (*Siganus luridus*) involved in some cases of Ciguatera poisoning (Chinain et al. 2021).

However, despite these new opportunities for a selective control through fisheries, the European Union has limitations in EU Legislation to Address Marine Biological Invasions. According to Kleitou et al. (2021), the commercialization of Invasive Alien Species (IAS) of Union concern should be allowed. In fact, including fishermen in mitigation actions can transform mitigation costs into gains for local fishermen communities. Thus, the IAS Regulation needs to be adapted to allow (and promote) the fishing of IAS species. Thus, it would be necessary to involve local fishermen in order to solve the problem caused by *R. okamurae*.

Moreover, fishermen, due to their local and traditional ecological knowledge, could be an essential observer in the early detection of new expanding alien species. Thus, local fishers and scientists should improve the collaboration to share information, building mutual confidence through programs that include permanent communication channels, including surveys of local fishermen, the development of specific citizen science platforms, or on-board observers programs. Their knowledge should also be used to assess the conservation status of changing marine ecosystems, because they possess intuitive and basic ecological knowledge that enables them to qualitatively assess changes in ecosystems (Pita et al. 2020). This is particularly useful since it is expensive to maintain constant and thorough scientific monitoring of these changes over large areas (except perhaps in Marine Protected Areas, for example Aguzzi et al. 2020). It is therefore recommendable to amend European legislation to allow the exploitation and extraction of alien species by the artisanal and local fleet.

A widely used method of reducing dolphin predation on nets is the use of acoustic alarms (called 'pingers') (Snape et al. 2018). Pingers have attracted much attention as a possible method to mitigate these problems (Dawsons et al. 1998). However, despite their widespread use, the economic effectiveness of these devices is relatively low (Maccarrone et al. 2014; Snape et al. 2018). Moreover, due to the highly adaptable behavior of this species of dolphin, although at first the pingers can produce deterrence in the animals, after getting used to the sound it indicates exactly where there is a net. In addition, pingers contribute to noise pollution in the sea (Kastelein et al. 2007; Gazo et al. 2008) that affects cetaceans and other marine species. Dolphin deterrent devices (DDDs) are a new family of device that is able to draw dolphins away from fishing nets by interacting with the dolphin's echolocation system, preventing the animals from echolocating the nets, unlike ultrasonic emitters that disorientate the dolphin. New experiments carried out in Adra (Almeria, South of Spain) between August and September 2022 have shown high effectiveness, so that the boat using these new devices did not suffer from predation. However, due to the high price of these devices, only two boats could be fitted with these devices. We do not know if the dolphins could be habituated over a long period of time, and the possible crossover effect if the whole fleet was fitted with these devices. Further studies are therefore needed before recommendations can be made.

Small-scale fisheries from temperate areas are in danger due to tropicalization and the encroachment of alien species, among others factors including the growth of recreational fisheries in coastal waters and overfishing, (for example, Lloret et al. 2018). In addition, there are other problems such as the price of fuel and rising prices which must be another source of loss of economic performance. Artisanal fishermen are undoubtedly the weakest social component within the fishing sector, which makes new compensatory measures necessary on the part of the authorities.

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Declarations

Data availability Data will be made available on reasonable request.

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