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Enhancing scientific knowledge to support the exploitation of invasive *Anadara* spp. in the Adriatic Sea

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A R T I C L E I N F O

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A B S T R A C T

Two invasive bivalves, *Anadara kagoshimensis* and *A. transversa* have historically established abundant populations in the Adriatic Sea, presenting a compelling case for managing their invasion through the development of a commercial fishery. Whether these species hold economic potential for human consumption, aquaculture, or alternative non-food applications, this research aims to provide essential scientific knowledge to support their sustainable exploitation. Data on their distribution, abundance and status in relation to MSY reference points was based on a large dataset which included data on 66 randomly selected locations across the Adriatic Sea, surveyed annually through experimental trawling survey from 2008 to 2023. Abundance hotspots for both species, were provided in spatially explicit maps and resulted to be primarily located in the western Adriatic coast, wherein two distinct populations per species were delineated in Italian waters. Stock assessments highlighted the broad availability of these bivalves, with a combined maximum sustainable yield (MSY) of 11486.2 tons for both species. Altogether, this diverse information provides a foundation for a possible commercial exploitation of both species, offering a means to manage the invasion while balancing ecological and economic interests.

1. Introduction

The number of introductions of Non-Indigenous Species (NIS) in both terrestrial and aquatic ecosystems is growing at an unprecedented rate, all over the planet and among all taxonomic groups, with no sign of saturation [1,2]. At the end of 2020, a total of 1006 NIS have been censused throughout the entire Mediterranean basin, of which most are Mollusca (222) [3]. Mollusca reached the highest diversity among established and casual (i.e., not established) Mediterranean NIS [4]. Notably, *Anadara transversa* (Say, 1822) (reported as *A. demiri*), and *A. kagoshimensis* (Tokunaga, 1906) (reported as *A. inaequivalvis*), were included in the list of the 100 "Worst Invasives'' in the Mediterranean Sea given their detrimental impact on biodiversity and socioeconomics [5]. Both species were recently evaluated as highly impacting on native species, biological communities, and food provision [6]; they were also included in the "inventory of alien and cryptogenic marine species with reported moderate to high impacts on biodiversity or ecosystem services or human health" [7].

Anadara kagoshimensis is indigenous to regions spanning from the central Indian Ocean to the western Pacific [8]. It was documented for the first time in the Mediterranean Sea in Italian Adriatic waters in 1966 [9], likely introduced through shipping and maritime transport [10] via the Suez Canal, either in the larval stage within ballast waters or in the benthic stages, attached through the byssus to the ships [11]. The

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species conquered several areas in the Mediterranean, Marmara, Black and Azov Seas [12], probably facilitated by discarding practices of commercial fishing and favourable environmental factors [13,14]. The species' life cycle facilitates dispersion through vectors like ballast waters, tidal currents and aquaculture products [15] and extensive banks have been historically recorded in the Adriatic Sea, spanning from the north-eastern region to the western Italian coast [8]. The species is widely distributed from coastal brackish waters to greater depths, mostly on silty-clay sediment but also on sandy and rocky bottoms [16, 17]. *A. kagoshimensis* can withstand challenging trophic conditions for suspension feeders and can tolerate fluctuating physical variables concerning tides, salinity, temperature and oxygen concentration [18]. It has successfully established abundant populations in the Adriatic Sea [10,19] facilitated by the capability to attach itself to various types of hard substrata through its byssus [19] and to bind oxygen in hypoxic conditions. In fact, the haemolymph of this ark clam contains nucleated erythrocytes packed with haemoglobin, enabling it to bind oxygen in oxygen-deficient conditions, and haematin, which is involved in the elimination of sulphides [20]. The rapid expansion of *A. kagoshimensis* in the Adriatic and Black Seas has been also linked to a decline in autochthonous bivalve populations such as *Chamelea gallina* (Linnaeus, 1758), *Mya arenaria* Linnaeus, 1758 and *Cerastoderma glaucum* (Bruguiere, 1789) [5,21,22].

Anadara transversa originates from the north-western Atlantic Ocean, [23]. It was first reported from the Mediterranean Sea in Turkey in 1972 [24]. Its first occurrence in the Adriatic Sea dates back to the 1970s [25]. The species has rapidly spread across different sectors of the Mediterranean [25,26]. It was presumably introduced within ballast waters [11]. According to Albano et al. [25], the introduction of *A. transversa*, most likely occurred via shipping, either in ballast waters and/or as fouling epibionts. According to the European Alien Species Information Network [6], a secondary pathway of introduction is the transport through an animal vector. Secondary dispersal in the Mediterranean Sea was probably favoured by the unintentional co-transport of larvae and/or juveniles alongside farmed bivalves [27]. The post-larval stage of *A. transversa* has a specialised drogue-like byssus that facilitates an extended period of planktonic drifting, being important at this stage of the species life cycle, increasing its dispersal ability [28]. *A. transversa* can colonise rocky hard and muddy/sandy-muddy substrates, and it is capable of tolerating highly polluted habitats [27,29]. It can survive even under hypoxic conditions due to respiratory pigments with high oxygen affinity [25], mirroring the adaptive traits of *A. kagoshimensis*. It is considered the first North American alien mollusc species in the Mediterranean Sea with such an invasive potential [30], being a powerful competitor for space through selecting a burrowing or a non-burrowing strategy [31]. The species' massive presence on collectors installed for the endemic Mediterranean bivalve *Pinna nobilis* (Linnaeus, 1758) in Brijuni National Park [32] underscores its adverse impact on keystone species as well as on other taxa of high conservation value.

Anadara spp. are commercially harvested and cultured for human consumption and aquaculture in many countries, including China, Korea and Japan [15], and are valued as sources of protein and for their considerable amount of total carotenoid content and associated health benefits [33]. They are also used in Asian countries for other purposes, encompassing medical, ornamental, and cultural applications.

The commercial value of these species in their native and donor regions highlights the potential for diversified utilisation of *Anadara kagoshimensis* and *A. transversa* in the Adriatic Sea, encouraging targeted research to support this process. Indeed, the responsible exploitation of novel or underutilised species, including invasive ones, is a key pillar of Blue Economy and Blue Growth strategies. Such approaches can contribute to sustainable fisheries management and align with global sustainability targets, notably SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water). Provided that biodiversity and ecosystem integrity are preserved, developing a commercial fishery and promoting market-based solutions for aquatic invaders is increasingly recognised as one of the most pragmatic and effective tools to manage biological invasions in the context of climate change. This perspective is supported by recent studies (e.g., [34]) and reiterated in a recent FAO technical paper [35], which underscores the importance of adaptive, ecosystem-based management frameworks that integrate non-indigenous species into broader fisheries governance. More specifically, the FAO has outlined nine key measures to guide fisheries responses to aquatic bioinvasions, including the development of commercial fisheries targeting NIS and the exploration of market opportunities for their use, which may include both food and non-food applications. As a matter of fact, many NIS are already harvested and consumed in the Mediterranean Sea [36], especially in the eastern sectors of the basin, where they reach the highest abundances [37]. Specifically, consuming Invasive Alien Species (IAS), either as human or animal food has gained popularity as a method to reduce the pressure on native ecosystems while compensating for economic losses [38]. This approach is increasingly recognised as a pivotal strategy for managing edible invaders, particularly in aquatic environments where eradication is often impracticable and continuous efforts are needed to control populations [34,35]. Moreover, eating marine Mediterranean invaders aligns with several international goals, particularly those addressing sustainable development, biodiversity conservation, and food security, including the Aichi Biodiversity Targets, particularly Target 9 [39] and the European Union Biodiversity Strategy for 2030 [40]. This strategy also aligns with the requirements of the Marine Strategy Framework Directive (MSFD) [41], which mandates EU Member States to integrate NIS considerations into their marine management strategies. Molluscs are extensively exploited for food production and also as a source of various bio-based materials [42]. Thus, exploring the potential harvest and commercialisation of the invasive *A. kagoshimensis* and *A. transversa* in the Adriatic Sea represents a promising opportunity worth investigating [15]. Based on these premises, the present study aims to provide key information to support the commercial exploitation of *A. kagoshimensis* and *A. transversa* in the Adriatic Sea. This overarching goal is pursued through a series of specific objectives which include to:

1. Assess the spatial distribution of the two species in the Adriatic Sea and identify the key factors influencing their distribution
2. Conduct a geographic comparison of the populations at the northern (N) and southern (S) sites
3. Analyse the biomass stability
4. Assess their status in relation to MSY-based reference points

2. Materials and methods

2.1. Sampling and data collection

The research was conducted within the Geographical Sub-Area 17 (GSA 17: Northern and Central Adriatic) as defined by the General Fisheries Commission for the Mediterranean (GFCM) of the Food and Agriculture Organization (FAO) [43]. This study area, located within Italian maritime boundaries and communitarian waters, covered an approximate expanse of 378,450 km^2, with depths ranging from 6.85 m to 93.35 m. Sampling and data collection were executed within the framework of the SoleMon project (an experimental trawl survey carried out with a modified beam trawl called "rapido", traditionally employed by local fishers targeting flatfishes and economically significant benthic species), whose methods are available in the SoleMon Handbook [44]. The primary aim of the SoleMon Project is to evaluate the population dynamics of commercial demersal species, especially *Solea solea* (Linnaeus, 1758), in the central and northern Adriatic Sea. Additionally, the project gathers data pertaining to other species, including *Anadara* spp., as well as marine litter. Data employed in this study were provided by 16 annual surveys carried out from 2008 to 2023. Each survey included, on average, 63 sampling stations. Quantitative assessments, including the enumeration of individual specimens of *Anadara* spp. and their total weighing, were performed. The standardised biomass values were recorded for each sample. Data on sampling effort (haul duration), date, depth, swept area, haul geographical coordinates, wet weight (kg), and the number of individuals (N) of *A. kagoshimensis* and *A. transversa* were recorded and archived in the TRawls sUrveys database sysTem [45]. The TruSt system enabled the calculation of their abundance (N/km^2) and biomass density (kg/km^2). The analyses of biomass trends for *A. kagoshimensis* and *A. transversa* as well as the assessment of individual sizes (expressed as kg/N) were performed on an annual basis throughout the duration of the 16-year study.

The data used in this study were previously collected in the dataset published by Scarcella et al. [46], and were described in detail in the associated datapaper by Chiappi et al. [47].

2.2. Spatial modelling

To identify the most important variables influencing the distribution of the two species and to delineate their distribution patterns, a species distribution model (SDM) analysis [48] was conducted. SDMs are commonly employed to map and predict species occurrence or abundance across space and time, implementing environmental data [49]. In the marine environment, these models have mainly been used for fish species [50]. However, some successful applications with bivalves have been documented in recent years [51]. They also show promising applications for forecasting the spread of invasive species under climate change scenarios (e.g., [50,52]).

Abundance data of each trawl was correlated with environmental variables in order to estimate their potential distribution along the Italian and communitarian waters of GSA 17. Daily environmental data on temperature (T°), salinity (S), chlorophyll (Chla), phytoplankton (Phyc) and primary production (PP) were retrieved from the Copernicus Marine Environment Monitoring Service (CMEMS) for this purpose. Additionally, grain size, depth and distance from the coast were considered as factors potentially affecting the distribution of the species. Correlations among variables were tested applying a Kendall's Tau correlation analysis [53].

For each species, three SDMs were evaluated: a zero-inflated model using the R package "pscl" and two generalised additive models (GAMs) [54] with different families (negative-binomial and Tweedy) through the R package mgcv. Significant variables were selected for each model by Backward Elimination (BE) which has been shown to be adequate when the events-per-variable (EPV) is high [55], as is the case for our study. Additionally, SDMs were designated with a 70:30 data split for training and testing. Model evaluation statistics were calculated; the optimal SDM was selected based on Root Mean Square Error (RMSE). The optimal model was then applied to the entire dataset to produce a map per species showing the potential distribution of each species in the Italian and communitarian waters of GSA 17. This analysis was carried out for the period 2008–2020, as daily environmental data were only available for those years.

2.3. Comparing northern and southern populations

Kruskal-Wallis test was performed in order to delineate possible differences in terms of average individual weights for each species according to the sampling area (North vs South). The delineation of the two sampling areas is based on the spatial discontinuity and on the average individual weight and is solely from a managerial perspective. No distinction was made from a biological or connectivity standpoint.

2.4. Analysing the biomass stability

Preliminary analyses were conducted to assess biomass trends with time spanning over several years and to identify the most suitable model. Since the data were not normally distributed, the time trend of biomass with time in years was evaluated by Generalised Linear Model (GLM), and GAM. As data distribution we assumed a gamma distribution with link = log. Model selection was then based on the Akaike Information Criterion (AIC). All the statistical analyses were carried out using the free statistical software R ver. 4.4.2 [56]. To fit the GAM model, we used the gam function of the package mgcv [57].

2.5. Assessing the maximum sustainable yield

To assess the exploitable quantity of both species, their status in relation to Maximum Sustainable Yield (MSY) reference points was determined by applying the Abundance Maximum Sustainable Yield (AMSY) model [58] in R studio. This model facilitates the estimation of relative population sizes by incorporating time series data of CPUE or other relative abundance indices as principal inputs. The input file structure includes three fields: sampling area, year, and biomass (expressed as kg/km^2). For the population growth rate (r), priors were established for *A. inaequivalvis* from 0.6 to 2.5, due to the absence of species-specific r priors for *A. kagoshimensis* and *A. transversa* on SeaLifeBase [59]. The prior range for r, set between 0.55 and 1.61, reflects the inherent uncertainty in these estimates. Priors were employed to define the biomass level relative to the carrying capacity (B/k), with 1 indicating no exploitation and 0.1 signifying 90 % exploitation. Adjustments to the biomass relative to the carrying capacity were made only for the initial year of the study period (i.e., 2008), with an unexploited range between 0.75 and 1. High resilience was assumed in the model, considering the negligible fishing mortality for *Anadara* spp., which are often discarded alive. A data smoothing procedure was implemented, as suggested by the model.

3. Results

3.1. Spatial modelling

Using SDMs, a distribution map was obtained for each species (Fig. 1). On average, both species exhibited similar distribution patterns, with hotspots near Ravenna and a prevalence in shallow waters. However, some differences were observed: *A. kagoshimensis* was less abundant than *A. transversa* but had a more widespread distribution, especially near the Istrian peninsula.

The Kendall Tau correlation analysis revealed a correlation between chlorophyll and phytoplankton, and between depth and distance from the coast. Therefore, only chlorophyll and depth were included as variables in the model analysis.

The model evaluation statistics for *A. kagoshimensis* revealed that the GAM with Tweedie family provided the best performance with an RMSE of 75994. The GAM with Negative Binomial family had a significantly higher RMSE of 1359024.36. The Zero-Inflated model had an RMSE of 105305.98. The model evaluation statistics for *A. transversa* revealed that the GAM with Tweedie family had an RMSE of 1875050. The GAM with Negative Binomial family showed an RMSE of 7243946. The Zero-Inflated model had an RMSE of 1366643. Differences were observed among the models' results, and the GAM with the Tweedie family was identified as the best performing model for predicting *A. kagoshimensis* and the second best for *A. transversa*.

The selected model revealed that the abundance of *A. kagoshimensis* was influenced by longitude and latitude, depth, year, temperature, salinity, grain size, and chlorophyll. In contrast, neither temperature, nor salinity, seemed to affect the abundance of *A. transversa*. *A. kagoshimensis* showed a preference for fine sand and silt substrates, maintaining a relatively constant abundance even as depth increases. Conversely, *A. transversa,* with a peak of abundance at 20 m, appeared to have a preference for coarse or fine sand, and was less abundant on silt substrates.

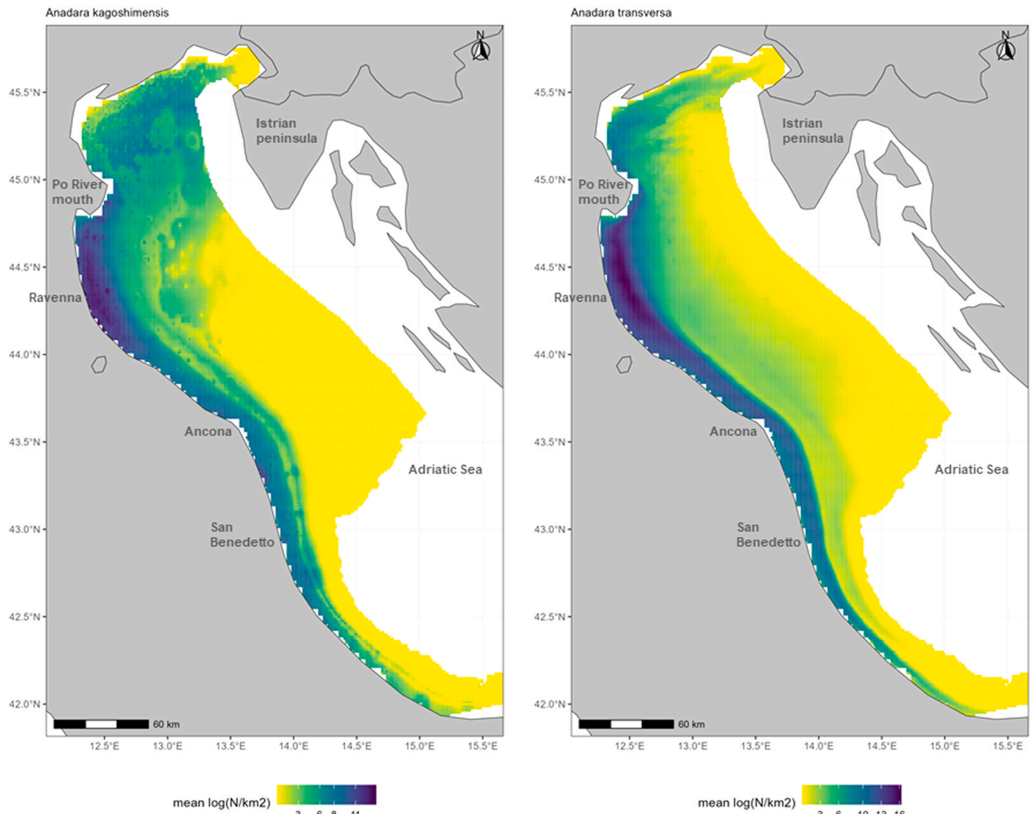

Fig. 1. Spatial distribution maps showing the mean modelled abundance of the entire sampling period of *A. kagoshimensis* (on the left) and of *A. transversa* (on the right).

Table 1
Variable importance of the different predictive variables for the selected model (i.e., GAM with the Tweedie family).

Anadara kagoshimensis	% Importance	*Anadara transversa*	% Importance
Longitude and latitude	41.4	Longitude and latitude	46.25
Depth	17.5	Depth	28.19
Year	11.1	Grain size	13.49
Temperature	9.0	Year	8.23
Salinity	8.7	Chlorophyll	3.84
Grain size	7.4		
Chlorophyll	4.9		

3.2. Comparing northern and southern populations

By analysing the number of individuals and weight (Supplementary Figure 1), and, in particular, the average individual weight (Supplementary Figure 2) per year, obtained as an average per station, it was possible to identify differences in the populations sampled in the north and in the south (Supplementary Figure 3). The Kruskal-Wallis test showed significant mean individual weight differences between northern and southern areas for both species (*A. kagoshimensis*: $\chi^2 = 38.37$, $p < 0.0001$; *A. transversa*: $\chi^2 = 7.71$, $p = 0.021$). Consequently, all the analyses reported here were conducted separately for the two sampling areas of each species.

3.3. Analysing the biomass stability

Based on AIC, the GAM model consistently outperformed the GLM model in every scenario. Therefore, only the GAM results will be presented in this study.

Both species exhibited biomass fluctuations across all sampling areas (Fig. 2). *A. kagoshimensis* experienced a decline from 2008 to 2013 in S and from 2009 to 2012 in N. In recent years, biomass levels have increased, surpassing the initial values in S and reaching the initial values in N. *A. transversa* showed a decline in S from 2009 to 2013 and from 2018 to 2020, with increases observed from 2014 to 2018 and from 2020 to 2022. Currently, it is beginning to decline again, although the biomass remains higher than in most other years. In N, *A. transversa* declined from 2008 to 2014 and has been recovering since then.

3.4. Assessing the maximum sustainable yield

In N, *A. kagoshimensis* had CPUE values ranging from 326 to 3579 kg/h of fishing per year throughout the sampling period, while S had remarkably lower values, ranging from 37.1 to 238 kg/h. The CPUE values for *A. transversa* exhibited a great variability between the two sampling areas in the Adriatic Sea: in N, CPUE values ranged from 1205 to 4023 kg/h, while S showed CPUE values from 4.74 to 3937 kg/h.

The MSY for *A. kagoshimensis* in N was estimated at 5375.8 tonnes, and in S was substantially lower, at 158.6 tonnes, The MSY for *A. transversa* in N was estimated at 3672.9 tonnes, while in S was estimated at 2278.9 tonnes. The exploitation ratio (F/FMSY) was calculated for each area to assess the temporal trends in exploitation status. The results indicated that all sampling areas are underexploited, as the F/FMSY values have remained below 1.0 in recent years (Supplementary Figure 4). This showed that the current fishing pressure is way below the MSY threshold.

Biomass underwent variations throughout the historical series, with a general upward trend in recent years always above BMSY levels (Supplementary Figure 5).

All examined species in each sampling area fell within the green quadrant of the Kobe plots, signifying healthy biomass levels and sustainable fishing pressures. Specifically, the biomass levels for each area are above the threshold required for MSY, while the fishing mortality rates remain below the MSY limit. (Fig. 3).

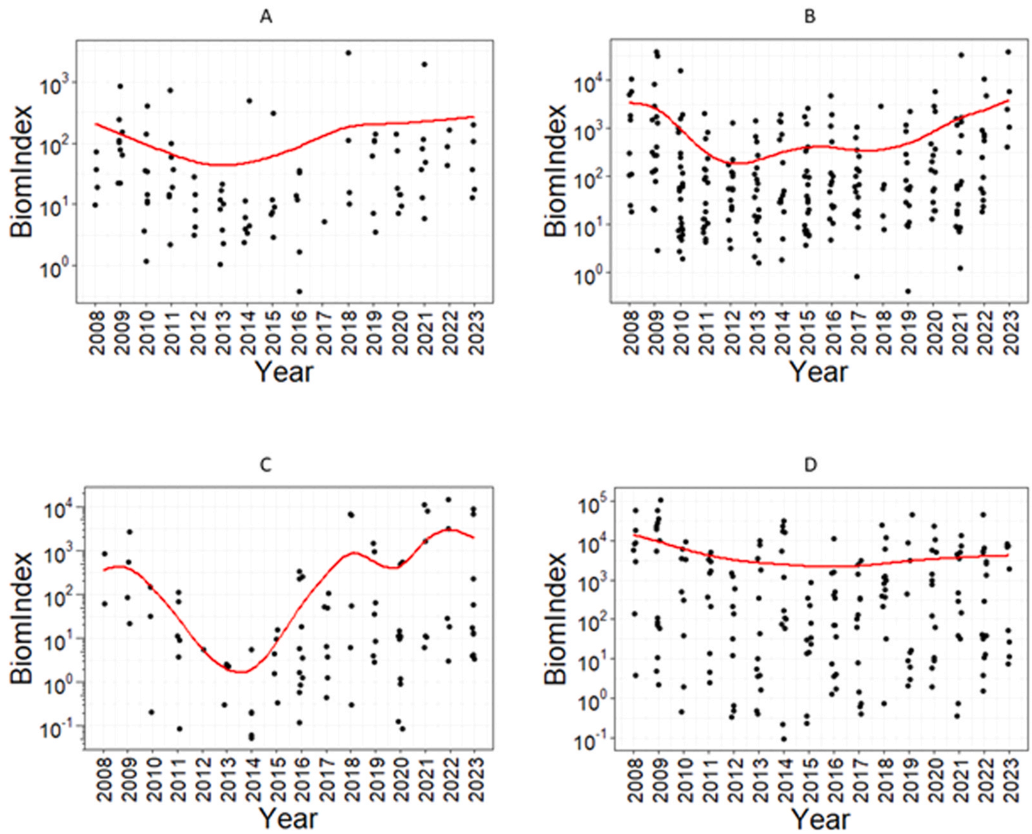

Fig. 2. Biomass (BiomIndex) as a function of time for S and N of *A. kagoshimensis* (A and B) and *A. transversa* (C and D). Note the logarithmic scale of the y axis. In each plot, the red line represents the GAM fitting model.

4. Discussion

Here, using a multidisciplinary approach, we addressed some essential information for supporting a potential fishery and commercialisation of *A. kagoshimensis* and *A. transversa* in the Adriatic Sea. This information relates to a series of questions, which are listed below:

4.1. Where are A. kagoshimensis and A. transversa distributed, and what are the primary factors influencing their abundance?

The geographical outputs presented in this study, based on a 16-year dataset, provide a detailed mapping of the distribution of *A. kagoshimensis* and *A. transversa* in the Adriatic Sea. These results extend the findings of Strafella et al. [8], which focused solely on *A. kagoshimensis* over a shorter period of five years (2010–2014).

SDMs identified grain size (granulometry), chlorophyll concentration, and depth as the primary factors influencing the abundance of both species. The hotspots for both species were located in a coastal area with sandy bottoms and high chlorophyll concentration, near the Po River mouth. Although both species exhibited similar distribution patterns, *A. kagoshimensis* could also be found further from the coast, on fine sand and silt, confirming its ability to occupy waters up to 30 m on sandy and muddy bottoms [16]. Additionally, the more pronounced coastal distribution of *A. transversa* suggests that this species may thrive in polluted ecosystems or even under hypoxic conditions, in agreement with the findings of other studies (e.g., [25,29]).

4.2. Are their biomasses stable over time?

Significant interannual changes in the biomass of *Anadara* spp. in all the sampling areas were observed. Similar fluctuations have been documented in other studies, emphasizing the influence of environmental factors on the stability of *Anadara* spp. populations [60, 61]. Considering that *Anadara* spp. are not generally harvested, and always discarded alive when caught (Authors' personal observation) the observed fluctuations should be primarily attributed to environmental variables rather than fishing-induced mortality. Future studies are needed to enhance the accuracy of biomass predictions in dynamic ecosystems.

4.3. What is the exploitable quantity of both species?

CPUE values of *A. kagoshimensis* and *A. transversa* in the Adriatic Sea varied greatly across the different sampling areas, with the highest values recorded for the northern Adriatic. The analysis by Morello et al. [62] of discard and by-catch samples from dredge hauls in the Ancona and S. Benedetto Maritime Districts revealed findings regarding the presence of various bivalve species. Morello et al. [62] identified *A. transversa* (formerly *A. demiri*) and *A. kagoshimensis* (formerly *A. inaequivalvis*) in average quantities considerably lower than those of *Chamelea gallina*, which was subsequently reported to have declined due to overexploitation; [63–65]). Our findings of a relatively lower abundance of *Anadara* spp. in areas south of Ancona, are consistent with these observations. Future studies could compare the CPUE of the two Anadara species caught with the "rapido" to the hourly yields obtained from hydraulic dredges in extensive Adriatic sampling. This comparison is pertinent given that the hourly yield of "rapido" is lower than that of hydraulic dredges

The AMSY model incorporated an assumption of high resilience for *Anadara* species, which is based on the fact that fishing mortality for these species is very low (e. g., [66]). Although both species are classified as invasive, it remains essential to consider the MSY paradigm when managing their fisheries. Indeed, establishing a fishery for these species could generate the need to ensure the sustainability of the population

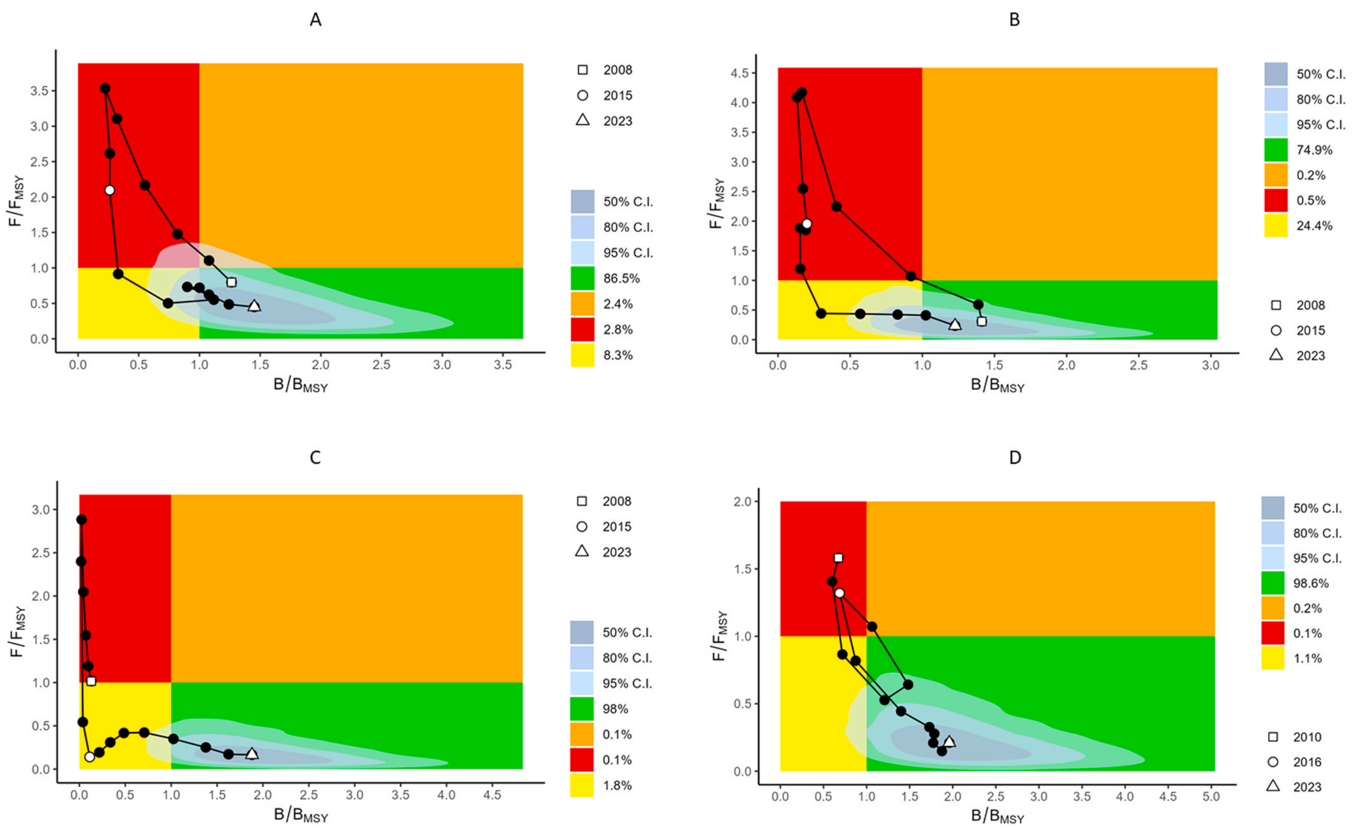

Fig. 3. Kobe plots for S and N of *A. kagoshimensis* (A and B) and *A. transversa* (C and D). Each plot is divided into four quadrants meaning: overfished population (top left), overfishing population (top right), underfishing population (bottom left), and underfished population (bottom right). The vertical line represents the biomass needed for sustainability (B/BMSY), with a low amount to the left and an appropriate amount for the fishery to the right. The horizontal line represents fishing mortality (F/FMSY), with an extreme fishing level above the line and sustainable fishing below. On the right, the colorimetric legend for confidence intervals (C. I.).

within the designated area, a situation which is often indicated as a *bioeconomic paradox* [67], a situation which may conflict with ecological objectives.

Nevertheless, this is not the case for *Anadara* spp. in the Adriatic Sea, as - to the best of our knowledge - no actions have been taken to manage these highly invasive species. Clearly, as recently stressed by FAO [35], the "do nothing" approach is not a viable option when alternative management measures can be implemented.

Creating a fishery for this species would probably mitigate many of the ecosystem-wide impacts attributed to *A. kagoshimensis* and *A. transversa.* The expansion of *A. kagoshimensis* in the Adriatic and Black Seas has been associated with declines in native bivalve populations such as *Chamelea gallina*, *Mya arenaria*, and *Cerastoderma glaucum* [5,21,22], raising concerns about spatial competition and habitat modification in areas of high *Anadara* spp. density. In contrast, *A. transversa* remains comparatively understudied, and its ecological role and potential impacts are still poorly understood, underscoring the need for targeted research. Other localised ecological changes (such as alterations in benthic community composition or sediment structure) have been observed in association with their presence, though these remain insufficiently quantified and require further investigation [32].

Given that the SoleMon dataset derives from a multi-species trawl survey, future analyses could explore spatial overlap and relative abundance trends to assess the extent to which *Anadara* spp. may be displacing or coexisting with native and commercially important species, as well as their impact on the overall biodiversity of Adriatic benthic communities. A targeted fishery could help mitigate these impacts by reducing *Anadara* spp. biomass and limiting its ecological dominance. However, this would require careful spatial planning to avoid unintended consequences for benthic communities, taking into account the invasive gear with which this species is currently harvested, i.e., the rapido [68] and the hydraulic dredge [69]. Considering both positive and negative effects of this potential fishery could bring to a scientifically based adaptive management approach that effectively addresses both conservation and fishery objectives.

Maintaining high densities of these species to support a fishery could potentially exacerbate their ecological footprint, including competition with native bivalves, modification of sediment characteristics, and shifts in trophic interactions (outcomes that, while not yet fully documented, are plausible given their biological traits and invasive history). Therefore, any management strategy must be grounded in rigorous ecological monitoring to accurately assess the impacts of these species, and supported by adaptive regulatory frameworks that can respond to emerging evidence. Overfishing *Anadara* spp. could lead to various levels of population decline, and our data provide key information to evaluate it. In line with the CPUE values, the high MSY values (especially in the northern Adriatic) indicated a robust population that can sustain, throughout the entire study area, very high fishing pressures up to 11486.2 tons per year. The data provided can serve as the basis for a management strategy, which can align with or exceed the MSY, depending on the adopted management approaches, with the aim of balancing ecological and economic needs [35]. According to Lovell and Stone [70], the economic impacts of aquatic invasive species can be substantial, and managing these species is essential to mitigate economic damage. Barbier [71] also emphasizes the necessity of sustainable management practices to balance ecological and economic interests. An integrated approach is therefore required, incorporating scientific assessments, monitoring programs, and adaptive management measures to properly regulate fishing pressure. As Buhle, Margolis, and Ruesink [72] highlight, managing invasive species in a cost-effective manner is crucial, and considering economic factors in management strategies is essential for long-term success.

From a fisheries perspective, these bivalves present a dual challenge. On the one hand, they may compete with native or commercially valuable species for space and resources; on the other, they could represent an emerging fishery resource if managed sustainably. Adaptive management strategies may include regulated harvesting, habitat monitoring, and stakeholder engagement to ensure ecological and economic viability. In this context, *A. kagoshimensis* and *A. transversa* appear to be promising candidates for exploitation, not only for direct human consumption but also for non-food applications such as animal feed, fertilisers, and biotechnological uses, avenues that are increasingly being explored for bivalve biomass due to their nutritional and biochemical properties [73].

This research provides data and analysis relevant to the implementation of the Marine Strategy Framework Directive (MSFD), particularly Descriptor 2 on NIS. By assessing the abundance and spatial distribution of *A. kagoshimensis* and *A. transversa*, the findings contribute to Criterion D2C2, which addresses the distribution of invasive species and their effects on native species. Furthermore, the discussion of potential habitat alteration and competition with native bivalves such as *Chamelea gallina* aligns with Criterion D2C3, which focuses on the extent to which invasive species adversely affect habitat types. These insights can support regional monitoring efforts and inform adaptive management strategies aimed at achieving Good Environmental Status (GES) under the MSFD.

5. Conclusions

This study offers a detailed examination of the distribution, abundance, and exploitable quantities, of two invasive bivalves, *Anadara kagoshimensis* and *A. transversa*, in the Adriatic Sea. These findings can be considered as key information for supporting management initiatives on these species, especially in the context of fishery, since both can be considered a nuisance and an underexploited source of proteins. Developing a commercial fishery of *Anadara* spp. in the Adriatic Sea could help mitigate ecological impacts and generate economic benefits for local communities. However, it requires careful planning and adaptive management to ensure sustainable exploitation and to avoid additional impacts on benthic communities resulting from increased trawling activity. We hope that our findings will contribute to the promotion of a well-managed commercial harvest of these bivalves, transforming them into valuable resources. This could support the development of a new fishery that mitigates the impacts of the invasion while simultaneously creating new economic opportunities.

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CRediT authorship contribution statement

Marina Chiappi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ernesto Azzurro:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Pierluigi Strafella:** Conceptualization, Supervision, Writing – review & editing. **Carmen Ferrà:** Formal analysis, Investigation, Methodology, Software, Visualization, Writing – review & editing. **Francesca Luzi:** Formal analysis, Investigation, Methodology, Software, Writing – review & editing. **Stefano Guicciardi:** Formal analysis, Investigation, Methodology, Software, Writing – review & editing. **Giorgio Mancinelli:** Writing – review & editing. **Alessio Bonaldo:** Writing – review & editing. **Antonina De Marco:** Writing – review & editing. **Beatrice Fracasso:** Writing – review & editing. **Sara Mancarella:** Writing – review & editing. **Chiara Roberta Girelli:** Writing – review & editing. **Francesco Paolo Fanizzi:** Writing – review & editing. **Giuseppe Scarcella:** Formal analysis, Investigation, Methodology, Software, Supervision, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2025.106889.

Data availability

Data and associated metadata used within this study are published under a CC BY 4.0 licence and available at https://doi.org/10.48372/ZS4D-EM32.

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