




What's for dinner? Assessing the value of an edible invasive species and outreach actions to promote its consumption

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Abstract The consumption of edible aquatic invasive species has gained popularity as a means to minimize their impacts while easing pressure on native resources and ecosystems. Weakfish *Cynoscion regalis* (Bloch & Schneider, 1801) is one of the most recent invasive fish species in the Iberian Peninsula (Europe) which once sustained an important fishery in the native range (Northwest Atlantic Ocean). Portugal ranks third in the list of the world's fish consumers, so promoting a weakfish fishery could at least minimize the impacts upon native species, since weakfish have innate traits that are appreciated by Portuguese fish consumers. However, introducing a new species to consumers is challenging owing to consumers' habits and unfamiliarity with the species. So, we aimed to (i) evaluate the acceptance of weakfish by a panel of Portuguese fish consumers and (ii) create outreach actions—partnerships with local Chefs and press releases—to explain to a broader audience what

invasive species are and promote the consumption of edible aquatic invasive species. We conducted a consumers survey that showed that weakfish has great chances of being well accepted by Portuguese fish consumers—90% would buy weakfish because they appreciated its appearance, flavor, and texture, besides being a wild fish. The outreach actions reached a few million people because 46 online articles were published, and three news pieces were broadcasted on national television. Our strategy increased the public's awareness about weakfish as an invasive species, which could be adapted for other non-indigenous marine species elsewhere in the world.

Keywords Weakfish · Invasive species · Blue economy · Commercial fishery · Outreach · Media

Introduction

The eradication of aquatic invasive species is often impossible (Vander Zanden and Olden 2008; Havel et al. 2015) and requires a continuous effort to keep some populations under control (Vander Zanden et al. 2010; Simberloff 2020). Invasive species benefit from a wide array of competitive advantages compared to native species, including the absence of predators and naïve prey (Colautti et al. 2004). In our globalized world, several species are overexploited in the native

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range but invasive elsewhere. This sparked the idea to use humans, the Earth's top predator, to control edible invasive species (Roman 2006; Nuñez et al. 2012; Lai 2015; Orth et al. 2020). The consumption of invasive species has become popular in the United States as a means to control the invasive lionfish *Pterois volitans* (Linnaeus 1758) and *Pterois miles* (Benett, 1828) through a campaign whose slogan was “Eat the lionfish” (NOAA 2011), and through the publication of the cookbook *The Lionfish Cookbook: The Caribbean's New Delicacy* (Ferguson and Akins 2010). A similar approach is being taken in Colombia by renowned Chef Jorge Rausch (The City Paper 2016).

Several chefs all over the world endorsed a similar approach. Chef Bun Lai from Miya's Sushi restaurant (Connecticut, USA) wants to convince the world that invasive species can be delicious, like the Asian sea squirt *Styela clava* Herdman, 1881, European green crab *Carcinus maenas* (Linnaeus, 1758), earthworms, among many others (Lai 2015). In the UK, celebrity Chef Gordon Ramsey featured the Chinese mitten crab *Eriocheir sinensis* H. Milne-Edwards, 1853, captured in the Thames River in one of his TV shows (Ramsey 2009). The Eastern grey squirrel *Sciurus carolinensis* Gmelin, 1788 was included in the seasonal menu of “The Jugged Hare” restaurant in London to promote its consumption while advocating for the conservation of the European red squirrel *Sciurus vulgaris* Linnaeus, 1758 (Hyslop 2015). In the United States, invasive Asian carps—bighead carp *Hypophthalmichthys nobilis* (Richardson 1845), black carp *Mylopharyngodon piceus* (Richardson 1846), grass carp *Ctenopharyngodon Idella* (Valenciennes, 1844), silver carp *Hypophthalmichthys molitrix* (Valenciennes 1844)—were introduced in the 1970s to control algae, weeds, and parasites in aquatic farms and canal systems but escaped into the Mississippi River Basin where they established breeding populations (NPS 2021). In the following years, they were fished to provide food to people facing economic problems through the campaign *Target Hunger Now!* (McCloud 2011). In Portugal, the Atlantic blue crab and weakfish were promoted as gourmet delicacies by Chef Leonel Pereira (Evasões 2018; Check-in 2021).

Controlling invasive species through fishing has a series of caveats for stakeholders. The intent of fishing invasive species is not to perpetuate a profitable fishery, but rather to control an invasive species (Nuñez et al. 2012), so farming or spreading an invasive

species is forbidden by law even if there is a profitable market for that product. Fishing invasive species is likely more effective in countries with higher fish consumption rates, like Portugal—third in the list of world fish consumers (EUMOFA 2016). On average, the Portuguese eat 56.8 kg of fish *per capita* in one year, twice the European Union's average (EUMOFA 2016; WWF 2017). Most seafood is sold fresh, without being processed or preserved (Almeida et al. 2015). Fresh seafood requires constant supply and various other means to guarantee the fish quality, which would be unfeasible to sustain without consumers being willing to pay a higher price. Also, 63% of the fish consumed in Portugal is imported, 35% is fished locally, and only 5% is produced in aquaculture facilities (WWF 2017). Portuguese consumers prefer wild species to farm-reared species (Cardoso et al. 2013; Fernandes 2017), often due to their skepticism about aquaculture which mostly relies on preconceived ideas that farmed fish is of lower quality (Ramalho and Dinis 2011). All these aspects could facilitate the introduction of a new wild fish species into the Portuguese food market. But what if this new species is an invasive species?

Weakfish *Cynoscion regalis* (Bloch and Schneider 1801), a species native from the Northwestern Atlantic, is one of the most recent introduced fish in the Iberian Peninsula (Europe) where it has established at least one viable population (Morais and Teodósio 2016; Morais et al. 2017). Weakfish was probably introduced in Europe through multiple introduction events and ballast water is considered the most likely introduction vector. If correct, weakfish would belong to a restricted list of fish that were introduced via ballast water (see table 1 in Morais et al. 2017). Weakfish is present in the Sado estuary (Portugal) before 2012, where it has reached an invasive status (Mundo da Pesca 2014; Morais and Teodósio 2016; Morais et al. 2017). For extensive details about the invasion history of weakfish in Europe and the Iberian Peninsula please consult Morais et al. (2017).

In the native range, weakfish supported local fisheries at least since the late 1800s (ASMFC 2016) but the stock is depleted since 2003 (ASMFC 2016). Since the mid-1990s, and despite the efforts made by the Atlantic States Marine Fisheries Commission, the stock is depleted due to overfishing and increased natural mortality (ASMFC 2017). In 2015, the last year for which weakfish price data is available, the

average retail price was 3.95 US\$ kg⁻¹ (or 3.26 € kg⁻¹—Fissues 2019). However, 3-pound (1.36 kg) fresh weakfish were being sold online for 36.40 US\$ (26.76 US\$ kg⁻¹ or 22.05 € kg⁻¹) (Fultonfishmarket 2019). In the invasive range, weakfish has been sold for 3 to 10 € kg⁻¹ in Setúbal's fish market—the main city along the Sado estuary (Fig. 1)—depending on the size of the fish. Similar sized wild native species, like meagre, European seabass, and gilthead seabream were sold for no less than 12 € kg⁻¹, 25 € kg⁻¹, and 25 € kg⁻¹, respectively [see Table S1 for detailed information about the prices of fish mentioned in this work]. Although Portugal is the top European seafood consumer, there is resistance to try new seafood products which can be decreased by promoting species' positive attributes (e.g., health benefits, environmental protection, origin) (Sanjuán-López et al. 2011; Nuñez et al. 2012) and providing information that familiarizes the customer with the new species.

Thus, the main objectives of this work were to (1) assess the potential of weakfish as a new fishing resource in Portugal by evaluating fish consumers' receptivity to this new species, and (2) put into practice public outreach actions (food tasting sessions, social media outreach, and press releases) to increase the public's knowledge on aquatic invasive species

and promote the consumption of an edible aquatic invasive species. This was accomplished by giving weakfish specimens to a panel of Portuguese consumers to evaluate their opinion on the fish. In parallel, we undertook several awareness events to inform the public about invasive species (e.g., negative impacts exerted by aquatic invasive species on ecosystems; benefits of removing invasive species from the environment) and raise awareness about the benefits of consuming weakfish to transform a threat into a source of new income to the local economy. We tested three hypotheses: (1) evaluation of weakfish appearance, flavor, and texture by Portuguese fish consumers is likely to be positive; (2) consumers' positive evaluation about weakfish may lead them to buy this species in the future and pay a fair price, and (3) consumers are more likely to prefer wild native fish species over weakfish, but weakfish over farmed native or imported fish species even if sold at the same price.

Materials and methods

Consumers' survey

A total of twenty-four specimens of weakfish *Cynoscion regalis* (Bloch & Schneider, 1801) were bought at

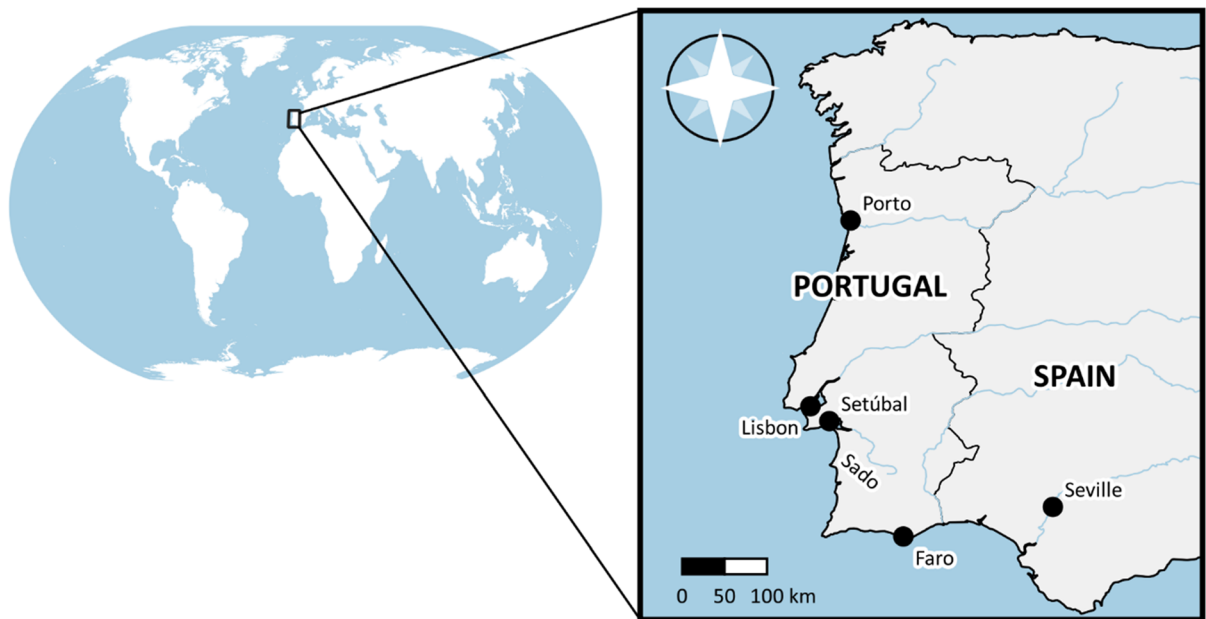


Fig. 1 Location of Setúbal (Portugal) and the Sado estuary in Portugal (Europe)

the Setúbal fish market in June 2017 (Fig. 1) and given to a panel of thirty fish consumers that cooked the fish in their homes. The fish were provided fresh and without gut contents. Fish consumers were chosen among a random subset of volunteers gathered for this survey who had never eaten weakfish nor heard about this species, and considering their gender and age group (young adults: 18–29, adults: 30–55, senior adults: > 55). These volunteers were recruited among colleagues, acquaintances, and friends of acquaintances all part of the Portuguese middle class, which included students, public servants, business owners, and retirees. Each consumer replied to a survey containing ten questions (Fig. 2). In questions 6 through 9, consumers were asked to compare weakfish to native fish species, and we used their common Portuguese names which corresponded to the following species: Atlantic horse mackerel *Trachurus trachurus* (Linnaeus, 1758), Atlantic salmon *Salmo salar* Linnaeus, 1758, European flounder *Platichthys flesus* (Linnaeus, 1758), European seabass *Dicentrarchus labrax* (Linnaeus, 1758), European pilchard *Sardina pilchardus* (Walbaum, 1792), gilt-head seabream *Sparus aurata* Linnaeus, 1758, meagre *Argyrosomus regius* Asso, 1801, and weakfish *Cynoscion regalis* (Bloch & Schneider, 1801).

Data from the weakfish survey were analyzed with a Chi-square test after assessing the test's assumptions—i.e., normal distribution and heteroskedasticity. When the assumptions were not met, we used the analogous non-parametric test, the Wilcoxon Signed-Rank test. All statistical analyses were done using R (version 3.4.2). Statistical significance was set at 0.05.

Outreach

We promoted a series of awareness events with two objectives, (1) share information about invasive species (i.e., introduction pathways, impacts, control, culinary use) and (2) promote weakfish as a fishery resource as a means to mitigate the putative impacts of this invasive species. So, we partnered up with two Chefs that prepared weakfish in their kitchens to assess their potential as a culinary delicacy. We then submitted two press releases through CCMAR's communication department about these events to raise the awareness of invasive species and weakfish to a broader audience. Simultaneously, we published

Fig. 2 The *Weakfish Survey* was given to a panel of thirty Portuguese fish consumers to evaluate their opinion on weakfish *Cynoscion regalis* (Bloch & Schneider, 1801), as well as their preference between weakfish versus several wild and aquaculture fish

social media content on the Centre of Marine Sciences (CCMAR) Facebook page about these initiatives.

Partnerships with local Chefs

The first event that we organized consisted of a lunch held on September 19th, 2017, in Loulé (Algarve) at the canteen of Algarve Mental Health Association. Here, Chef Avelino Falé prepared weakfish for teachers and staff that eat daily at the canteen (Fig. 3). The second event was hosted by “Sea” Chef Leonel Pereira, owner of the Michelin star restaurant *São Gabriel* in Almancil (Algarve). He was enthusiastic to test weakfish recipes in his experimental kitchen *Creative Cook Garage*, along with another edible invasive species that is not consumed in Portugal, the hydrozoan *Blackfordia virginica* Mayer, 1910 (Hydrozoa) (CCMAR 2019) (Fig. 4).

Press releases

The Centre of Marine Sciences' communication department published, on our request, two press releases in September 2017 to announce the tasting session that occurred at the Algarve Mental Health Association canteen and detailed information about two non-indigenous species present in the Guadiana estuary, weakfish and the Atlantic blue crab *Callinectes sapidus* Rathbun, 1896 (Decapoda). Mentioning another new invasive species in the press releases was part of a synergistic strategy to inform the public about invasive species, how common they have become, and how some can be introduced in the shopping list of Portuguese consumers. These press releases were published on the research centre's website and Facebook (CCMAR 2017a, b), and sent to the press using a list with more than two hundred contacts—including Lusa (the largest news agency in Portuguese in the world) and the main Portuguese television networks, newspapers, and radio stations.

THE WEAKFISH SURVEY

This survey is being conducted by Inês Cerveira, as part of her Master Thesis in Marine Biology at the University of Algarve. The thesis' title is "Weakfish *Cynoscion regalis* (Pisces: Sciaenidae) (Bloch & Schneider, 1801) ecology in its non-indigenous range and its potential as a new fishing resource" and the advisors are Dr. Pedro Morais and Professor Maria Alexandra Teodósio.

Name _____ Age _____ Contact _____

Question 1 Please provide a general assessment about weakfish's appearance, flavour, and flesh texture.

	Bad	Indifferent	Good
Appearance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Flavour	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Texture	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Question 2 Please mention which cooking technique you used to cook weakfish.

Boiled Grilled Roasted Fried Other

Question 3 Would you buy weakfish from the market? Yes No

Question 4 How much would you pay for weakfish? _____

Question 5 What would be a fair price to pay for a wild fish as weakfish? _____

Question 6 Do you prefer wild weakfish or other wild fish as gilthead seabream , seabass , or meagre ?

Question 7 Do you prefer wild weakfish or other fish produced in aquaculture as gilthead seabream , seabass , or meagre ?

Question 8 For the same price, would you rather buy wild weakfish or other fish produced in aquaculture as gilthead seabream , seabass , or meagre ?

Question 9 Order the following fish from 1 (favorite) to 7 (least favorite) according to your culinary preferences.

flounder gilthead seabream horse mackerel
meagre salmon sardine weakfish

Question 10 Do you prefer wild fish or aquaculture fish ?

Thank you for your collaboration!



Fig. 3 Tasting session at Algarve Mental Health Association (ASMAL) canteen. Chef Avelino Falé and his staff (ASMAL's students) (left) who prepared the weakfish served at ASMAL—roasted weakfish and potatoes with red bell peppers (right)



Fig. 4 Image posted by Chef Leonel Pereira on Instagram about his experiments with weakfish at his experimental kitchen in the São Gabriel restaurant (Creative Cook Garage 2018)

Evaluating outreach impact

We conducted an extensive internet search to evaluate the impact of the two press releases. The impact was measured by assessing the number of articles published and interviews that were broadcasted since it is impossible to determine how many people read or viewed each news piece. The news articles had to explicitly refer to information in the press releases. A Google search was performed on March 28, 2018. We used a combination of keywords, both in English and Portuguese, singular and plural, and referring to the non-indigenous species described in the press releases (i.e., espécie invasora, corvina, corvina americana, corvinata, rainha, weakfish, *Cynoscion regalis*, caranguejo, caranguejo-azul, blue

crab, *Callinectes sapidus*), the research institute (i.e., Centro de Ciências do Mar, CCMAR), the university (Universidade do Algarve, UALG), the study sites (Guadiana, Algarve, Portugal), and two of the scientists of this project (Maria Alexandra Teodósio, Inês Cerveira).

Three months after the two press releases, the Portuguese news agency LUSA interviewed the authors of this paper, along with Chef Leonel Pereira, to explain the reasons for the appearance of invasive species in Portuguese estuaries, their potential for commercial exploitation, and as a culinary delicacy. The interview was held on December 30, 2017, and published as a digital article with an audio file with a total duration of 6'40'' (LUSA 2017). A similar online search was conducted applying the methodology described above but now adding a new set of keywords (i.e., siri, medusas, alforrecas, Algarve, Restaurante São Gabriel, Chef Leonel Pereira).

Results

The weakfish survey

A total of thirty valid consumer surveys were obtained, 70% were women and 30% were men (Fig. 5A). The average age of the consumers was 45 ± 18 years distributed similarly across three age groups—young adults- 18 to 29 years old, adults—30 to 55 years old, senior adults- over 55 years old (Fig. 5B). The youngest and oldest consumer was 22 and 78 years old.

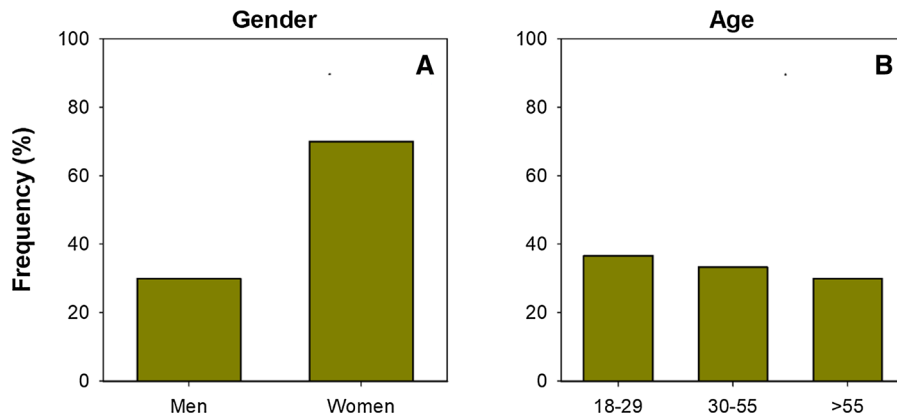


Fig. 5 Gender (A) and age distribution (B) of the consumers that replied to the Weakfish Survey

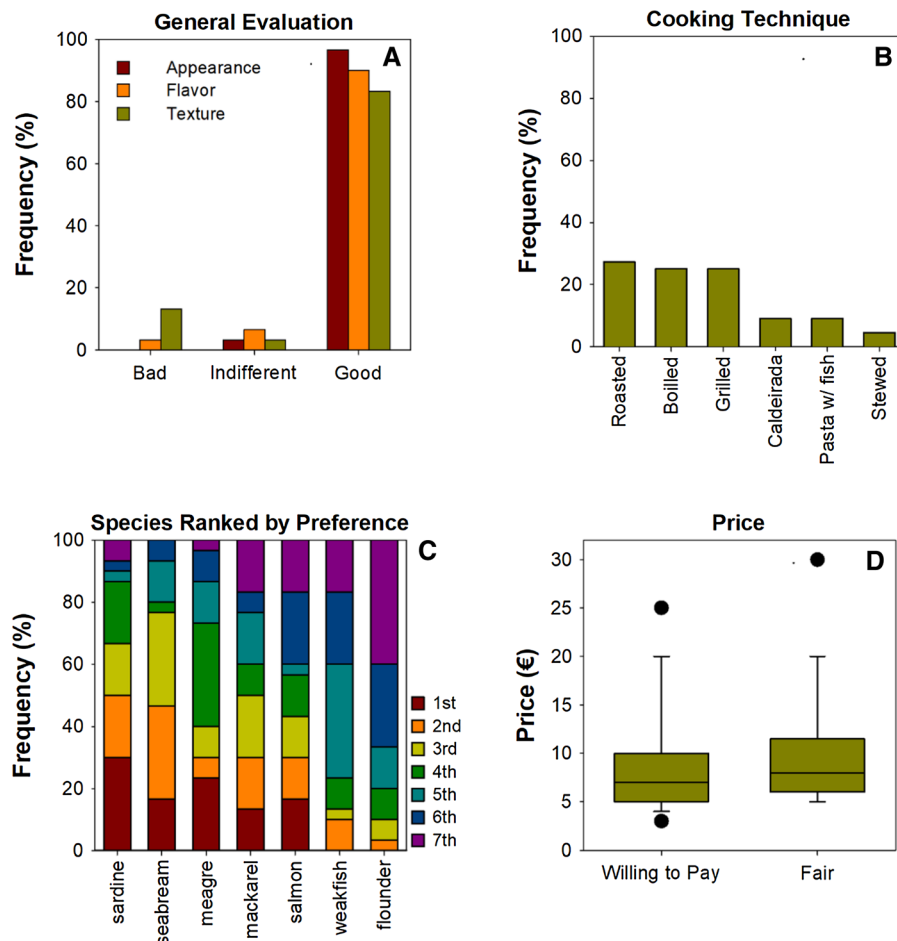


Fig. 6 A Evaluation of weakfish's appearance, flavor, and texture by a panel of consumers. B Cooking methods chosen by consumers to cook weakfish at their homes. C Preference ranking of seven fish species—European pilchard *Sardina pilchardus* (Walbaum, 1792), gilt-head seabream *Sparus aurata* Linnaeus, 1758, meagre *Argyrosomus regius* Asso, 1801,

Atlantic horse mackerel *Trachurus trachurus* (Linnaeus, 1758), Atlantic salmon *Salmo salar* Linnaeus, 1758, weakfish *Cynoscion regalis* (Bloch & Schneider, 1801), and European flounder *Platichthys flesus* (Linnaeus, 1758). D Comparison between the average price that consumers were willing to pay for weakfish and the price that they consider to be the fair price

The majority of consumers rated weakfish appearance as good (97%, $\chi^2 = 114.0$, $df = 2$, $p < 0.05$), as well as its flavor (90%, $\chi^2 = 144.67$, $df = 2$, $p < 0.05$), and texture (83%, $\chi^2 = 34.2$, $df = 2$, $p < 0.05$) (Fig. 6A). Regardless of the evaluation that consumers gave to texture, the flesh characteristic was mentioned as ideal for shredded or sliced fish recipes.

The top cooking methods were roasting (27.3%), boiling (25.0%), and grilling (25.0%), and lastly, the other ways of preparation were Portuguese fish stew (*caldeirada*) and fish pasta (*massada de peixe*) (Fig. 6B). Please note, that six consumers prepared the fish in three different ways—grilled, roasted, and stewed (*caldeirada*). Weakfish was never ranked as the favorite fish and most consumers ranked weakfish in the fifth position (37%) (Fig. 6C). After computing the average rank for each of the seven species, weakfish ranked in the sixth position. The overall average ranks were the following: sardine- 2.8, gilthead seabream- 2.9, meagre- 3.5, mackerel- 3.9, salmon- 4.1, weakfish- 5.1, flounder- 5.7. Most consumers would buy weakfish if available at the market (90%, $\chi^2 = 64$, $df = 1$, p -value < 0.05). They would be willing to pay $8.3 \pm 6.2 \text{ € kg}^{-1}$, which is significantly less than what they consider to be a fair price ($9.5 \pm 6.4 \text{ € kg}^{-1}$, $t = 13.5$, $p < 0.05$) (Fig. 6D).

Consumers significantly prefer wild fish (83%) over farmed fish (0%) ($\chi^2 = 35$, $df = 2$, p -value < 0.05), while 17% had no preference (Fig. 7A). The majority would also prefer buying wild native fish (87%) over weakfish (10%) ($\chi^2 = 38.6$, $df = 2$, p -value < 0.05) (Fig. 7B). However, they would prefer buying weakfish (63%) if the native fish available at the market would be farmed fish (33%) ($\chi^2 = 16.2$, $df = 2$, p -value < 0.05) (Fig. 7C). Consumers also prefer buying weakfish (57%) over imported farm-reared fish (33%) ($\chi^2 = 9.8$, $df = 2$, p -value < 0.05) (Fig. 7D).

Measuring outreach impact

The two press releases resulted in thirty-eight online articles, and three news pieces broadcasted on national television. The online articles were published in Portuguese and during two months, between September 28 and November 28, 2017. Twenty-two news pieces mentioned weakfish, while sixteen mentioned the Atlantic blue crab. Of the twenty-two items referring to weakfish, fourteen were published in

online news websites, that include some of the leading Portuguese daily (*Público*, *Diário de Notícias*, *Correio da Manhã*) and weekly newspapers (Expresso), TV networks websites (*RTP*, *SIC Notícias*, *Porto Canal*), and local newspapers (e.g., *Diário Online Região Sul*, *Jornal do Algarve*) (Fig. 8). Eight online publications were made in blogs. All references are listed as a supplement (Table S1).

Regarding the TV broadcasts, two national TV channels reported the presence of weakfish and other invasive species in Portuguese estuaries. This coverage resulted in three appearances on TV with a total duration of 19'57'': (1) *Jornal das 8* on *TVI* (2'17'', October 8th, 2017—often reaches 14.0% audience (1.3 million people) and 24.4% share) (TVI 2017) (Fig. 9A), (2) *Portugal em Direto* on *RTP 1* (14'15'', October 9th, 2017—4.4% average audience (416 thousand people) and 26.6% average share) (RTP1 2017a) (Fig. 9B), (3) *Telejornal* on *RTP 1* (2'40'', October 30th, 2017—often reach 9.2% audience (870 thousand people) and 16.6% share) (RTP1 2017b) (Fig. 8).

The interview published in the Portuguese news agency Lusa featuring the research team and Chef Leonel Pereira resulted in twenty-four news published between December 30, 2017, and February 2, 2018. Twenty-four news pieces were published on news websites including some of the most relevant online newspapers in Portugal (e.g., Expresso, *Jornal de Notícias*, Destak, Observador, O Jogo), local newspapers (e.g., A Voz do Algarve, *Jornal da Madeira*), and two in the websites of private businesses (O Instalador 2018, Somanjar 2018) (Table S2).

Discussion

The Weakfish Survey showed that weakfish has the potential to be accepted by Portuguese fish consumers. There is interest among consumers that could turn viable a fishery on weakfish to minimize the impacts of this invasive species while enhancing the local blue economy. Overall, the evaluation of weakfish's characteristics was good, and most consumers of our panel would buy this species if available at the market. The outreach regional events highlighted in the press releases allowed us to reach a national audience due to successful media coverage. We also provide an overview discussion about the benefits and risks of

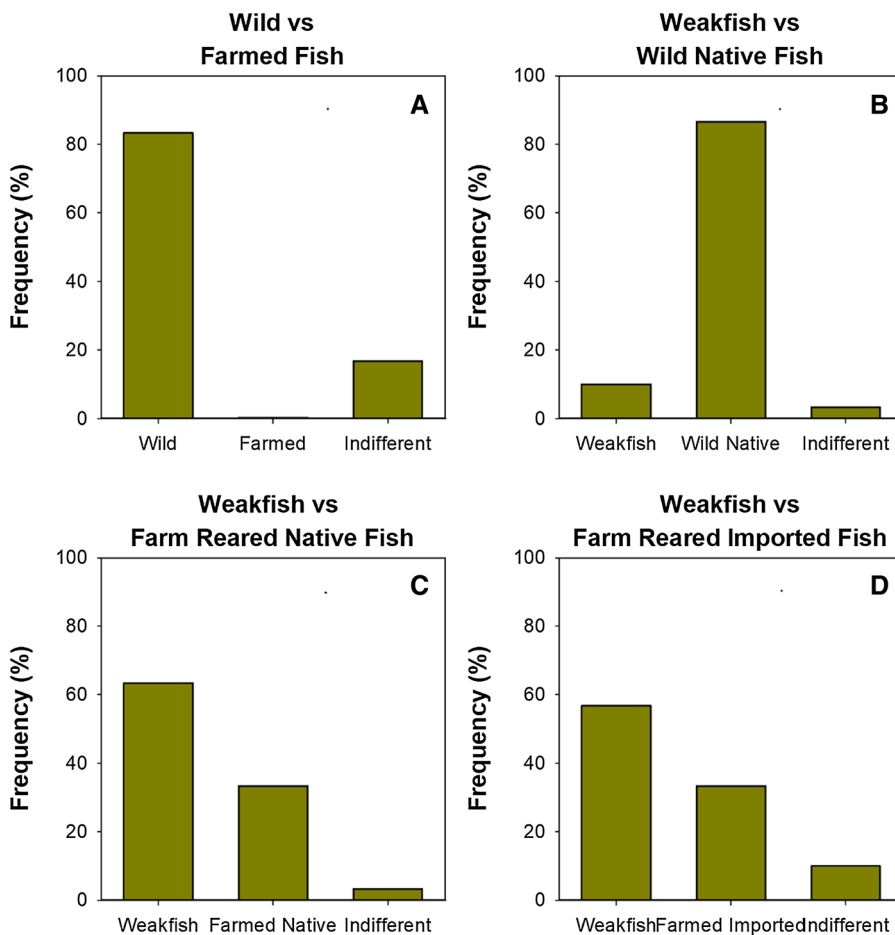


Fig. 7 Consumers' preference between wild and farmed fish (A), weakfish and wild native fish (B), weakfish and farm-reared native fish (C), and weakfish and farm-reared imported fish (D)

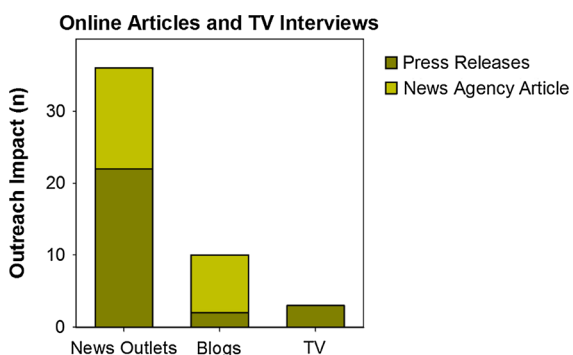


Fig. 8 Number of news articles published and broadcasted mentioning weakfish as an invasive species in Portugal, as a consequence of the press releases made by the communication department of CCMAR in September 2017, and the article published by the news agency LUSA on December 30, 2017

creating a management plan focused on promoting weakfish as a fishery to mitigate the species ecological impacts and diversify the sources of income of local fishers, fish vendors, and restaurants.

The weakfish survey

The Weakfish Survey provided useful insights into the acceptability of weakfish by Portuguese fish consumers. The weakfish appearance, flavor, and flesh texture were the most appreciated traits, and most consumers (90%) would buy weakfish during a future visit to the market. Fish consumers advised that the flesh texture is ideal for shredded or sliced fish recipes, which are techniques used in several Portuguese fish recipes (Modesto 1983). So, linking weakfish with



Fig. 9 Screenshots of the interviews given to *Jornal das 8* (TVI) (A) and *Portugal em Direto* (RTP 1) (B) aired on October 8, 2017, and October 9, 2017, respectively

traditional recipes is important while promoting the species to consumers.

Fish consumers also found a good value in weakfish. They were willing to pay at least 60% more (i.e., 8 € kg⁻¹) than the average price of 6.5 € kg⁻¹ in 2017, which is still below the minimum price range of wild Atlantic salmon (16.5 € kg⁻¹), European seabass (25.5 € kg⁻¹), gilt-head seabream (23.5 € kg⁻¹), and meagre (18 € kg⁻¹) (Table S3). This supports our hypothesis that weakfish's average selling price was underestimated. This also means that local fishers and fish vendors can obtain additional income from this fishery.

Fish consumers preferred wild fish—including weakfish—over farmed species when sold for the same price. Although this preference could be related to sociodemographic aspects (e.g., age, education, income) (Myrland et al. 2000; Cardoso et al. 2013), our panel was composed of a diverse sociodemographic group. So, this generalized opinion was unexpected since older consumers are the ones that tend to disproportionately prefer wild fish over farmed fish (Cardoso et al. 2013). Promoting weakfish as a wild species will help environmental agencies develop a fishery for this invasive species and minimize its putative impacts.

Although the generalized opinion on weakfish traits was positive, it is unlikely that weakfish will ever become the Portuguese's favorite fish species, despite that all weakfish sold in Portugal are wild fish (Morais et al. 2017). Weakfish was ranked sixth among seven wild fish species—only ahead of flounder, and far behind sardine—an economic and culturally important species for the Portuguese (Chícharo et al. 1998). Consumers justified their choices with personal preferences and consumption habits.

Overall, the invasive weakfish has an intrinsic marketing advantage over farmed fish and wild European seabass, gilt-head seabream, and meagre due to its lower price. These are two features that should be considered when promoting a weakfish fishery.

Outreach—act locally, think nationally

The Weakfish Survey and outreach events indicated that Portuguese fish consumers are likely to include weakfish in their shopping list. The outreach events also served to grab the media's attention to the ecology of invasive species, describe their impacts, and promote their use as new food delicacies to reduce their impacts upon native species and increase the revenue of local fishers.

The media's interest in invasive species exceeded our expectations, both in number and time during which news and interviews were published and broadcasted. As a measure of comparison, the press release we published in June 2016 about the first weakfish found in the Guadiana estuary—at the time it was thought to be the first record of weakfish in Portugal—only generated 10 news articles, mostly in regional journals (A Voz do Algarve 2016; Correio da Manhã 2016; Correio da Manhã -Algarve 2016; Diário Online 2016; Folha do Domingo 2016; Jornal do Algarve 2016; Mundo da Pesca 2016; Sul Informação 2016; Tudo Num Click 2016; TV Europa 2016). Although it is impossible to indicate the number of people who read the online news pieces and watched the broadcasted interviews, we estimate that they have reached over two million people in Portugal and abroad. All media contents are available online and were posted by some of the most important news outlets in Portugal (Tables S1 and S2).

An “act locally and think nationally” strategy drew attention to a local problem—the invasion of weakfish in southern Portugal—while raising awareness to the broader problem of invasive species, either aquatic or terrestrial, across a broader geographical scale. This strategy can be replicated for other edible invasive species anywhere in the world but adapted to local sociological contexts and legislation.

Commercial fishery to control invasive species

Long-term harvesting programs aiming to control and reduce the population size of aquatic invasive species have been successfully implemented (Hauton et al. 2007; Holbrook et al. 2016; Závorka et al. 2018), especially in confined areas (Weidel et al. 2007; Wittmann et al. 2012). This has been the case of a management plan on invasive rusty crayfish *Orconectes rusticus* (Girard, 1852) in the Sparkling Lake (Wisconsin, United States) where the population size decreased 99% in 8 years (2001–2008) and did not increase significantly in the first four years postharvest (Hansen et al. 2013). Another successful case study was the control of the Asian carp in the Mississippi and Ohio River basins (ACRCC 2016). Control plans focused on prevention, detection, fishery management, control, and outreach (ACRCC 2016, www.AsianCarp.us). For three years, commercial harvest decreased the population size which remained low in the following years (Love et al. 2018). However, there are cases where the population size may rebound once removal rates decrease, as predicted for the invasive populations of red lionfish *Pterois volitans* (Linnaeus, 1758) and common lionfish *Pterois miles* (Bennett, 1828) (Barbour et al. 2011).

The eradication of aquatic organisms has proven to be difficult when invasive species are not confined to small and enclosed areas (Simberloff 2014). We recognize that the eradication of weakfish is extremely unlikely given its broad distribution in the Iberian Peninsula (Morais et al. 2017) and limited resources. Therefore, when numerical eradication is unfeasible, functional reduction seems to be the ideal approach—i.e., the reduction of a population size below levels that cause deleterious ecological effects within high-priority locations (Green and Grosholz 2021).

We are working on establishing the basis for a functional reduction approach through a four-step process: (i) acquisition of fundamental scientific

knowledge to later estimate how many individuals must be suppressed from an ecosystem to maintain ecological integrity, also to identify what is the density range that must exist in an ecosystem to make suppression efficient (see Fig. 3 of Green and Grosholz (2021) for details); (ii) establish communication with resource managers and conservation practitioners while acquiring scientific data; (iii) engage with fishers, restaurant owners, and the public to raise awareness about invasive species with a focus on edible species; and (iv) continue investing in a citizen science program to keep tracking the species. Our main goal will be establishing a suppression program in highly invaded estuarine ecosystems, like the Sado estuary, to maintain ecological integrity while increasing the income of local fishers, fish vendors, and restaurants.

The goal of controlling an invasive aquatic vertebrate is to reduce predation pressure upon native species and the chances of introduction into surrounding areas. However, the eradication or functional reduction of invasive vertebrate species may result in unwanted and unexpected impacts on native species and ecosystems (Ballari et al. 2016). Surprisingly, data about the mechanisms involved in this process are extremely limited and difficult to generalize (Ballari et al. 2016). So, the need for a profound ecological knowledge about weakfish ecology in the invaded area is critical to avoid unwanted outcomes.

The involvement of motivated local knowledge experts (fishers and anglers) and citizen scientists increases the success of a long-term control plan while raising awareness about biological invasions (Encarnação et al. 2021a,b). Adopting any population control program also entails several risks, as not being able to remove enough individuals to decrease the population density (Pasko et al. 2014), harming native species through by-catch (Pasko et al. 2014), and other unexpected ecological consequences by altering the food web structure (e.g., biological overcompensation, opening ecological niches for other species) (Zavaleta et al. 2001; Zipkin et al. 2009). Therefore, any population control plan for weakfish—or any other invasive species—must be done after assessing its ecology in the invaded range and interaction with native species, as well as determining which life stages are more likely to be affected by harvest. So far, it has been found that Sado's weakfish has a generalist feeding strategy and preys the same functional groups

it targets in the native area (Cerveira et al. 2021). Also, although weakfish, meagre, and European bass are in the same trophic level, however, weakfish exhibits higher trophic overlap with meagre, suggesting that weakfish could directly impact meagre if food and habitat become limiting (Cerveira et al. 2021).

In terms of economic benefits, we showed that weakfish has the quality traits appreciated by Portuguese fish consumers. It is easy to harvest, and it can be sold away from the region of capture without the risk of introduction into other areas. So, the implementation of an adequate marketing strategy and scientific-based functional reduction program could make weakfish fisheries a paradigmatic example of how to transform an ecological threat into an economic opportunity for local fishers, fish vendors, and restaurants while providing a healthy source of marine protein. However, we must not forget that creating a profitable fishery may discourage the eradication of the target species (Nuñez et al. 2012), particularly if it becomes overpriced in comparison to native species since it may lead to its protection in detriment of native species (Lambertucci and Speziale 2011). So, all stakeholders should be informed about the negative effects of invasive species, that introducing non-indigenous species and farming an invasive species is forbidden by law, and that the economic benefits that invasive species may generate are smaller than the long-term costs associated with a program that controls the population of an invasive species and mitigates the impacts upon native species and ecosystems (Lambertucci and Speziale 2011; Varble and Secchi 2013). In other words, the purpose of the management plan is not the perpetuation of a viable fishery but rather the substantial decrease of an invasive species population (Nuñez et al. 2012). Simultaneously, outreach campaigns focusing on the conservation of native fisheries should be encouraged, as well as the commercialization of native species that are not being valued to shift the focus from perpetuating an invasive species fishery and introducing it somewhere else.

Conclusion

Our knowledge about Portuguese consumers' preferences regarding fish confirmed the three main hypotheses of this work. Weakfish has the potential

to become a targeted fishery in Portugal and represent an additional source of income for local fishers and fish vendors while transforming an ecological threat into an economic opportunity. The mean selling price of weakfish was underestimated by fish vendors because consumers were willing to pay 5 € kg⁻¹ and 1.5 € kg⁻¹ above the minimum (3 € kg⁻¹) and average selling price (6.5 € kg⁻¹), respectively. Consumers also recognized that one of the main attributes of weakfish is being a wild species, which must be highlighted when promoting the species to consumers. Overall, the interest shown by the media and Chefs demonstrates that edible invasive species' impacts can be minimized once ecological data exists to implement science-driven fisheries.

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Authors' contribution MAT and PM conceived the research questions and study design. IC and VB conducted the surveys. IC, VB, and MAT conducted the outreach actions. IC and PM analyzed the data. IC wrote the initial draft of the paper and MAT, and VB provided substantial feedback on this initial version. PM provided guidance during the writing of the article and revised the article according to the suggestions made by the editor and reviewers. All authors gave final approval for publication.

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Availability of data and material The raw data presented in this work can be made available upon request.

Declarations

Conflict of interest The authors do not have any conflicts of interest or competing interest.

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