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ORIGINAL RESEARCH

Long-Term Passive Acoustic Monitoring to Support Adaptive Management in a Sciaenid Fishery (Tagus Estuary, Portugal)

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Abstract Passive acoustic monitoring (PAM) is useful for monitoring vocal fish but has had so far limited application in fisheries management. Here, four years (2016–2019) of concurrent daily catch and effort fishery data in Portugal and species-specific vocal activity in the Tagus estuary are compared to describe biological and small-scale fishery dynamics for a large sciaenid fish, the meagre (*Argyrosomus regius*), that aggregates to spawn. Consistent patterns in seasonality of acoustic and fisheries variables indicate that most fishing takes place within the Tagus estuary in spring and summer months, when higher vocal activity related to spawning aggregations is detected in the PAM station. Good fit of statistical models shows that PAM (sound pressure level in the third-octave band with centre frequency at 500 kHz during dusk) and PAM-supported variables (mean weekly catch per first sale transaction) can provide useful surveillance indicators to improve local management. Signs of overexploitation and hyperstability are detected and communicated to the estuarine fishing communities with the aim to initiate an adaptive local management cycle. The approach can be relevant for fisheries targeting other vocal fish that seasonally aggregate and face similar threats of overexploitation.

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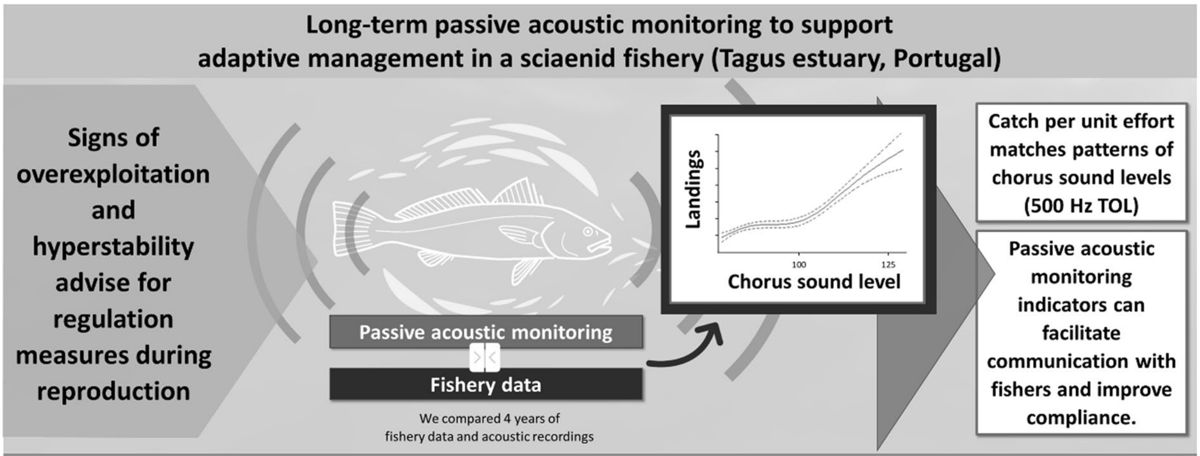
Graphical Abstract



Keywords Meagre (*Argyrosomus regius*) · Seasonal migration · Spawning aggregations · Overexploitation · Hyperstability · Surveillance indicators

Introduction

The family of sciaenid fish (*corvinas*, croakers and drums) includes some of the biggest teleosts (maximum size can exceed 170 cm in the genus *Argyrosomus*, Griffiths 1996; Potts et al. 2010; González-Quirós et al. 2011) and many species are targeted by commercial and recreational fisheries worldwide (Gannon 2008; Morales-Nin et al. 2012; Erisman et al. 2012; Ferguson et al. 2014). Sciaenids are also known for being vocal fish, producing some of the loudest biological sounds in the marine realm, audible to the human ear (Smith 1905; Erisman and Rowell 2017). The family includes several dozen genera and more than two hundred taxa, with species-specific sound repertoires and features (Ramcharitar et al. 2006; Luczkovich et al. 2008a; Parmentier et al. 2018; Bolgan et al. 2020), including choruses that can vary in intensity depending on water temperature (Monczak et al. 2019; Vieira et al. 2022). Most vocal sciaenids show temporal periodicity in sound production, often associated with a marked daily spawning synchronicity, mainly towards dusk (Holt et al. 1985; Saucier and Baltz 1993; Locascio and Mann 2011; Aalbers and Sepulveda 2012; Montie et al. 2016; Vieira et al. 2022). In the process, some species create ephemeral sex-biased groupings (Fitzhugh et al. 1993; Aalbers and Drawbridge 2008), sometimes leading to spectacular concentrations (Sadovy de Mitcheson 2016; Erisman and Rowell 2017). Several require estuarine and coastal salt-marsh habitats to complete their life cycle (Griffiths 1996; Ferguson et al. 2008; Luczkovich et al. 2008b; González-Quirós et al. 2011; Morales-Nin et al. 2012; Lowerre-Barbieri et al. 2016).

Sciaenids of the genus *Argyrosomus* that use estuaries to complete their life cycle also tend to have late maturation, high longevity and few predators in their adult phase, other than humans (Griffiths 1996; Potts et al. 2010; González-Quirós et al. 2011). Predictability of aggregation close to land, large size and piscivory, turn *Argyrosomus* species attractive and accessible to small-scale fisheries along the eastern Atlantic and the Indo-Pacific. For example, meagre (*A. regius*) sounds, audible during estuarine spawning aggregations, have been used for centuries by fishers to improve catchability in the Gironde estuary (Lagardére and Mariani 2006). Estuarine aggregations can attract commercial, subsistence and recreational activities, both legal and illegal (Griffiths 1996; Silberschneider and Gray 2008; Mota 2018; Sadovy de Mitcheson et al. 2019). Large fishing effort and high catchability during aggregation also turn such populations vulnerable to overexploitation (Sadovy de Mitcheson 2016; Heyman et al. 2019). Complex mating systems (Connaughton and Taylor 1996; Aalbers and Drawbridge 2008; Lowerre-Barbieri et al. 2016) can further increase vulnerability at low population levels through Allee effects (Rowe and Hutchins 2003). Sciaenid overexploitation is usually related to insufficient management due to limited monitoring investment, unaccounted fishing mortality, scant regulation or inadequate compliance (Potts et al. 2010; Prista et al. 2011; Mirimin et al. 2016; Erisman and Rowell 2017; Heyman et al. 2019).

In Portugal, meagre heavier than 50 kg can be occasionally caught (maximum register by research team: 67 kg), corresponding to fish with more than 20 years of age (maximum known register: 43 years) and, arguably, more than 15 years of recurrent seasonal migrations to the Tagus estuary for reproduction. The species is known to have been present in the Tagus and Sado estuaries since the Mesolithic (6000 BP – 4500 BP), with signs of exploitation by collector settlement-subsistence systems (Gabriel et al. 2012). In the late nineteenth century important fisheries existed in these estuaries during summer months (April to August), when adult meagre entered the rivers to spawn (Baldaque da Silva 1892). Industrial and urban pollution deteriorated the Tagus estuarine habitat in the mid-twentieth century (Raimundo et al. 2011; Rodrigues et al. 2020; Batista et al. 2022), possibly contributing to the disappearance of meagre for decades. Meagre return to the Tagus estuary was reported in the late 1990s, initially as juvenile concentrations detected and targeted by fishers (Costa and Cabral 1999). In the past two decades there has been regular presence of spawners and recruits in the estuary (Prista 2013), supporting an important small-scale seasonal commercial fishery, mainly for adults, and year-long recreational fishing, mainly for juveniles (Mota 2018).

Passive acoustic monitoring (PAM) is a useful monitoring technique for vocal fish that has so far been little used for fisheries and environmental management purposes (Luczkovich et al. 2008a; Gannon 2008; Aalbers and Sepulveda 2012; Parmentier et al. 2018; Di Iorio et al. 2020). Recent automations in species identification and sound variables detection and quantification, associated to increasing use of continuous PAM recordings (Vieira et al. 2015, 2019; Monczak et al. 2019), have made available longer series of species-specific acoustic data. Here, we review sciaenid literature in which PAM has been used concurrently with other sampling techniques and extend the remit of comparisons to a context of reduced spatial overlap between methods. We use four consecutive years (2016–2019) of concurrent daily commercial fishery data for meagre in Portugal (catch per unit effort, CPUE) and species-specific PAM variables from a station in the Tagus estuary (Vieira et al. 2022) to explore the potential relevance of PAM to enhance the utilization of aggregate CPUE data in the management of this small-scale fishery. Knowing PAM to be reliable for delimiting the temporal dynamics of meagre reproduction in Portugal (Vieira et al. 2019, 2022), we use the statistical relationships of this analysis to increase the confidence in the use of longer term indices based on the catch data. We further hypothesize that stationary PAM can be an unbiased, albeit imprecise, sampler of adult meagre estuarine abundance and delineate the additional research steps necessary to test it. The use of sound-based or PAM-supported (catch-based) surveillance indicators (Shephard et al. 2015) within a participatory management framework (Heyman et al. 2019) can be relevant for other fisheries that target vocal fish and face similar threats.

Material and Methods

The Study System

The Tagus estuary (Portugal) is one of only five known large concentration areas of meagre reproduction within the Northeast Atlantic and the Mediterranean Sea (Haffrey et al. 2012; Almeida et al. 2022). Sexually mature fish (4–5 years old onwards) perform seasonal migrations to the natal estuary, where they stay on average 2–3 months during the summer spawning season. In the late nineteenth century similar concentrations were reported during summer months in the Sado estuary (Baldaque da Silva 1892). Nowadays, some adult fish also enter other Portuguese estuaries, such as the Sado, Mira and Guadiana rivers, in summer months (Prista 2013), but without forming spawning aggregations. In the remaining months of the year adult fish disperse in coastal waters and are occasionally caught as bycatch (Prista 2013; Castro et al. 2021). Meagre´s current distribution in Portugal partially overlaps with that of weakfish (*Cynoscion regalis*), a non-native sciaenid originally from the western Atlantic and recently

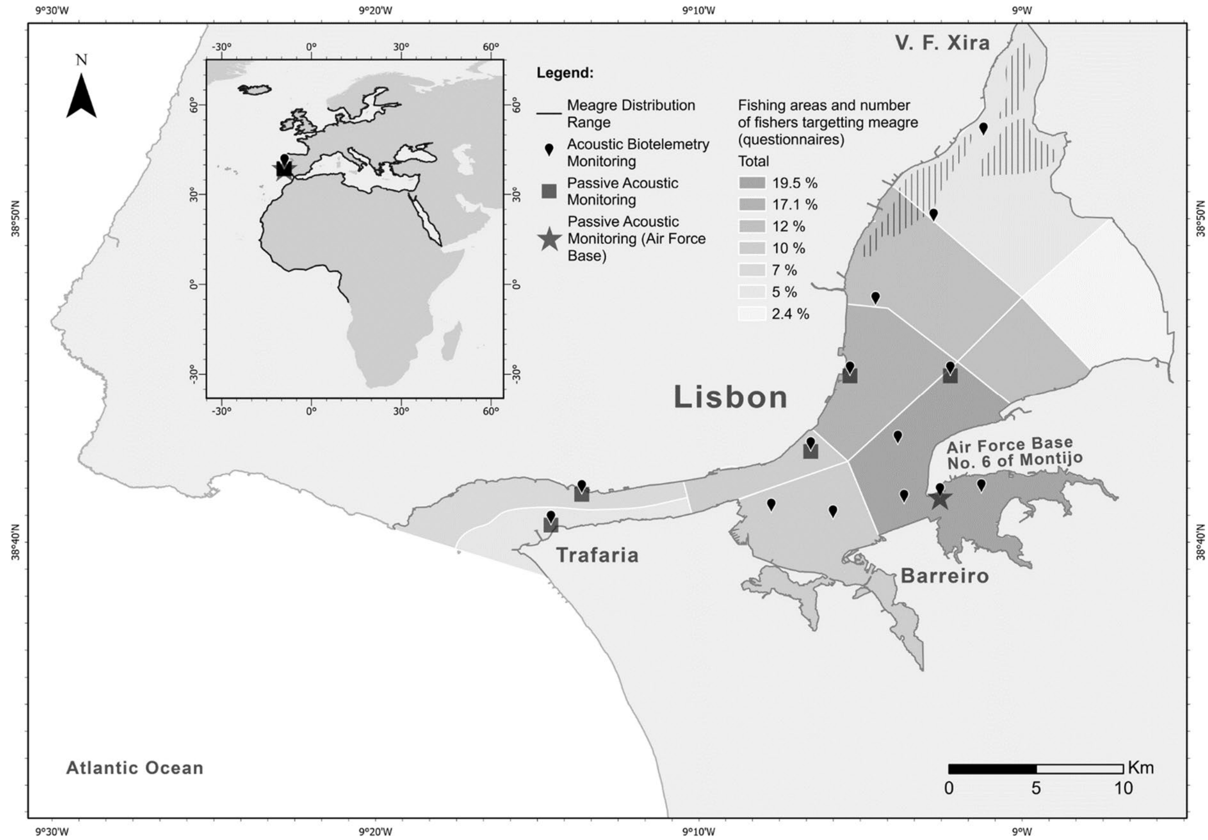


Fig. 1 Map of the study area, including: the meagre geographic distribution range; the intensity of fishing per area by Tagus estuary vessels with port of register in Lisbon, V. F. Xira, Trafaria, and Barreiro (targeting meagre); and the CoastNet Monitoring Infrastructure (Acoustic Biotelemetry and Passive Acoustic monitoring)

introduced to the Iberian Peninsula (Morais et al. 2017; Gomes et al. 2017). However, although weakfish currently forms regular part of commercial landings in Portugal and Spain, its value and consumer preference are still low in comparison to meagre (Bañon et al. 2017; Cerveira et al. 2022).

Tagus Estuary

The Tagus River estuary is among the largest in Europe (> 300 km^2), although a large fraction of the inner estuary is within the intertidal zone, becoming exposed at low tide. Regular environmental monitoring currently takes place (Rodrigues et al. 2020), including the CoastNet research infrastructure (Castellanos et al. 2021) of in-situ sensors with sound (PAM) recorders and an array of biotelemetry receivers to track tagged fish (Fig. 1), such as meagre, and a land-based observatory for marine mammals (Batista et al. 2022). Adult meagre start to enter the Tagus estuary in February/March where they mainly reproduce in May and June. During this period adult meagre will mainly use the deepest channels of the middle and lower section of the Tagus estuary (Marques and Quintella unpublished). Ongoing tracking studies indicate that adults can stay in the estuary until August/September and that young juveniles may overwinter in and around it. Juveniles mostly feed on crustaceans, mainly mysidacians and brown shrimp (*Crangon crangon*) in the Tagus (Cabral and Ohmert 2001), with an ontogenetic transition to piscivory that also leads to some cannibalism (Hurbans et al. 2017). Immediately after entering the estuary adult meagre start feeding on cuttlefish (*Sepia officinalis*), changing latter in the spawning season to thinlip grey mullet (*Chelon ramada*). The latter is a catadromous species

Table 1 Fishing activity for meagre during 2016–2019 (aggregate) by vessels with port of register within the Tagus estuary (see also Fig. 1) and national totals in the same period. In parentheses the number of Tagus estuary fishers that replied the survey dedicated to the meagre fishery

Port of vessel register	Number of vessels (in survey)	First sales with meagre, transactions Nº	Meagre catch, tones	Meagre first sale value, million €
Outer South (Trafaria)	148 (16)	36,154	489.3	3.47
Outer North (Lisboa)	34 (5)	2540	34.7	0.23
Inner South (Barreiro)	44 (8)	13,242	181.5	1.22
Inner North (Vila Franca)	73 (14)	16,154	248.5	1.55
Total (Tagus estuary)	295 (43)	68,090	954.1	6.47
Total (Portugal)	1600	107,397	1369.2	9.89

that forms large aggregations in the beginning of its trophic migration in several Portuguese estuaries, including the Tagus river (Pereira et al. 2021).

The Tagus Fishing Communities

Close to 300 small fishing vessels (<9 m) with a port of register within the Tagus estuary (Fig. 1) reported some landing of meagre between 2016 and 2019 (Table 1). Other seasonal fisheries in the Tagus estuary include octopus (*Octopus vulgaris*), sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*) and a year-round activity of harvesting the invasive clam *Ruditapes philippinarum* (Coelho et al. 2021; Batista et al. 2022). During the summer months, meagre becomes the main target species within the estuary practically for all fishers that are not dedicated to bivalve harvesting. Annual landed biomass by vessels registered in Tagus ports on average exceeds 200 tonnes and is worth more than 1 million € (in the four years of the study the average first sale price for meagre was around 6–7 € per kg). Fishing for meagre takes place with nets, longlines and lines. Around 100 fishers participated so far in meetings promoted by the co-authors with three fisher associations since late 2021. Also, 43 fishers replied individually a questionnaire dedicated to the meagre fishery during 2022 (Marques, unpublished and

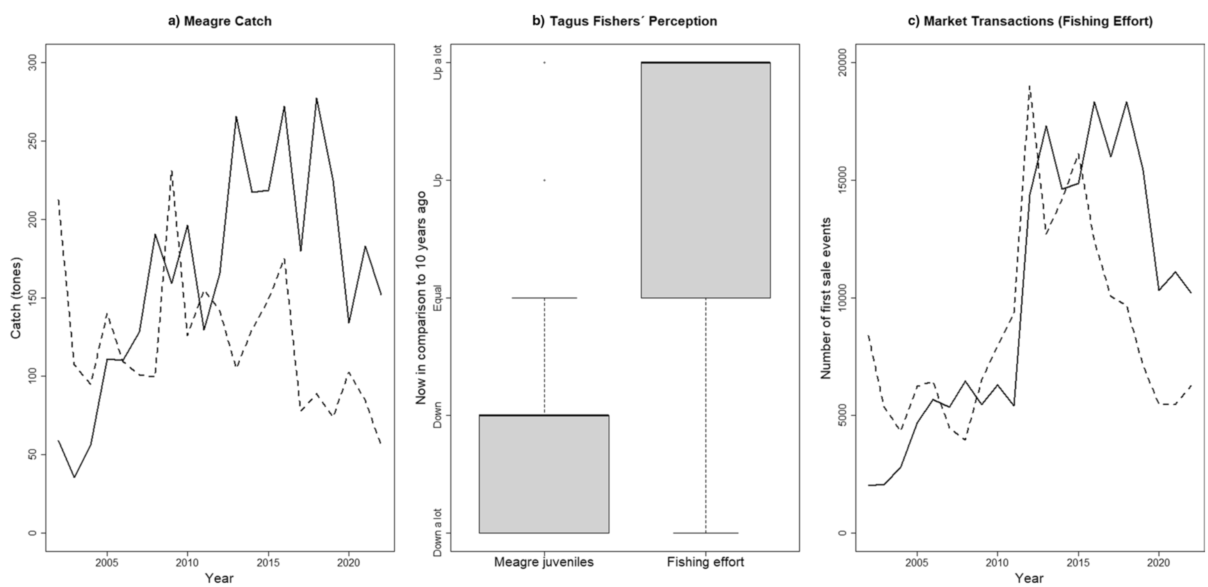


Fig. 2 Annual catch (biomass, panel **a**) and fishing effort (number of first sale transactions, Panel **c**) for meagre in Portugal during 2002–2020 based on fisheries data, separately for vessels registered in ports within the Tagus estuary (solid line) and remaining (broken line). Panel **b** reports boxplots of Tagus fishers´ perceptions on the evolution of juvenile meagre abundance and fishing effort in the past decade (5-level ordinal scale response in 2022 questionnaire survey)

Table 1). The latter extends earlier inquiries by Mota (2018) in the same communities, covering issues related to the description of the fishing practice, perceptions on state of the resource and opinions on management measures and related governance (see also Stratoudakis et al. 2023 for equivalent inquiries to other estuarine fisheries). Although survey results and methodology will be reported in a separate publication, some auxiliary information is used here to characterise the communities and identify the main fishing areas (shade map within Fig. 1). Two answers are also used in the results to demonstrate the current perception of higher exploitation rate in comparison to 10 years ago (in Fig. 2b), reinforcing a perception that was already detected by Mota (2018) in relation to the period 2013–2017.

The fishery is regulated by a limited entry licensing system. The minimum landing size is 42 cm and has also to be respected by recreational fishers. Recreational fishing has a bag limit of 10 kg per day plus the largest individual (trophy) and can only take place during daytime. Within the Tagus estuary nets and longlines have specific requirements and limits for minimum mesh, height and size of nets, and number of hooks and nets per licensed vessel. Juvenile meagre and, in more recent years, weakfish can be caught as bycatch in gillnets for seabass. There are no temporal limits to meagre fishing. Nevertheless, net deployment is limited in practice by the presence of the local jellyfish (*Catostylus tagi*) that clog fishing nets from June onwards, until the first rain outflows in autumn (Gueroun et al. 2021). Finally, fishing is prohibited near the commercial port of Lisbon and within the extensive navigation corridors of the river Tagus. The prohibition is valid at the river mouth and towards the cargo terminals, as well as along the busy passenger ferry lines linking the two margins (Alves et al. 2021).

Monitoring

Passive acoustics has been shown to be a non-invasive and cost-effective method for monitoring vocal fish (Connaughton and Taylor 1995; Luczkovich et al. 1999; Ramcharitar et al. 2006; Parmentier et al. 2018). There have also been several appeals to extend PAM into fisheries monitoring and regulation (Gannon 2008; Luczkovich et al. 2008a) and into marine conservation (Aalbers and Sepulveda 2012; Howe et al. 2019; Di Iorio et al. 2020), but without known management applications so far (Heyman et al. 2019). PAM has been used for estimating animal population size and density, mainly for terrestrial but also for marine mammals. This occurs when the more traditional methods of visual surveys or physical trapping are less viable and when probability of sound detection can be estimated and density of recorded vocalization can be associated to a vocalization rate (Marques et al. 2013). Such requisites are not usually met in fish PAM, but concurrent sampling with other marine survey methods show that PAM variables correlate with several fish population parameters (Table 2).

In the case of the meagre fishery in Portugal there is no dedicated monitoring program and no stock assessment (Prista 2013). The species is not detected in routine fish monitoring surveys of the Portuguese continental shelf directed to pelagic (Daily Egg Production Method—DEPM; and active acoustic surveys, led by IPMA since the 1980s) or demersal species (scientific trawling, led by IPMA since the 1970s). Further, the small-scale fleet segments that mainly land meagre (Prista 2013; Castro et al. 2021) have little representation in the standard biological fish market sampling, with limited length frequency data and no other biological information regularly collected. Finally, the reliability of commercial landing data for meagre is unknown due to generic concerns with possible underreporting or misreporting of valuable target species (Maunder et al. 2006). Nevertheless, earlier studies with regional catch data segments (Prista et al. 2011; Prista 2013) showed internal consistency in the meagre data series, with consistent auto-correlation patterns at a monthly scale in each segment. At the time, time-series analysis revealed the system to be stable during the first decade of the twenty-first century, not detecting evidence of changes in the exploitation patterns (Prista et al. 2011). The rationale used by Prista et al. (2011) for the parsimonious detection of alert signals in fisheries exploitation is similar to that proposed by Shephard et al. (2015) for surveillance indicators. The latter aim to monitor key aspects of the ecosystem when existing information is insufficient to define targets and support formal state assessment and specific management advice (Shephard et al. 2015).

Table 2 Utilization of PAM and concurrent sampling methods to estimate sciaenid population parameters with relevance for environmental or fisheries management. Multiple methods are listed according to the main concurrent method used. Acronyms: *CPUE* catch per unit effort, *DEPM* daily egg production method, *GSI* gonadosomatic index, *SPL* sound pressure level

Concurrent Sampling Method	Species	Location	PAM variable	Population parameters	Reference
Active acoustic survey in inner estuary, Density, Abundance and Biomass	*Cynoscion othonopterus*	Colorado Delta, Gulf of California, Mexico	251–498 Hz SPL	Spawner distribution and abundance	Rowell et al. (2017) Erisman and Rowell (2017)
Egg sampling from tank collectors, Counts	*C. nebulosus* *Sciaenops ocellatus*	Captivity	Number of calls; Call duration; 100–3000 Hz SPL	Diel patterns of reproduction; Egg production	Montie et al. (2016) Montie et al. (2017)
Egg sampling from tank collectors, Counts	*Argyrosomus regius*	Captivity	Calling rate	Seasonal and diel patterns of reproduction	Vieira et al. (2019)
Environmental sampling, Water Temperature and Salinity	*C. regalis* *Micropogonias undulatus*	Offshore observatory, New Jersey, USA	Maximum night 200–300 Hz SPL	Diel call patterns and relation with upwelling events	Mann and Grothues (2009)
Environmental sampling, Substrate types, Dissolved Oxygen	*C. nebulosus*	Tampa Bay, Florida, USA	Calling intensity (4-level scale)	Spawning habitat delimitation and characterization	Walters et al. (2009)
Environmental sampling, Substrate types	*Bairdiella chrysoura* *C. nebulosus*	Middle March, North Carolina, USA	Chorus presence; 150–1500 Hz SPL	Spawning habitat characterization; Diel call patterns	Ricci et al. (2017)
Environmental sampling, Substrate types	*Sciaena umbra*	Mussel farm in Northern Adriatic Sea, Italy	Pulse rate	Seasonal call patterns and habitat preferences	Colla et al. (2018)
Environmental sampling, Water and Air Temperature	*A. regius*	Tagus estuary, Portugal	Chorus duration; 447–562 Hz SPL	Seasonal and diel patterns of reproduction	Vieira et al. (2022)
Experimental fishing with trawl, CPUE	*M. undulatus*	Neuse river estuary, North Carolina, USA	Calling intensity (4 level scale); 600–1200 Hz SPL	Juvenile distribution and relative abundance	Gannon and Gannon (2010)
Experimental fishing with gillnets, CPUE	*B. chrysoura* *C. nebulosus* *M. ondulatus* *Pogonias chromis*	Mission-Aransas estuary, Texas, USA	50–22500 Hz SPL; 50–2500 Hz SPL; 250–500 Hz SPL	Soniferous species and sciaenid relative abundance; Seasonal and spatial call patterns	Souza Jr et al. (2023)
Experimental fishing with haul seines, CPUE; **Environmental sampling**, Water Temperature and Salinity	*B. chrysoura* *C. nebulosus* *M. undulatus* *P. chromis* *S. ocellatus*	May river estuary, South Carolina, USA	Calling intensity (4-level scale); 50–1200 Hz SPL; Calling rate; Number of calls	Juvenile presence, distribution and relative abundance; Seasonal and spatial call patterns	Monczak et al. (2022) Mueller et al. (2020) Monczak et al. (2017) Montie et al. (2015)
Fish sampling, GSI, Sperm motility, Plasma testosterone	*C. regalis*	Delaware Bay, USA	Calling intensity (5-level scale)	Seasonal and diel patterns of reproduction	Connaughton and Taylor (1995)

Table 2 (continued)

Concurrent Sampling Method	Species	Location	PAM variable	Population parameters	Reference
Fish sampling with hooks and spearfishing, GSI, Gonad histology; **Egg sampling** with dip net; **Environmental sampling**, Water Temperature, Salinity; **Video** recording of spawning events	*Atractoscion nobilis*	Net-pen semi-natural conditions, Catalina Harbour, South California, USA	Calling intensity (4-level scale); Calling rate; SPL	Seasonal and diel patterns of reproduction; Spawner behaviour; Critical spawning habitat	Aalbers and Sepulveda (2012); Aalbers and Drawbridge (2008)
Plankton sampling of recently fertilized eggs; **Environmental sampling**, Water Temperature, Salinity, Dissolved Oxygen	*P. chromis* *C. nebulosus*	Bay systems in Louisiana, USA	Calling intensity (6-level scale)	Seasonal and diel patterns of reproduction and habitat preferences	Saucier and Baltz (1993)
Plankton sampling with Bongo nets, Egg counts; **Environmental sampling**, Water Temperature, Salinity	*B. chrysoura, C. nebulosus, C. regalis, S. ocellatus*	Pamlico Sound and inlets, North Carolina, USA	Maximum SPL; Calling intensity (4-level scale)	Spawning area identification and delimitation; Essential fish habitat	Luczkovich et al. (1999) Luczkovich et al. (2008a)
Plankton sampling (unsuccessful); **Environmental sampling**, Water Temperature, Salinity; **Fish sampling** with lines; **Egg sampling** in tanks; **Spotter plane** for aerial detection (unsuccessful)	*S. ocellatus*	Several sounds along Georgia coast, USA; Captivity	Calling intensity (4-level scale); Pulses per call; Calling rate	Spawning area identification and characterization; Seasonal and diel pattern of reproduction; Essential spawning habitat	Lowerre-Barbieri et al. (2008), Lowerre-Barbieri et al. (2016)—coordinated multi-method survey without PAM
Plankton sampling with horizontal tows, Egg daily cohort density; **Environmental sampling,** Surface and bottom water temperature; **Fish sampling** (indirect), GSI, DEPM adult parameters	*P. chromis*	Cape Coral estuarine canal basin, west Florida, USA	Maximum night 100–200 Hz SPL; Total acoustic energy; Chorus duration	Seasonal and diel patterns of reproduction; Egg production; Spawning biomass (DEPM indirect estimation)	Locascio et al. (2012), Locascio and Mann (2011), Macchi et al. (2002) – indirect; Fitzhugh et al. (1993) – indirect

Fisheries Data

Daily first sale meagre landings data for mainland Portugal are available since 1995, but more reliable from 2002 onwards (Prista et al. 2011). Landings (hereafter catch) correspond to catch because discards are negligible for this valuable species (Castro et al. 2021). Data are made available at IPMA by the Directorate General of Fisheries (DGRM), duly anonymised to prevent identification of individual vessels. First sale transaction data correspond to weight and value of species sale in auction (or contract) for each daily transaction per vessel. Each fishing trip with landings of a species can have more than one transaction per day (i.e., multiple buyers), depending on the size of the catch and the respective buyer needs. Register of sale takes place at the port of landing, but each vessel also has a port of vessel origin/registration. Here we use the port of vessel origin to distinguish small-scale vessels registered within the Tagus estuary from remaining fishing vessels in Portugal, as this in practice corresponds to two distinct phases of meagre fishing, estuarine and oceanic (Prista 2013). For the analysis we use two data sets:

(i) the shorter series 2016–2019 to compare fisheries data from the Tagus-registered vessels with meagre PAM variables (period selected to avoid presence of weakfish in acoustic data);
(ii) the longer series 2002–2022 of fisheries data to provide a first estimate of temporal trends in meagre CPUE and the proportion of national catch obtained within the Tagus estuary.

Daily and weekly fishery data are aggregated to provide estimates of catch (kg) and fishing effort (number of first sale transactions). The latter is used as a proxy for the number of fishing days with meagre landings, itself a proxy of fishing effort. Exploratory analysis showed that the number of daily transactions was highly correlated with the number of distinct vessels declaring landings in that day (Pearson correlation coefficient between 0.78 and 0.9 for estuarine fleet components by port of register). Most inner estuary vessels operate exclusively within the Tagus estuary, some outer estuary vessels occasionally operate in the ocean under good weather conditions (see Table 1). For a few of these vessels, meagre is a target species all year round, but for the majority meagre targeting is seasonal. Entry of adult fish to the estuary increases fishing effort due to seasonal meagre fishers and the intensification of regular activity. Number of transactions in first sale may also increase per landing event in relation to higher yield and larger fish size.

Passive Acoustic Monitoring

Continuous acoustic recordings were obtained in the Tagus estuary from April 2016 to September 2019 (Air Force Base 6, Montijo, Portugal; 38º42'N, 8º58'W). At this location, distinct sounds from two native vocal fish species are usually detected: the meagre and the Lusitanian toadfish (*Halobatrachus didactylus*—Vieira et al. 2015). More recently weakfish have also been detected at this site. We therefore discarded data from 2020 onwards to minimize hypothetical confounding with weakfish vocalizations. It should be noted that the remaining PAM recording stations shown in Fig. 1 were only deployed after 2019, when weakfish sounds started becoming conspicuous in the estuary.

Recordings were made using a High Tech 94 SSQ hydrophone (sensitivity – 165 dB re. 1 V/μPa, frequency response within ± 1 dB up to 6 kHz) anchored near the bottom and connected to a stand-alone 16 channel data-logger (LGR-5325, Measurement Computing Corp, Norton, MA, USA; 4 kHz sampling rate, 16 bit). Close to the pier, where the hydrophone is placed, the water column varies with tide from 3 to 6.5 m. The region in front of the pier is deeper (8 to 10 m), with the bottom mostly composed of sandy/silty substrate. Meagre tend to produce choruses in the area in front of the pier, a region crossed by ferry-boats connecting Lisbon to Montijo and by small fishing boats operating in the estuary. Lusitanian toadfish nest close to the pier and at the banks, where shelters are made available by members of the research team.

An automatic sound recognition system with hidden Markov model (HMM)-based supervised machine learning was used to annotate the continuous recordings. This was applied to detect and identify the presence of meagre sounds, assuming that the time series of an observed sound can be represented by a linear Markov model (for details on the machine-learning algorithm see Young et al. 2006). Vieira et al. (2021, 2022) demonstrated this sound recognition system to be highly effective for recordings in the

Tagus estuary. For the purposes of the present study, we used four PAM variables that can be attributed to meagre sounds: counts of isolated grunts, presence and duration (in hours) of chorusing and one-third octave band sound pressure levels centred at 500 Hz (hereafter named TOL500). According to Vieira et al. (2021), TOL500 changes mostly due to the presence of meagre choruses. Because meagre chorusing activity usually starts at late afternoon and continues to the early hours of the next day (Vieira et al. 2022), we considered 24 h periods starting at noon to facilitate data viewing and interpretation.

HMM models were trained using sounds from choruses containing different degrees of call overlap and dominated by either long grunts or isolated pulses (see Vieira et al. 2022). An additional model was used to recognise long grunts with a high signal-to-noise ratio, either isolated or in a chorus. In this study we only considered isolated grunts. Although the detection of isolated grunts might be restricted to sounds with high signal-to-noise ratio, they provide additional information about the presence outside the periods of major activity. TOL500 was computed as a 20 min averaged value, centred around sunset and calibrated adapting the code available by Merchant et al. (2015) (FFT 1024, Hann window, 50% overlap, averaged for each second). The correction factor for calibration was calculated using the hydrophone sensitivity, system gain and zero-to-peak voltage of the analog-to-digital converter. To reduce the subjectivity of measuring the chorus duration, we combined the labels of the automatic recognition system with a 20-min moving average of TOL500. Chorus duration was defined as the sum of the chorus labelled minutes per day where the 20-min averaged TOL500 was above 90 dB re. 1 μPa.

The TOL centred at 500 Hz encompasses a frequency band from 447 to 562 Hz. In the Tagus estuary, the other main components of biophony are the Lusitanian toadfish, with most energy below this frequency band, and the weakfish, whose calls overlap the frequencies of the meagre. Other sources contributing with noise to this frequency band are ferryboats and small fishing boats. Nevertheless, during 2016–2019, the soundscape within the TOL500 frequencies is largely dominated by meagre, since the other relevant sound sources are intermittent (for instance, at rush hour ferryboats can be recorded at the hydrophone less than 15% of the time, Vieira et al. 2021).

Data Analysis

Generalized Additive Models (GAMs) were used to model weekly data of three meagre catch variables: proportion of catch within the Tagus estuary, catch by inner estuary vessels and, as a CPUE index, mean biomass per transaction. A binomial error distribution with a logit link was used for the proportion of catch in the estuary and a negative binomial error distribution with a log link function for the others. In the CPUE model effort was introduced as an offset of the logarithm of weekly meagre transactions by inner estuary vessels. Analysis was performed separately for the shorter data set (2016–2019) with concurrent PAM data and the longer data set (2002–2022) of national catch. In the former, explanatory variables were four PAM variables: number of isolated grunts (square rooted), presence of chorus, total duration of chorusing and mean TOL500 in a week. Year was added as a categorical variable, testing also the significance of its interaction with sound variables. In the longer data set, only the effect of year (as a smooth continuous variable) and the effect of season (as a smooth effect over 52 weeks) were considered, the latter in interaction with a categorical variable indicating whether landings were from Tagus estuary vessels or not.

Exploratory analysis of mean/variance relationships of the daily and weekly data (not shown) revealed variance to be higher than the mean and to increase non-linearly, both for Tagus vessels and the remaining oceanic fishing vessels in Portugal. Dispersion parameter was iterated in the daily data of the short data set (starting with values close to 1 and comparing quality of fit with models considering higher and lower dispersion) and subsequently adjusted to higher values for weekly aggregates. Model selection was based on the three steps described by Wood and Augustin (2002). Full models were initially built, and backwards stepwise elimination used statistics of significance of partial effects, plots of partial effects with error bands and comparisons of nested models with Akaike´s Information Criterion (AIC) to reach the most parsimonious model. First order interactions between year and significant sound variables in the final model were then tested. Selected final models

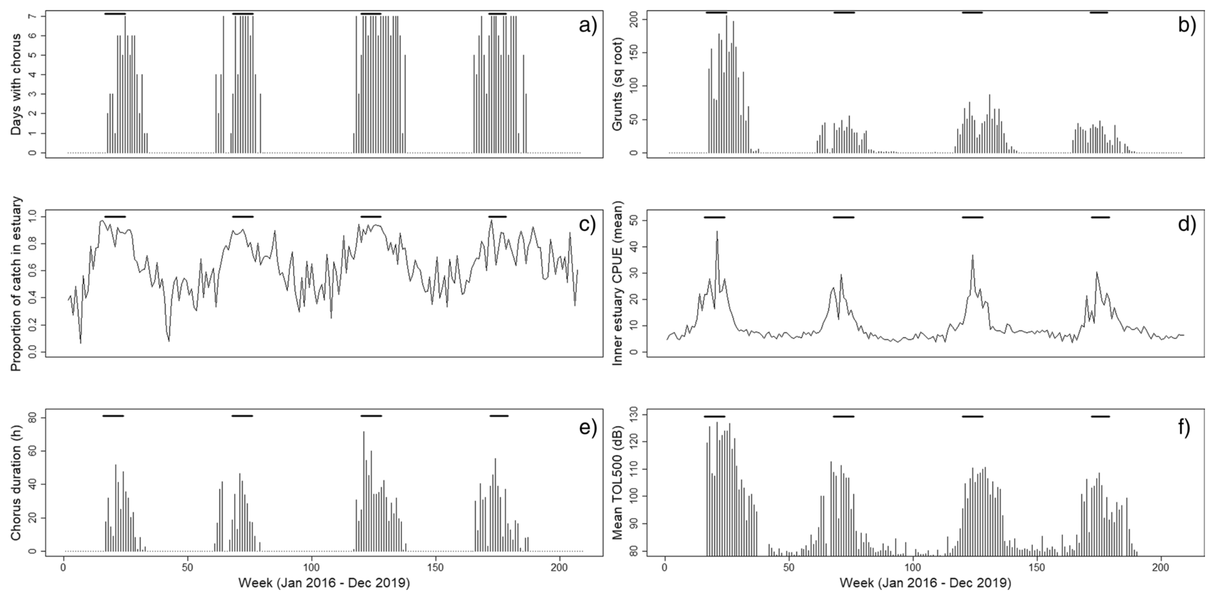


Fig. 3 Weekly register (from January 2016 to December 2019) of PAM variables from Montijo and corresponding commercial fishing activity by Tagus estuary vessels. Top panels: number of days with chorus (**a**) and number of isolated grunts recorded (**b**); Mid panels: proportion of national meagre landings by Tagus vessels (**c**), mean CPUE for inner estuary vessels (**d**); Bottom panels: total duration of chorusing (hours, **e**), mean TOL500 (**f**) per week. Dark bar at the top of graphs indicates weeks 24 to 36 (from mid-April to mid-June) in each year, the approximate peak of meagre spawning activity

were inspected with residual plots. Modelling was performed in R 4.2.0 (R Core Team 2022) using the libraries *mgcv* (Wood and Augustin 2002) and *MASS* (Venables and Ripley 2002).

Results

Meagre catch and first sale market transactions in Portugal have increased during the first decade of the twenty-first century, mainly due to the recovery of the spawning population in the Tagus estuary (Fig. 2). However, in the second decade catch and effort have initially plateaued and subsequently started to recede. Decline starts earlier and is more marked in meagre caught outside the river Tagus, especially in the last 5 years. These patterns are corroborated by the perception of Tagus´ fishers that, in the summer of 2022, considered fishing effort to have increased severalfold in the most recent decade. Similarly, they considered abundance of young meagre (<6 kg) to have declined a lot in the same period. The weekly temporal dynamics in the data set of 2016–2019 (Fig. 3) show that most fishing for meagre took place within the Tagus estuary from March–April to August–September. During that period meagre chorusing progressively became a regular daily feature within the estuary. Local abundance, approximated by CPUE of inner estuary vessels, peaked around the mid-spawning season, when TOL500 also reached a maximum. Overall, Fig. 3 shows a very good match between fishing and PAM variables´ seasonality during the four years of concurrent observations. This includes synchronicity in some fine-scale patterns, as for example the rapid oscillation of values between weeks 68 and 71 in 2017. The same general seasonality patterns, but with higher variability, were observed when daily data were considered instead of weekly (results not shown).

GAM results indicate that a large proportion of variation in meagre catch data was explained by PAM variables (Table 3 and Fig. 4). Variation in the proportion of meagre caught by Tagus estuary vessels per week was only significantly related to the presence of chorusing in the given week (46% of deviance explained). TOL500 had a marginal effect, with proportion of catch in the estuary increasing with increasing sound level. Weekly total catch of meagre

Table 3 Summary results for model selection process for GAMs fitted to catch response variables in relation to PAM explanatory variables (continuous or categorical). Tabulated values correspond to AIC for the selected final model and each individual term inclusion in the null model. AIC in bold corresponds to explanatory variables retained in the final model and in parentheses AIC of model including interaction term with year for each retained explanatory variable

Response variable (error distribution)	Model (% explained deviance)	Year, categorical	Grunts, continuous (smooth effect)	Chorus presence, categorical	Chorus duration, continuous (smooth effect)	Mean TOL500, continuous (smooth effect)
Proportion in estuary (Binomial)	165 (46%)	189	179	**165**	168	167
Week catch, sum (Negative Binomial)	2634 (89%)	**5184**	3125	3177	**2918 (2634)**	**2817 (2657)**
Week CPUE, mean (Negative Binomial)	2429 (80%)	3346	**2530** (2433)	2500	**2452** (2430)	**2441** (2437)

by vessels registered in the inner Tagus estuary were significantly related with total duration of chorusing and TOL500, but these relationships varied significantly across years (89% of deviance explained). Relationship with isolated grunts was marginal and also had a more complex relationship: for small values of catch it was positive, becoming subsequently negative. Finally, mean weekly CPUE by inner Tagus vessels was significantly related to three PAM variables (80% of deviance explained), positively in the case of chorusing duration and TOL500 and negatively in the case of isolated grunts. Importantly, relationships of PAM variables with CPUE were time-invariant, as their interaction with year did not improve the model fit (Table 3). The same general relationships, but with a smaller proportion of deviance explained, were obtained when daily data were modelled instead of weekly (results not shown).

The good correspondence between fishery data and PAM variables in the shorter data set increased confidence in the quality of meagre catch reporting and permitted to extend the analysis to the longer series (PAM-supported indicator). The observed changes in CPUE over the past two decades suggests that there was a large increase in fishing effort around 2009–2010, with a corresponding reduction in CPUE (Fig. 2). Reduction in oceanic relative abundance occurred a year earlier than in the Tagus estuary. CPUE since then has been approximately half of earlier values in both systems (Fig. 5). The same model also confirmed that highest CPUEs in the estuary are observed around peak spawning (weeks 18–26), while in oceanic waters the peak occurs much later in the year (Fig. 5 b and d respectively). In addition, analysis of the temporal dynamics of the proportion of meagre catch fished in the ocean (Fig. 6) revealed a continuous decline along the past two decades, with current values of meagre biomass fished outside the estuary below 30% of the total annual catch, as opposed to more than 70% in the start of the series. Some preliminary indication of decline can also be detected within the 2016–2019 PAM series (Fig. 3), although this was not the primary purpose of this analysis. For example, this is apparent in Fig. 3f, if we look at the number of weeks (or the aggregate TOL500) that had values above 100 (the lower limit of the change in the steepness of the relationship with CPUE in Fig. 4o). Further, if we consider the number of days (between Julian day 105 and 165) with TOL500 > 110 (based on the inflection in the relationship with CPUE shown in Fig. 4o), we get 30 days for 2016, 13 for 2017, 16 for 2018 and 4 for 2019.

Discussion

The present analysis revealed consistent patterns between PAM variables of meagre vocal activity in a fixed location within the Tagus estuary and meagre fishery variables based on aggregate commercial catch data across the estuary. Analysis was presented on weekly intervals over four years, but similar

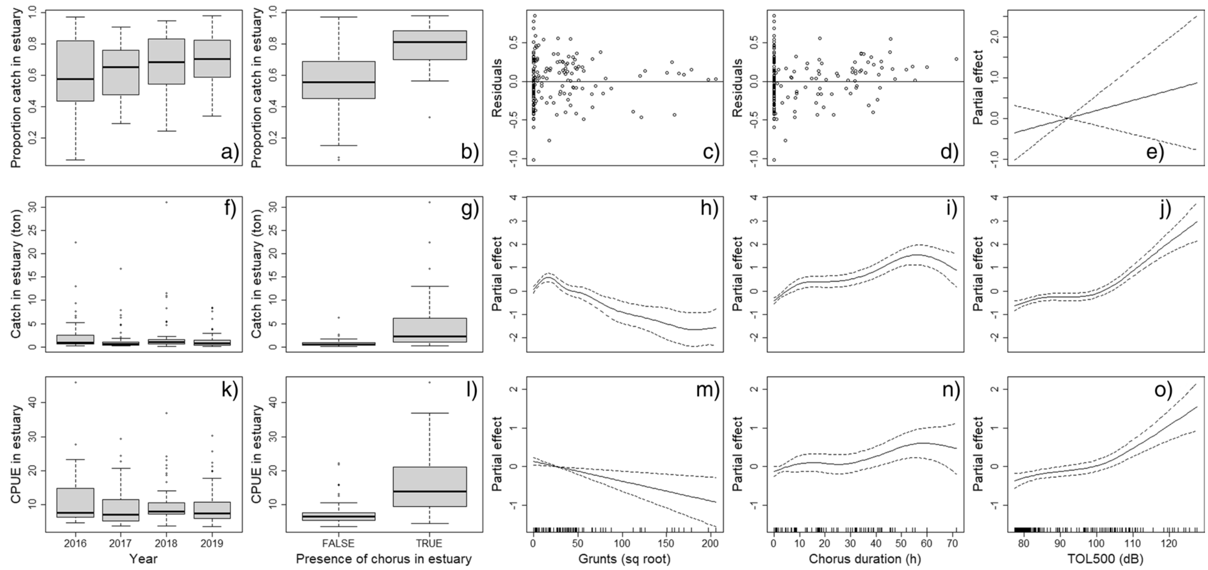


Fig. 4 GAM partial effects of relationships between weekly meagre fisheries data (upper row: proportion of national catch by Tagus vessels; middle row: Tagus meagre catch; bottom row: Tagus CPUE) and PAM variables (second column: presence of days with chorus within a week; third column: number of isolated grunts, square root; fourth column: duration of chorusing, hours; fifth column: mean TOL500) from the Montijo station daily recorded during 2016–2019 (first column). Non-significant sound variables are shown in relation to the residuals of the selected model (top right panel is marginally non-significant but shown to demonstrate overall trend)

results were obtained with daily data. This is in line with PAM literature focusing on the comparison of relative indices of local abundance concurrently obtained (Table 2). The literature review showed that PAM for sciaenids provided congruent results with active acoustics (Rowell et al. 2017) and experimental CPUE (Gannon and Gannon 2010; Monczak et al. 2022; Souza Jr et al. 2023). However, the above studies were designed to test PAM as a method to monitor fish relative abundance and relied on a tight spatial overlap with the other sampling method. This was not the case here, as the comparison was between a fixed-point acoustic recorder in a shallow part of the estuary and the aggregate catch by small boats (< 9 m) from the inner estuary. The congruence between PAM and catch variables, despite the mismatch in the spatial resolution of the two methods, deserves attention, as it may contribute to the extension of the rationale and the potential use of PAM tested so far.

Unlike PAM validation studies, the main objective here was to evaluate the potential of standard fisheries data to be used for management advice and communication with fishers. PAM in shallow estuaries is known to have a limited spatial range of detection due to transmission loss of the acoustic signal (Biggs and Erisman 2021) and meagre detection range in the Tagus estuary will be similar to that reported in other studies. Nevertheless, previous studies in Portugal and in the Tagus estuary have demonstrated the ability of PAM to delimit the seasonal and diel dynamics of meagre reproduction reliably (Vieira et al. 2019, 2022). A difference of the present study with those reported by Gannon and Gannon (2010), Monczak et al. (2022) and Souza Jr et al. (2023) is that the CPUE here is estimated over a larger area based on opportunistic sampling by commercial rather than scientific catch data. Individual catch data are known to be very variable (i.e., low precision) due to differences between fisher performances and fine scale unresolved spatiotemporal variation. Nevertheless, if there are no problems with reporting quality (Maunder et al. 2006), meagre catch data in aggregate provide a daily and seasonal census of the fishing activity in the estuary. The observed temporal synchronicity between PAM and catch data (Fig. 3) indicate that the latter provide a reliable biological signal, increasing confidence to use the longer series (2002–2022) to complement the exploratory analysis on meagre

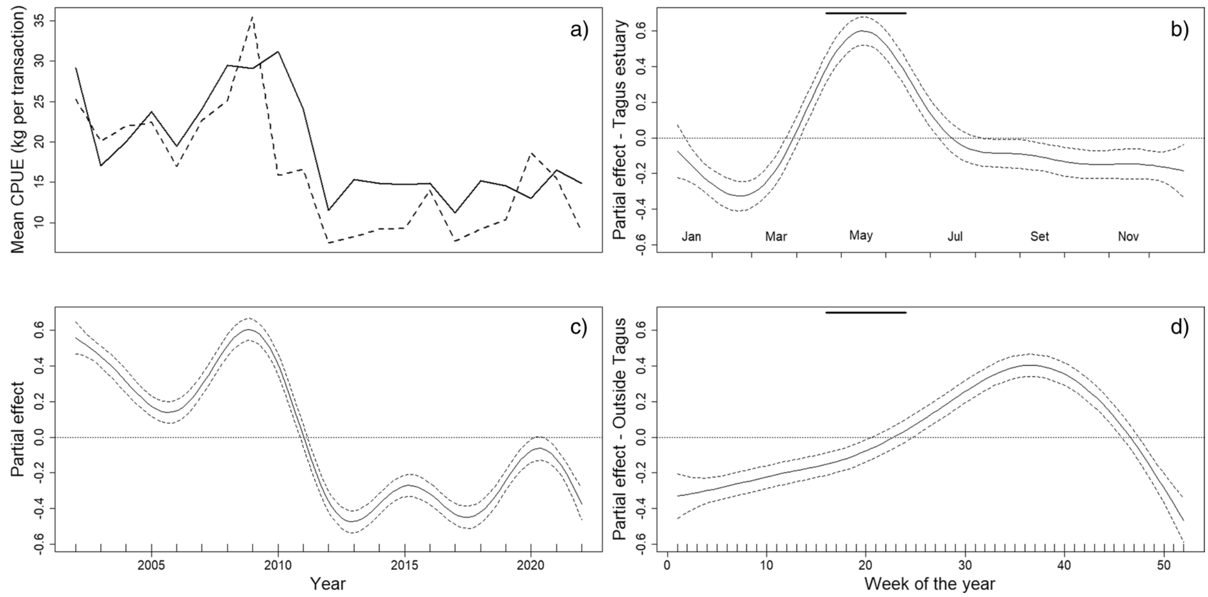


Fig. 5 Decadal (left) and seasonal (right) patterns in meagre CPUE commercial data from Portugal during 2002–2022: (**a**) raw data, separately for Tagus vessels (solid line) and remaining (broken line) vessels; (**b**) and (**d**) Seasonal (weekly) partial effect of CPUE GAM in the Tagus estuary and outside respectively; (**c**) Annual trend partial effect of meagre CPUE GAM. Dark thick line at the top of seasonal graphs corresponds to weeks 24 to 36 (from mid-April to mid-June) in each year

exploitation dynamics (Prista et al. 2011) for another decade.

The PAM station in Montijo provided support for the exploration of the longer CPUE series, but may also contribute directly to cost-effective long-term monitoring for meagre fisheries management. Assuming CPUE as a proxy of relative abundance, the GAM relationships with each PAM variable (Fig. 4) can be analysed to describe the relationship between sound production and fish density, along the lines of the hypotheses proposed by Rowell et al. (2017). Isolated grunts indicate the onset of adult presence (initial positive relation with catch) but are inversely related with subsequent increase in catch and are negatively related with CPUE (Fig. 4h and m respectively). This is possibly due to a decreased detection of isolated grunts when chorusing occurs (peak density/reproductive season), but it may also be an artefact of the much higher values for 2016 (Fig. 3b) that are difficult to explain at this stage. Presence of chorusing within a week provides the best descriptor of adult fish presence in the estuary (Figs. 3c and 4b), but days with chorus per week are insensitive to changes in relative abundance, as a plateau can be easily reached (Fig. 3a). Nevertheless, the variable shows sensitivity to abrupt changes in water temperature (Vieira et al. 2022), as for example the hiatus observed during the spring of 2017. Total chorus duration per week correlates with CPUE, but the relationship is weak and also seems to reach a plateau (Fig. 4n). TOL500 is the most promissing PAM variable to use as a long-term indicator for the meagre fishery, since it is the easiest to estimate, shows the strongest linear relationship with CPUE (Fig. 4o) and is time-invariant (i.e. no significant modification of the relationship between years). The relationship of TOL500 with CPUE seems to become steeper for sound pressure levels above 100 dB, possibly due to the logarithmic nature of the variable.

For TOL500 to serve independently as an indicator of local abundance, we must hypothesize that stationary PAM can be an unbiased, albeit imprecise, sampler of meagre adult density within the Tagus estuary during the reproductive season. Sound pressure level is known to decline rapidly with distance from the source, and the rate of decline is habitat-dependent in shallow estuaries (Biggs and Erisman 2021). Based on the position of the PAM station and the surrounding bathymetry and habitat characteristics, we consider that PAM recordings in this station can

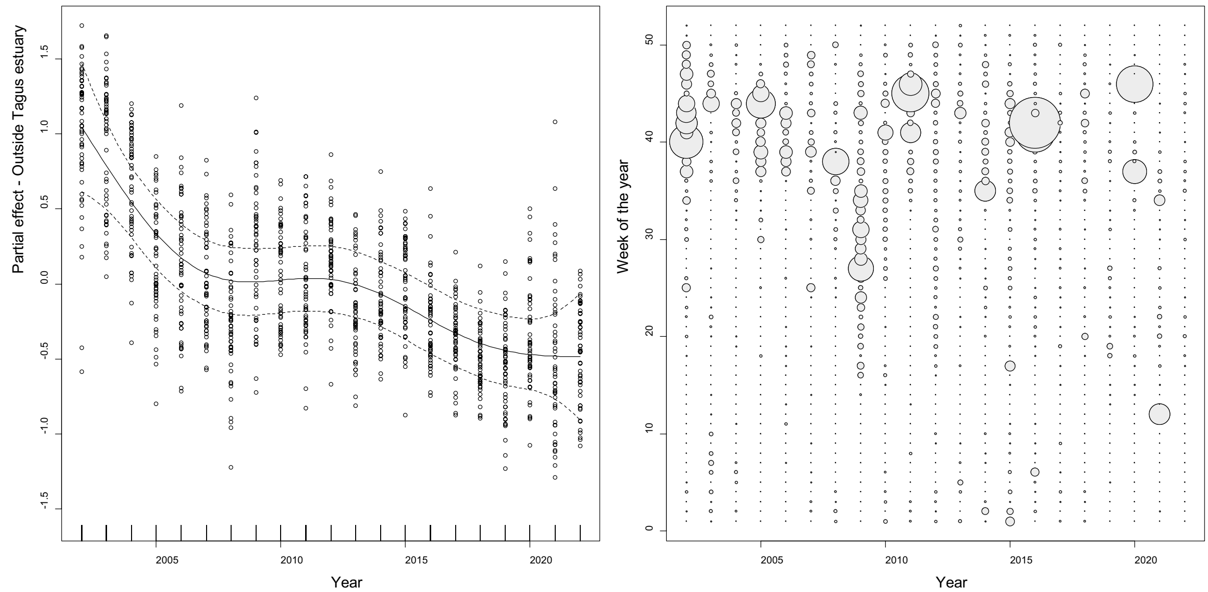


Fig. 6 Decadal patterns of proportion of meagre catch outside the Tagus estuary during 2002–2022 (left panel, GAM partial effect) and weekly distribution of catch outside the Tagus estuary along this period (right panel, size of circles proportional to landings). Partial effect of week (seasonal effect) is not shown, as it mirrors the seasonal effect for Tagus presented in Fig. 5

reliably capture meagre sounds only up to a few hundred meters away. For TOL500 to serve as an indicator of local abundance, evidence of random presence of adult meagre within the range of detection and absence of territoriality must be proven. Existing information on the general distribution and dynamics of adult meagre within the Tagus estuary, based on telemetry (Quintella and Marques unpublished), and the respective distribution of small-scale fishing activity for meagre, based on the questionnaire survey (Fig. 1), provide some initial support for this hypothesis. The area adjacent to the PAM station is recognised as one of the most important fishing areas and biotelemetry indicates regular movements of adult fish in the lower and mid-estuary, without the establishment of territories. Under these conditions, PAM can be considered an unbiased sampler of adult fish abundance in the estuary, as proximity of imminent spawners to the recorder (and hence the probability of high TOL500) can be seen to be a function of the number of estuarine presences of adult fish (season-dependent, Prista et al. 2011) and the respective fish activity levels (temperature-dependent, Vieira et al. 2022).

For PAM to become a robust long-term instrument to support the adaptive management of meagre in the Tagus estuary, additional steps of research will be needed. One important question relates to species identification in PAM records (Gannon 2008), since calls of the invasive weakfish have also become regular after 2019 within the Tagus estuary (Amorim et al. 2023). Both weakfish and meagre produce grunts during the breeding season that mainly differ in the time interval between pulses in a grunt (weakfish: 58 ± 7 ms, meagre: 17 ± 1 ms; Amorim et al. 2023). Although their sounds are easily distinguished, additional effort will be needed to guarantee automatic separation in annotations and, especially, to separate their contribution in TOL500, given the overlap in the frequency niche of their grunts. Other challenges relate to the hypothesis of unbiased PAM sampling that will need to be addressed with the assistance of the multi-sensor infrastructure of CoastNet (Fig. 1). This refers to sound transmission limits (Biggs and Erisman 2021) and masking by background noise (Gannon 2008) in the context of increasing anthropogenic noise within a busy urban estuary (Alves et al. 2021; Vieira et al. 2021). Sound transmission limits will have to considered in relation to the distribution and dynamics of adult meagre within the estuary to evaluate whether PAM can be considered an unbiased sampler. These relationships can be tested, after the separation of weakfish sounds, by comparing PAM records among stations with contrasting levels of noise and local presence of adult meagre (Fig. 1 shows the full array of sensors currently within the estuary). The latter can be based on the analysis of daily movements of tagged fish as detected and spatially resolved by the biotelemetry array of acoustic receivers in the estuary (MIGRACORV project results, under analysis). Finally, direct methods of estimating meagre abundance and biomass, based on active fisheries acoustics (Rowell et al. 2017) or egg production methods (Holt et al. 1985; Fitzhugh et al. 1993; Stratoudakis et al. 2006), will need to be coupled with concurrent PAM to develop reference points (Shephard et al. 2015) based on sound variables.

PAM variables and PAM-supported results also facilitate communication and increases the credibility of findings, since meagre acoustic behaviour is well known among fishers in the Tagus estuary. A similar confirmatory role of PAM was found for the grouper family, where diver-based visual censuses compared well with PAM in the short-term (Rowell et al. 2012) and the long-term (Koenig et al. 2017). Such congruent results facilitate, in turn, recursive feedbacks between the state of meagre in the estuary and knowledge about the system (Blythe et al. 2017) and increases the legitimacy of potential measures to protect reproduction (Stratoudakis 2021). Temporary cessations of fishing to protect the main period of reproduction is understood and respected by fishers, when supporting evidence indicates population declines. Beyond the communicative value of PAM variables in the contact with fishers, fisheries-independent monitoring with PAM-based reference points can avoid the illusion of plenty associated with hyperstability in the CPUE (Maunder et al. 2006; Erisman et al. 2011).

The CPUE series analysed here indicates a transition in exploitation around 2010, with higher effort and lower relative abundance in more recent years, and this is in line with fisher perceptions in the Tagus estuary (Fig. 2b) and the results reported in an earlier questionnaire survey (Mota 2018). Mean weekly CPUE remains apparently stable since then at a higher exploitation rate, but there are several signs of overexploitation that deserve attention. The continuous erosion of the oceanic catch component (Fig. 6a) and the recent decline in total yield and effort (Fig. 2a and c) indicate that the overexploitation signs are possibly retarded and masked by hyperstability in CPUE (Maunder et al. 2006; Erisman et al. 2011; Sadovy de Mitcheson 2016). Hyperstability can result from fisher behaviour in relation to biological processes operating at different scales. Earlier erosion of the oceanic component in the catch can be related to the shift from bycatch to target during the seasonal migration of adult meagre to the estuary where they concentrate. Apparent stability in CPUE within the estuary, despite declining total catch and effort, can be related with an increasing frequency of the illegal practice to target ephemeral reproductive aggregations. Meagre are repeated batch spawners that create temporary aggregations in the few hours prior to the reproductive event between females with hydrated oocytes and ripe males. In recent years of declining abundance, it is known that some fishers have modified their practices to trace and illegally trap such aggregations (Mota 2018).

In conclusion, the present study provided indications that the meagre fishery in the Tagus estuary needs to move beyond the current phase of minimal technical management measures and consider additional protection of the reproduction in the Tagus estuary. It is also suggested that PAM may serve as a long-term cost-effective instrument towards adaptive fishery management in the Tagus estuary and can facilitate communication with fishers. For that, additional research steps were delimited. Increased participation and communication can help to legitimise tighter input control measures (Oyanedel et al. 2020; Stratoudakis 2021) and improve compliance in a fishery that has grown in the past two decades under limited surveillance and control. Stepping-up fishery monitoring through PAM and introducing effective regulatory measures to protect reproduction through participatory processes is a way to manage other small-scale fisheries for vocal fish that face similar problems of overexploitation and underinvestment.

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Declaration

Conflict of interest No financial or other interest to declare.

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