1 **Inferring abundance trends of key species from a highly**
2 **developed small-scale fishery off NE Atlantic**

3 Alexandre Alonso-Fernández^{1,*}, Jaime Otero¹, Rafael Bañón¹, José Manuel Campelos²,
4 Fernando Quintero², Jorge Ribó², Francisco Filgueira², Luisa Juncal², Fabio Lamas²,
5 Asunción Gancedo² and José Molaes^{2,3}

6 ¹*Instituto de Investigaciones Marinas (IIM-CSIC), Eduardo Cabello 6, 36208 Vigo*
7 *(Pontevedra), Spain*

8 ²*Servizo de Planificación, Consellería do Mar e Medio Rural, Xunta de Galicia, Rúa*
9 *dos Irmandiños s/n, 15701 Santiago de Compostela (A Coruña), Spain*

10 ³*Instituto Tecnolóxico Para o Control do Medio Mariño de Galicia (INTECMAR),*
11 *Xunta de Galicia, Peirao de Vilaxoán, s/n, 36611 Vilagarcía de Arousa (Pontevedra),*
12 *Spain*

13 *Corresponding author: Tel: (+34) 986 231930; Fax: (+34) 986 292762; e-mail:
14 alex@iim.csic.es

Abstract

Small-scale fisheries (SSFs) are large contributors to worldwide catches and local economies; however, SSFs have been historically under-attended in national and international policies. This work presents a standardization of catch-per-unit-of-effort data obtained from onboard observers for twenty commercial coastal species caught by the SSFs off the Galician coast from 2000 to 2016 using generalized linear mixed models. Operational, environmental, temporal and spatial data were included in the models as explanatory variables. The relative index of abundance for most species varied from year-to-year over the study period and between geographical areas (ICES 9.a and 8.c). Seasonal patterns, likely related to annual biological cycles, were found. Vessel size showed restricted significant effects in abundance estimates, and soak time of fishing operations revealed nonlinear responses of catch rates. Fishing at night or during daylight hours also have significant differences in catch rates that varied among species pointing to behavioural effects on catchability. Catch rates were often negatively related with depth as expected for species with a coastal distribution. Furthermore, seafloor type indicated species-specific habitat preferences, and sea surface temperature played a limited role in abundance estimations. The most common trend of species' abundance indices showed opposite patterns among geographical areas, suggesting that local conditions may have a significant influence on fluctuations not only at the species level, but also at the community level. Annual fishing effort in terms of operational vessels and working days for the main fishing gears operated by the SSF fleet showed an overall sign of decline. This study revealed a generalized lack of correlation between landings and abundance indices, thus landing data was considered, in general, a poor indicator of population status. The data presented increase the fishery knowledge of one of the most important European SSF fleets that ultimately would allow implementing

40 future assessment strategies. It also underpins the fact that fine scale spatial, and
41 temporal observer data, together with environmental and operational information, are
42 critical to infer suitable and unbiased abundance indices within a complex SSF context.

43 **Keywords:** dynamic factor analysis, glmmTMB, catch-per-unit-of-effort, generalized
44 linear mixed models, small-scale fishery, NE Atlantic

1. Introduction

Sustainable use of exploited marine species requires an appropriate estimation of population abundances including indices for those often-neglected stocks targeted by small-scale fisheries (SSFs). Overall, SSFs provide large amounts of catches (Chuenpagdee and Pauly, 2008). However, the lack of attention that these fleets have experienced historically is reflected in the misleading statistics reported by many countries to international bodies such as the Food and Agriculture Organization of the United Nations (FAO) precluding accurate assessments of the status of many fisheries elsewhere (e.g. Costello *et al.*, 2012; Pauly and Zeller, 2016). Nonetheless, nowadays it is widely recognized that SSFs play a major role in worldwide fish catches and food supplies and security. They, globally, provide employment to the largest number of fishers, as compared to industrial fisheries, and contribute to the development, growth and wellbeing of local economies, societies and cultures (Chuenpagdee and Pauly, 2008; Teh and Sumaila, 2013; Weeratunge *et al.*, 2014). However, despite its importance, SSFs have been traditionally under-attended and marginalized in national and international policies (Pauly, 2006). However, today's profile of SSFs have changed as recognized by its multifaceted contribution to social wellbeing in fishery-dependent coastal communities (Weeratunge *et al.*, 2014). Indeed, there are significant efforts to include them in the international agenda discussing and putting forward new measures to develop specific regimes and governance frameworks for this complex sector (McClanahan *et al.*, 2009; Kittinger *et al.*, 2013).

In general, this poor attention has been largely the case because most of the SSFs worldwide are not formally assessed, and this is of particular concern given that poorly understood fisheries seem to be in substantially worse shape than the relatively well-studied ones (Costello *et al.*, 2012). The lack of effective management in many fisheries

around the globe are mainly due to a lack of appropriate data which prevents the evaluation of the status and productivity of those fish stocks mostly in developing countries but also in industrialized ones. However, to overcome this deficiency, researchers have developed a suite of assessment and management tools to evaluate and operate these 'data-limited fisheries' (Le Quesne *et al.*, 2013) including co-management approaches (e.g. Gutierrez *et al.*, 2011), territorial use rights for fishing (e.g. Macho *et al.*, 2013), and many others (see Carruthers *et al.*, 2014 for a review).

Conventional assessment methods require basic species' biological knowledge (maturity, individual growth), annual catches, and a reliable trend in stock size. Yet, all these requirements are not always satisfied, thus, different approaches are frequently used to evaluate stock status, estimate overfishing thresholds and set catch limits (Carruthers *et al.*, 2014). Indices of abundance are crucial during the assessment procedure. Ideally, these indices must be based on fishery-independent surveys. However, scientific monitoring is not always available as is the case for most of the SSFs worldwide, so as for several industrial fisheries of particular relevance (e.g. pelagic sharks and tunas). In such cases, the construction of stock indices of abundance can be based on fishery-dependent data (Maunder and Punt, 2004). One of the most common sources of fishery-dependent data is catch and effort information obtained from fishery observers on-board commercial vessels or logbooks. These data are used to construct a standardized index of relative abundance with the objective of removing most of the annual variation not attributable to changes in abundance (Campbell, 2015). Ultimately, this index can be used in stock assessment models (e.g. Maunder, 2001; Maunder and Langley, 2004).

Standardizing techniques are multiple and steadily used as part of the assessment procedures for many stocks of typically large pelagic fish (e.g. Campbell, 2015). In

addition, standardization of catch and effort has been applied to several other demersal (walleye pollock, Battaile and Quinn II, 2004; cod, Brynjarsdóttir and Stefánsson, 2004) or small pelagic species (Japanese Spanish mackerel, Li *et al.*, 2015). Apart from assessment, standardization methods have been applied to tackle ecological questions. For instance, Baum *et al.* (2003) and Shepherd and Myers (2005) evaluated the status of many shark and small coastal elasmobranchs populations in the Northwest Atlantic and Gulf of Mexico, respectively. Moreover, Baum and Myers (2004) and Ward and Myers (2005) compared the catch rates of several pelagic species between two distinct time periods in the Gulf of Mexico and the Pacific Ocean, respectively. Additionally, other authors have used these tools to assess the influence of ocean conditions on the dynamics of catches per unit effort (e.g. Teo and Block, 2010). In summary, standardizing catch and effort data using information from fishery-dependent sources has been proved a useful tool when addressing ecological and/or assessment issues in data limited situations.

A great majority of SSFs tend to be concentrated in poor and developing countries (Chuenpagdee and Pauly, 2008). However, large artisanal fleets operate in industrialized countries too. In particular, in the European Union (EU) more than 80% of the fishing fleet is considered as small-scale. Several regions in the Atlantic and Mediterranean Sea show a highly socio-economic dependence on this small scale-fishing sector (Macfadyen *et al.*, 2011; Natale *et al.*, 2013). Within this context, Galicia (NW Spain) is one of the highest fishery-dependent communities in EU coastal waters (Natale *et al.*, 2013; Surís-Regueiro *et al.*, 2014). However, despite its great importance, comprehensive studies on the dynamics of the main commercial species targeted by the Galician SSFs are lacking or poorly addressed, thus, it is timely to understand better the fluctuations and status of the main exploited resources.

As commented above SSFs are now part of the international agenda (FAO, 2015) including the case of European coastal waters and its Common Fisheries Policy (Iborra, 2012). As such, there is a demand of increasing the knowledge on the dynamics of several species targeted by SSFs usually characterized by being poor in data (ICES, 2012). That would allow the future implementation of better assessment and management measures for these stocks. Therefore, the objective of this paper was to obtain indices of relative abundance for a number of species of commercial interest harvested by the multi-gear small-scale fishing fleet operating off the Galician coast (SW Europe). Catches and effort were modelled as a function of operational, spatial, temporal and environmental variables by means of fitting a series of generalized linear mixed models (GLMMs) to data collected by fishery observers. Standardized trends in relative abundance were estimated for the period 2000 to 2016 for a set of key commercially species including 15 fish and 5 invertebrates (3 cephalopods and 2 crustaceans) as an attempt to infer population trends that will serve for future implementation of more specific assessment and management practices for this group of species fished in southern European Atlantic coastal waters.

2. Material and Methods

2.1. Study area and Galician SSF

Galicia is an autonomous region of Spain located in the north-western corner of the Iberian Peninsula, between the river Eo (43° 32' N, 7° 01' W) and the river Miño (41° 50' N, 9° 40' W) comprising ICES Divisions 9.a and 8.c (Fig. 1). The Galician coast has a length of 1498 km, representing 19% of the Spanish coastline and is characterised by the presence of the “rías” that are tectonic estuaries penetrating the coast almost perpendicular to the coastline. These “rías” receive the main fresh water contribution at their heads, and the inner positive circulation and water exchange with the shelf are both affected by the continental runoff and coastal wind-driven upwelling. Galician waters are at the northern boundary of the Iberian-Canary Current upwelling system. Coastal winds at these latitudes (42° to 44° N) are seasonal; however, more than 70% of the total variability of coastal winds occurs during periods of less than 1 month (Álvarez-Salgado *et al.*, 2002).

The combination of the topographic features and coastal orientation with the oceanographic conditions makes Galician waters be very productive (Aristegui *et al.*, 2006) and able to support extensive coastal fisheries and shellfish harvesting (Surís-Regueiro and Santiago, 2014). Indeed, Galicia is one of the main fishing regions in Europe counting 4400 fishing vessels in 2018 of which 89% were registered as artisanal vessels (accessed on 15/03/2018; <https://www.pescadegalicia.gal/rexibuque/>). In 2015, the SSF fleet employed 5732 crew members, which represent 53.9% of the total fishers working in fishing vessels with a base harbour in Galicia. Fishers were organized in 63 fishers' guilds called “cofradías” distributed along the coastline. The direct turnover of the fishing activity developed by the SSF in Galicia was 92.1 million of euros in 2015

(<http://www.pescadegalicia.gal/gl/publicacions/ocupesca>). So far, several studies have analysed the Galician fisheries, though most of them have dealt with socio-economic and governance issues (e.g. Molares and Freire, 2003; Cambiè *et al.*, 2012; Macho *et al.*, 2013), or addressed specific biological or ecological topics (e.g. Otero *et al.*, 2008; Villegas-Ríos *et al.*, 2014; Alonso-Fernández *et al.*, 2017). However, there is a lack of studies dealing with the fluctuations in abundance of the main commercial species that could be used for implementing better management practices (Freire and García-Allut, 2000).

2.2. Small-scale fishery definition

Many different criteria exist to classify fishing sectors and specifically separate SSFs from large-scale industrial fisheries. However, this usually results in differing concepts among countries and regions within countries. For instance, the EU has tried to broadly harmonize the basis that characterise SSFs defining them essentially as fisheries carried out by vessels of less than 12 m and not using towed gears (Macfadyen *et al.*, 2011). Yet, other authors have expanded this definition by including other attributes of the fishery such as the operational range of activity (Natale *et al.*, 2015). In Galicia, small-scale fishing is formally defined as the fishery carried out by the registered vessels in the fleet called “artes menores” (minor fishing gears) in the National Census of the Operating Fishing Fleet. The current legislation is very clear and can be summarized as follows: this fleet is composed of fishing vessels up to 15 m length between perpendiculars or 18 m total length, a maximum of 50 gross registered tonnage (GRT) or 52 gross tonnage (GT), and up to 367 kW (Decree 15/2011, DOG N°31, 15/02/2011). Apart from this broad categorisation and in order to regulate the fishing effort, the fleet is further classified into seven GRT segments: type I (vessels <1.5 GRT), type II (1.50–2.49 GRT), type III (2.50–4.99 GRT), type IV (5–7.49 GRT), type V (7.50–9.99

GRT), type VI (10–19.99 GRT) and type VII (≥ 20 GRT). This segmentation is somehow an arbitrary categorization that has changed over the years (categorization was initially composed by only 4 groups) and is established for the SSF fleet as a whole. However, it does not necessarily mean that the current seven groups are represented in each fishing gear. The artisanal fleet is characterised for being a multi-gear and multi-species fishery, for having low to moderate levels of technology, and for mainly using passive gears such as gill nets, trammel nets, traps or hooks and lines. The fleet operates between the intertidal zone (under the administration of the regional government, Xunta de Galicia) and shallow oceanic grounds down to about 100 m depth and typically leaves and returns to port on the same day. These vessels target many valuable species sold in local markets and uses different fishing strategies during the year, which may depend on seasonal resources availability, market demand and regulations and legislation passed by the regional government in co-management with other stakeholders. Each vessel can license up to five types of fishing gears that might shift during the fishing season. By law, the definition of SSFs in this region excludes other components of the fleet whose fishing activity develops beyond internal waters though not far from the coast, thus being a state-level competence. These vessels might be labelled as small-scale or artisanal by other agencies or authors, for instance, purse seiners targeting small pelagics, or gillnetters (“volanteiros”) targeting hake (Tzanatos *et al.*, 2013). In this work, we will use the terms artisanal fishery and small-scale fishery as synonyms. In any case, the vessels’ operational characteristics of the SSF fleet in Galicia together with other socio-economic features (e.g. low technology and productivity, family-based companies, or local market selling) agree well with other definitions used elsewhere in Spain (e.g. Andalusia; Piniella *et al.*, 2007).

2.3. SSF monitoring and official data on landings and effort

To date, two main sources of information about stock performance are available for the species targeted in this study: i) official landings and fleet statistics compiled by the regional government, and ii) catch and effort data collected by on-board observers.

i) Official statistics: the regional government of Galicia through its department of maritime affairs (i.e. Consellería do Mar, Xunta de Galicia) is in charge of compiling data on landings directly from the auctions. This information was used to evaluate the importance of small-scale fisheries in the region and compare the standardized relative indices of abundance with the official landings for the studied species. Note however, that landings disaggregated by fishing sector, i.e. industrial vs artisanal, were only available from 2002 onwards and effort from 2004. Moreover, official statistics on landings for the species of the genera *Solea* and family *Rajidae* appear under a unique label (no species-specific records were available), thus, interpretation of global trends should be taken with caution for those species. In addition, the regional government compiles data on fleet statistics from the fishers' guilds. In particular, the number of operational vessels and working days per fishing gear. The number of operational vessels is the sum of those authorised vessels that have declared fishing activity with a given fishing gear at least one day in a year. The number of working days is the sum of days that every single operational vessel notifies any fishing activity with a particular fishing gear to the authorities. This information was used to evaluate the trends in effort for the Galician SSFs.

ii) SSF monitoring: the Galician government through its Technical Unit of Artisanal Fisheries (Unidade Técnica de Pesca de Baixura, UTPB, in Galician) has monitored the artisanal fleet since 1999. An on-board observer is assigned to fishing vessels randomly selected from this sector and covers the full set of multiple gears used in Galician waters and all along the geographical range (Fig. 1). In a single trip/day each

vessel usually performs several hauls. At each haul, observers record all basic operational data such as date, geographical position, fishing depth, gear type and size, soak time, and GRT (see Bañón *et al.*, 2006 for further details on the sampling procedure). Apart from the operational data, observers also record the number and weight of all retained and discarded taxa. During the first year of monitoring, 1999, the sampling protocol suffered from several changes, thus, we used data from 2000 onwards. The resultant database analysed in this study counts 48073 hauls performed by 1717 different vessels using 32 different gears from January 2000 until December 2016.

2.4. Studied species

The Galician SSF is characterised for being a multi-gear and multi-species fishery. As such, roughly, 50 species are targeted for commercial purposes by the artisanal fleet (López-Veiga, 1992), yet only a few species can be considered key taxa from an economic point of view (Freire and García-Allut, 2000; Surís-Regueiro and Santiago, 2014). Most species are caught by several gears, and only some taxa are the main objective of a specific fishery (e.g. common octopus, *Octopus vulgaris*, by the octopus trap fishery, see Bañón *et al.*, 2018). In this study, we have focused on 20 species including 15 fish, 2 crustaceans and 3 cephalopods (Table 1). These species are of interest for both the regional government of Galicia, which is in charge of the management issues within coastal waters where these species are primarily fished (Supplementary Table S1), and international bodies such as the International Council for the Exploration of the Sea (ICES). More specifically, within the set of species analysed here there are a number of taxa for which information has been requested by specific working groups (ICES, 2013) and/or included within the commercial populations used for the assessment of the Marine Strategy Framework Directive

(MSFD) Descriptor 3 to determine the overall status of the Northeast Atlantic Ocean region (EU, 2010) (Supplementary Table S1).

2.5. Environmental data

Environmental conditions can determine habitat preferences and, thus, influence catchability (e.g. Linløkken and Haugen, 2006). In this study, we have included in the models information on sea floor type based on traditional fishers' knowledge (Stephenson *et al.*, 2016). Three categories were considered in order to harmonize all the information gathered from the fishers during the on-board surveys: hard (rocky bottoms), mixed (mixture of rocky and soft bottoms) and soft (sand, mud, etc.) bottom types. Furthermore, to evaluate the role of thermal conditions as an indicator of habitat preference we compiled data on sea surface temperature (SST, in °C). Optimum interpolation SST data available at daily 0.25° latitude $\times$ 0.25° longitude grid resolution from a combination of satellite and in situ measurements (Reynolds *et al.*, 2007) were obtained from the NOAA Earth System Research Laboratory (<http://www.esrl.noaa.gov/psd/>) for the period 2000 to 2016. Each haul was assigned the SST data from the grid cell in which that haul falls in. At the latitude of our study site temperature shows marked seasonality. Therefore, in order to avoid confounding relationships and interpretations, SST was deseasonalized and detrended using generalized additive models before including it as a predictor in the models (Alonso-Fernández *et al.*, 2014).

2.6. Statistical analyses

A given species can be caught by a relatively large number of different fishing gears (Supplementary Figures S1–S7). Thus, before fitting any model, we selected the data for the most representative gear for each species in order to reduce sources of variation.

The selection of the fishing gear was the result of a balance among the following three criteria: i) proportion of hauls with zero catch (“the less the better”), ii) total number of individuals sampled (“the more the better”) (Supplementary Figures S8–S27), and iii) the spatio-temporal coverage (Supplementary Figure S28). The first and second criterion were used as proxies of gear catchability. Once selected the most representative gear for each species (Table 1), we assumed constant catchability by species/gear along the time series.

The standardization of catch rates is a common procedure within classical assessment routines of multiple stocks worldwide (Campbell, 2015). Multiple statistical modelling techniques have been steadily used including generalized linear models, as the most common method, but also generalized additive models, generalized linear mixed models, regression trees, artificial neural networks and others (Maunder and Punt, 2004; Thorson and Ward, 2013; Li *et al.*, 2015). Typically, when standardizing catch rates researchers have to deal with count data, that is, the number of fish caught per haul, tow, set, etc. This kind of data often include many zero-valued observations, being this fact particularly relevant for less abundant or by-catch species. A large presence of zero observations in fisheries can occur for many reasons (Maunder and Punt, 2004), and the non-consideration of this excess of zeroes might reduce the ability to detect relevant relationships and make inaccurate inferences (Potts and Elith, 2006). However, despite this is a common feature in fisheries data, zero-inflated models (ZIMs, Cameron and Trivedi, 1998), have been less used than other statistical tools in count models (but see Minami *et al.*, 2007; Brodziak and Walsh, 2013). Apart from zeroes, another concern when dealing with fishery-dependent data is that the sampling unit (i.e. haul, tow, or set) could be thought of as repeated measures if many hauls (or tows or sets) are made on the same fishing trip or by vessels that have been monitored

during several fishing trips across years. This might induce correlations among observations that may be accounted for and points to the fitting of mixed-effects models (Thorson and Minto, 2015). Therefore, generalized linear mixed models (GLMMs) are becoming more popular in recent times and more frequently used to estimate abundance indices for fishes (e.g. Baum and Blanchard, 2010; Thorson and Minto, 2015). In summary, ignoring zero-inflation can yield biased parameter estimates, and omitting random effects ignoring correlation may make statistical tests anti-conservative (Bolker *et al.*, 2009; Brooks *et al.*, 2017).

In this paper, we standardized the catch rate of each species (*sp*) by modelling the number of individuals caught (*N*) in each haul (*i*) using the following statistical modelling approach. Counts were standardized by means of fitting GLMMs and zero-inflated GLMMs to the observer's data. Zero-inflated models are mixture models where a binomial GLM is used to model the probability of measuring a zero, and the count process is modelled by a Poisson (ZIP) or negative binomial (ZINB) GLM. This implies that the processes that lead to zero observations can differ from those that lead to non-zero catches, a likely assumption in fisheries data (Maunder and Punt, 2004). We hypothesized here that the presence of substantially more zeroes might be caused by failing to record any catch, and were modelled as a function of depth of operation and/or sea floor type as the main descriptors determining bathymetric distribution and habitat preference, respectively. These type of zeroes are generally categorized as false zeroes (Martin *et al.*, 2005).

In each model the response variable was modelled as a function of explanatory variables assumed to influence catchability including: soak time (*T*), year (*YR*) and month (*M*) of operation, coastal zone (*ZN*), sea floor type (*SF*), haul depth (*DP*), sea surface temperature (*SST*), gross register tonnage (*GRT*), and proportion of soak time at

night (ST). YR and M were categorical variables with 17 and 12 levels, respectively; however, in the case of *Conger conger*, due to data limitations, M was replaced by season (SE) with only 4 levels (“Winter”, “Spring”, “Summer”, “Autumn”). ZN was included as a categorical variable dividing the Galician coast into the two ICES divisions 9.a and 8.c. SF was a categorical variable with three levels (“Hard”, “Mixed”, “Soft”), and DP and GRT were included as log-transformed continuous variables. SST anomaly was also added as continuous variable. Finally, ST was included in the model as a categorical variable with three levels (<25%, 25–75%, >75% indicating the percentage of soak time between dusk and dawn). Note that for one particular fishing gear, “Vetas” (gillnet), it exists a secondary fishing modality (“volantillas”) that, despite being very similar, it was included as a factor in the model (Fm, Fishing modality). One reasonable interaction was further included in the models when data were sufficient: YR by ZN interaction, which may capture different temporal trends for each ICES division. Only years with at least 10 sampled hauls were included (Table 1). A summary of the explanatory variables and distribution of data per fishing gear are available in Supplementary Table S2 and Figures S29–S36. To deal with likely nonlinearities in GRT, T and SST responses, e.g. a saturating effect due to long soak time or at large vessel sizes, we used two degree polynomial functions. Furthermore, vessel (*a*) and fishing trip within vessel (*b*) were included as nested random effects allowing for variation between vessels and between fishing trips within vessels. Random effects were assumed to be normally distributed with mean 0 and variances σ_a^2 and σ_b^2 . Before any model fitting, variance inflation factors (VIF) were calculated to detect collinearity issues (Zuur *et al.*, 2007). Calculation of VIFs revealed no signs of collinearity among explanatory variables with all values below a cut-off level of 3.

Fishing effort was included in the models as an offset. However, the measure of effort varied depending on the gear type used to standardize the catch rates of each species. In particular, for each haul i , the offset was equal to the gear size (S), i.e. the number of pieces deployed for gillnets and trammel nets, the number of hooks for longlines, or the number of traps for trap fishing. Furthermore, it is also a common practice to consider the duration of gear deployment as a metric of fishing effort for passive fishing gears (e.g. Baum and Myers, 2004). However, including soak time as part of the offset assumes a linear relationship between soak time and the probability of positive catch. However, it is known that gear saturation can exert a significant non-linear effect on catchability (Olin *et al.*, 2004; Ward *et al.*, 2004; Bacheler *et al.*, 2013). Therefore, as already mentioned, soak time was included in the models as a continuous explanatory variable (T in minutes, log transformed) using a polynomial function of order two.

The models were fitted using Template Model Builder (TMB) via maximum likelihood estimation and the Laplace approximation for handling random effects (Kristensen *et al.*, 2016) using the R package “glmmTMB” (Brooks *et al.*, 2017). The negative binomial can be parameterized differently regarding the dependence of the variance (σ^2) on the mean (μ): i) a variance that increases linearly with the mean (NB1); and ii) a variance that increases quadratically with the mean (NB2). Competing models (e.g. different distributions, Poisson vs Negative Binomial, and variance parameterization, NB1 vs NB2) were compared based on the Akaike Information Criterion (AIC) (Supplementary Tables S3–S23). Annual predictions of abundance per geographical zone for each species were obtained by keeping the offset at a reasonable constant value differing among fishing gears and the explanatory variables set at their

mean value or most representative level for categorical variables (Supplementary Table S24).

To further compare the performance of the index of abundance estimated for each of the studied species we calculated Spearman rank correlation coefficients between the annual predictions of abundance and the official SSF landings per zone for each species from 2007 onwards, when the level of uncertainty in the origin of the landings (industrial vs. SSF) is negligible. Finally, to evaluate the coherence of the species-specific temporal trends in relative abundance between regions we applied a Dynamic Factor Analysis (DFA, Zuur *et al.*, 2003a). DFA is a multivariate time-series analysis technique frequently used to detect common patterns in a set of time series (e.g. Zuur *et al.*, 2003b).

All analyses were performed with R language (R version 3.4.3, R Development Core Team, 2017) and using the packages “glmmTMB_0.2.0” (Brooks *et al.*, 2017), “MARSS_3.10.4” (Holmes *et al.*, 2012) and “ggplot2_2.2.1” (Wickham, 2009).

3. Results

3.1. Official landings and fishing effort of SSFs in Galicia

The contribution of the artisanal fleet to total landings in Galician fish markets varied among species, years and zones (Fig. 2 and 3). More specifically, from the beginning of the time series until 2006, a certain amount of landings was of unknown origin, that is, registered landings during those years were not assigned to any specific fishing sector (SSF or industrial) in both ICES 9.a (Fig. 2) or ICES 8.c (Fig. 3). This fact prevents an accurate evaluation of the evolution in SSF landings during the complete study period (2000–2016). Thus, hereafter, we only consider landings from 2007 onwards to study the main patterns in SSF landings in Galicia. Overall, official landings by the SSF fleet for the set of 20 species included in this study yielded an average of ~6230 tons per year, increasing from a total of ~5621 tons in 2007 to ~7171 tons in 2016. These numbers represent, on average 48.7% of the total landings of these 20 species (SSF plus industrial) in Galician fish markets.

O. vulgaris was the most important species for the SSF sector among the studied species with an average of ~2439 tons per year, by contrast European flounder was the less relevant with ~16 tons per year (Fig. 2 and 3 and Supplementary Figure S37). Regarding species such as *D. labrax*, *L. bergylta*, *S. rhombus*, *S. officinalis*, *O. vulgaris*, *M. brachydactyla* and *N. puber* the SSF landings represented more than 70% of the total landings; while *S. canicula* and *L. vulgaris* accounted for less than 10%. In Galicia, the general relative contribution of SSFs to total landings of the 20 species showed an increased from 40.1% to 69.7% in the ICES area 9.a, and from 43.5% to 58.4% in 8.c during the period 2007–2016 (Fig. 2, 3 and Supplementary Figure S37).

3.2. Standardized indices of abundance

Among the 20 fitted models, Poisson models revealed clear signs of overdispersion, indeed, a negative binomial distribution was more appropriate for 5 taxa, whereas a zero-inflated negative binomial distribution was more optimal for the other 15 species (Table 1 and Supplementary Tables S3–S23). Models including nested random effects, that is, vessel and fishing trip within vessel, were more optimal in all cases, and random effects were reasonably normally distributed in the final models (Supplementary Figures S38–S57).

The statistical significance of the explanatory variables varied across species (Table 2), though several common patterns can be outlined. The Year $\times$ Zone interaction term resulted significant in all species where data were sufficient to account for this effect (Supplementary Figures S38–S57). In general, the standardized index of relative abundance showed wide interannual fluctuations for all studied species (Fig. 4) with most taxa remaining relatively stable during the study period and in both zones. However, we found significant declines in relative abundance in ICES 8.c for *R. undulata* ($-10.2\% \text{ year}^{-1}$, 95% C.I.: -15.9 to -4.1), *P. pollachius* ($-4.1\% \text{ year}^{-1}$, 95% C.I.: -7.5 to -0.7) and *M. surmuletus* ($-2.2\% \text{ year}^{-1}$, 95% C.I.: -3.8 to -0.4) (Supplementary Figure S58a). In ICES 9.a significant decreasing trends in relative abundance occurred for *S. maximus* ($-7.1\% \text{ year}^{-1}$, 95% C.I.: -12.3 to -1.6), *S. rhombus* ($-6.6\% \text{ year}^{-1}$, 95% C.I.: -11.2 to -1.7), *M. brachydactyla* ($-5.8\% \text{ year}^{-1}$, 95% C.I.: -8.6 to -2.9), *T. luscus* ($-3.0\% \text{ year}^{-1}$, 95% C.I.: -5.3 to -0.6) and *R. undulata* ($-2.8\% \text{ year}^{-1}$, 95% C.I.: -4.9 to -0.7 C.I. 95%) (Supplementary Figure S58b). Positive trends were only present in ICES 8.c for *S. senegalensis* ($9.4\% \text{ year}^{-1}$, 95% C.I.: 1.9 to 17.5), and in ICES 9.a for *S. canicula* ($5.5\% \text{ year}^{-1}$, 95% C.I.: 1.25 to 10.0) (Supplementary Fig. S58). While relative abundance of *P. pollachius*, *M.*

surmuletus and *O. vulgaris* were consistently higher in ICES 8.c, and *T. luscus* in ICES 9.a, the rest of species experienced important fluctuations between the southern and northern areas during the study period (Supplementary Figure S59).

With the exception of *T. luscus*, *P. pollachius*, *D. sargus*, *S. canicula* and *R. undulata*, the models revealed significant intrannual differences in abundance (Fig. 5 and Supplementary Figures S38–S57). More specifically, we found consistent seasonal patterns with maximum catch rates during winter months for *M. surmuletus*, *S. officinalis*, *M. brachydactyla*, *P. flesus*, *S. solea* and *C. conger*. However, *L. bergylta*, *O. vulgaris* and *P. lascaris* reached maximum values during summer months. Species with closed fishing periods, i.e. *L. vulgaris* and *N. puber*, showed a decreasing pattern with maximum values at the beginning of the fishing season (Fig. 5).

Regarding the operational features, vessel size (GRT) showed contrasting effects among species and resulted statistically significant only for *P. pollachius*, *S. rhombus*, *P. lascaris*, *S. senegalensis* and *D. sargus* (Table 2 and Supplementary Figures S38–S57). In the case of soak time, this variable exerted a strong significant effect on catch rates for several species (i.e. *M. surmuletus*, *P. lascaris*, *S. officinalis*, *N. puber*, *O. vulgaris* and *C. conger*). However, in most cases the effect was negligible (Table 2 and Supplementary Figures S38–S57). The quadratic term in soak time was significant for several species (*M. surmuletus*, *P. lascaris*, *S. officinalis*, *N. puber*, *O. vulgaris* and *C. conger*) indicating a non-linear response of catch rates to the haul duration. Furthermore, catch rates at night-time were significantly higher for *C. conger*, and lower for *M. surmuletus*, *S. officinalis* and *O. vulgaris* (Table 2 and Supplementary Figures S38–S57).

Catch rates for most species varied significantly with depth of fishing operation (Table 2 and Supplementary Figures S38–S57). Overall, this relationship was negative with higher catch rates in shallower waters. However, *T. luscus*, *S. canicula* and *S. solea* showed higher catch rates at deeper locations (Table 2 and Supplementary Figures S38–S57). For those species modelled with a ZINB GLMM (Supplementary Table S3), depth resulted significant in the binomial part for most of them with the exception of *C. conger* and *L. vulgaris*. This effect suggested an increasing proportion of absence with depth for *P. pollachius*, *M. surmuletus*, *S. canicula*, *L. bergylta*, *R. undulata*, *S. officinalis* and *D. labrax*; and an increasing proportion of occurrence for *T. luscus*, *M. brachydactyla*, *S. maximus*, *S. rhombus* and *S. senegalensis*.

Regarding the environmental factors, seafloor type resulted particularly significant for those species associated to specific habitats. For instance, higher abundance of flatfishes (*S. maximus*, *S. solea*, *S. senegalensis*, *P. lascaris* and *P. flesus*), *R. undulata*, *S. officinalis*, *M. surmuletus* and *M. brachydactyla* occurred in soft bottoms. Similarly, rocky reef species such as *P. pollachius* and *L. bergylta*, but also *N. puber* and *O. vulgaris* showed high catch rates in hard bottoms (Table 2 and Supplementary Figures S38–S57). For those species modelled with a ZINB GLMM (Supplementary Table S3) seafloor resulted significant in the binomial part, with a higher proportion of absence in soft bottoms for *P. pollachius* and in hard bottoms for *S. rhombus* and *S. senegalensis*. In the case of sea surface temperature, the effect of this variable was negligible for the majority of the species being significantly positive related to abundance just for the cases of *M. brachydactyla*, *R. undulata*, *S. officinalis* and *O. vulgaris* (Table 2 and Supplementary Figures S38–S57).

3.3. Common trends of abundance indices and correlation with official statistics

491 The most common trend in abundance showed contrasting patterns over time
492 between ICES divisions (Fig. 6). In ICES division 8.c we found an increasing trend
493 from 2003 to 2011 followed by a slight decline up to 2016 (Fig. 6a). This trend was
494 mainly dominated by *S. senegalensis*, *P. lascaris*, *D. sargus* and *O. vulgaris* (Fig. 6b
495 and Supplementary Figure S60). In the case of ICES division 9.a, the trend showed a
496 declining pattern from 2001 onwards (Fig. 6c) with *S. rhombus*, *M. brachydactyla*, *S.*
497 *senegalensis*, *S. maximus* and *R. undulata* showing the higher associations with this
498 decreasing trend (Fig. 6d and Supplementary Figure S61).

499 In general, considering only reliable SSF statistics from 2007 onwards, landings
500 from the artisanal fleet did not show high correlations with the estimated indices of
501 abundance (Fig. 7). Only *O. vulgaris* in ICES 8.c and *P. flesus* and *M. surmuletus* in
502 ICES 9.a showed significant positive correlations (Fig. 7).

4. Discussion

4.1. SSFs management in Galicia and study constraints

Galicia is a region with strong ties to the sea and the fishing activity in particular (Pérez, 1996). This long-standing tradition with deep roots in history (Ferreira, 1998) has made the region extraordinarily dependent on the fisheries sector (Natale *et al.*, 2013; Surís-Regueiro and Santiago, 2014), which can reach up to 7% of a given zone's income and employment even in an urban area (e.g. Ría de Vigo; Surís-Regueiro *et al.*, 2014). Fisheries activities in Galicia are widely diverse, from aquaculture, especially on floating rafts for mussels and shellfishing on foot for intertidal bivalves, to sea fishing in distant waters and coastal fishing (Surís-Regueiro and Santiago, 2014). The latter sector counts a large fleet of small-sized vessels and, together with the shellfishing, constitutes the core of Galician fisheries (Eiroa del Río, 1986) and is of outstanding socio-economic importance (Garza-Gil and Amigo-Dobaño, 2008). The regional government has managed marine coastal resources of Galicia since 1981, mainly through the implementation of territorial user rights for fishing (e.g. bivalves, Macho *et al.*, 2013) or by means of developing specific exploitation plans in co-management with other stakeholders (e.g. goose barnacle, Molares and Freire, 2003; or common octopus, Bañón *et al.*, 2018). However, the multispecies and multigear idiosyncrasy of Galician SSFs in conjunction with numerous other reasons, including a lack of biological and ecological knowledge on the stocks, hampers the evaluation of population status and makes it difficult to develop appropriate management actions for most of the exploited resources in Galician waters, particularly for fish species. Indeed, some authors suggest that specific management for the artisanal sector and the resources they exploit is deficient and has led to multiple failures (Freire and García-Allut, 2000). In recent years, the government, through its department of maritime affairs (i.e. Consellería do

Mar, Xunta de Galicia), has made an effort to revert this situation and has developed a system to compile basic information required to evaluate the performance of Galician fisheries and to infer the species status. With this information in hand, we provide new insights for a group of data-poor species exploited by an important artisanal fleet in southern Atlantic European waters.

The majority of global reported fishery catch has been subjected to some sort of stock assessment; however, still a 22% remains unassessed with the small-scale fishery sector being a key component of this percentage (Costello *et al.*, 2016; Rudd and Branch, 2017). This is of particular concern because small-unassessed fisheries seem to be in substantially worse condition than their assessed counterparts especially in developing countries but also in industrialized ones (Costello *et al.*, 2012). Therefore, there is a pressing need to provide information about the stock status for small artisanal fisheries that are of great socioeconomic importance for coastal areas including European waters (EU, 2013). One of the difficulties associated to small-scale fisheries and data-poor fisheries in general is the lack of survey data. When these data are not available, estimation of population abundances is notoriously difficult and assessment methods and management actions are strongly based on catches using a wide range of methods specifically designed for data-limited situations (Carruthers *et al.*, 2014; Chrysafi and Kuparinen, 2016; Froese *et al.*, 2017). Apart from surveys, information recorded by on-board observers is frequently used to obtain indices of abundance to be further integrated into stock assessment models (e.g. Maunder and Langley, 2004). This is a common practice in large fisheries (e.g. Campbell, 2015) though rare in small-scale fisheries. Notwithstanding, analyses of catch rates obtained from observers are subjected to several constraints despite estimations from fisheries-dependent data are comparable to catch rates (e.g. Bourdaud *et al.*, 2017) or habitat usage (e.g. Pennino *et*

al., 2016) obtained from surveys. Among the limitations it must be pointed out that, the fishing activity is non-randomly spatially distributed. Moreover, in the case of the Galician SSF given its huge size and multigear nature, observers can only cover a small portion of the fleet. On average, for the fishing gears analysed in this study, the observers went on-board at least once per year in roughly 7% of the operational vessels, ranging from ~4% (“Nasa nécora e camarón”, crustacean trap) to ~14% (“Boliche”, boat seine). Additionally, with the exception of the common octopus and the velvet swimming crab, there is not a specific fishery targeting each of the species analysed here, and catch rates for those species with low sampling representativeness could be influenced by fishing trips with elevated number of zeroes or hauls with exceptional catches. To alleviate the potential biases ascribed to these facts, we selected the gear that best “samples” each taxa, and standardized the catch and effort by means of fitting zero-inflated negative binomial models to deal with the excess of zero observations and avoid inaccurate inferences, and included a random structure in the models to account for other unknown sources of variation (Maunder and Punt, 2004). One further potential constraint would be the problem of unfished cells/strata that characterized fisheries dependent data (Walters 2003). However, in our particular case this does not seem to be a particular issue since the fishing effort distribution (and sampling) remained relatively stable along the study period, and, in general, the fishing activity covers almost the whole area of distribution of the targeted coastal populations. Finally, other potential source of variability may be associated to the spatial distribution of the species. Geostatistical models have been recently developed in search for more precise abundance estimators and overall better model performance (Thorson *et al.*, 2015). However, we opted here for a fixed Year $\times$ Zone interaction effect because this

treatment of space and time suffices to cover our objective of obtaining a time series of relative abundance for the two regions of interest.

4.2. Annual and seasonal fluctuations in abundance

In general, predicted abundance showed remarkable year-to-year fluctuations for most species with a rough stability over the 17-year period in most cases. However, some taxa showed signs of significant decline of different strength (e.g. surmullet, pollack and undulate ray in 8.c; and undulate ray, pouting, Atlantic spinous spider crab, brill and turbot in 9.a). By contrast, other species increased their catch rates during the study period (e.g. Senegalese sole in ICES 8.c and lesser spotted dogfish in ICES 9.a). Overall, we found two main opposite trends. While in the northern region, ICES division 8.c, the most common trend extracted by the DFA showed an increment over time until 2011; in the south, ICES division 9.a, it was observed a relatively continuous decline from 2001 onwards. The species that drove these changes also differed among geographical areas suggesting that local conditions may have a significant influence on fluctuations not only at the species level, but at the community level too. Using fishery-independent data, Punzón et al. (2016) showed generalized increases in the frequency of occurrence and abundance for the majority of species in the demersal fish community along the NW Spain shelf over the period 1983–2010 (e.g. pouting, European conger, surmullet, common sole or lesser spotted dogfish), and associated those trends to an increase in sea temperature. Other authors working with different data sets have suggested that coastal rocky reef fishes in this region have decreased dramatically since early 1950s. In particular, Pita and Freire (2014), using data from recreational spearfishing competitions, suggested that commercial overfishing was responsible for this decline. However, it is unclear how the skills or tactics of each spear fisher, and/or environmental conditions (e.g. visibility) were accounted for in this study, complicating

a direct comparison with our results. For instance, their data seem to show an increase in relative catch probabilities of ballan wrasse over the last decades contrasting with our stable estimates of abundance for this species. Apart from these two studies, little is known about the status of the populations in our area of study. Nevertheless, we should take the obtained trends with caution given the short length of the time series, which prevents a contrast with the period of highest reported landings dated back in the 1960s or with the times preceding the full development of the coastal fishery. Thus, our results cannot then corroborate the view stated by other authors that using catch reconstructions (Villasante *et al.*, 2015) or recreational spear fishing data (Pita and Freire, 2014) have suggested that coastal resources in Galician waters are experiencing worrisome declining patterns caused by overfishing. We might stress then that the trends in abundance depicted here should therefore serve as a reference point for monitoring the evolution of the fishery status and the development of future management strategies in search for the long-term sustainability of important resources for the Galician artisanal sector.

Apart from the annual trends, catch rates showed seasonal patterns that varied in shape depending on the species. These patterns might respond to annual biological cycles (e.g. reproduction, feeding), to species' population dynamics (e.g. recruitment, migration), or even to fishing strategies. For instance, lower catch rates for ballan wrasse occurred in late autumn and early winter coinciding with the spawning season and associated reduced activity pattern of this species during that period (Villegas-Ríos *et al.*, 2014). On the other hand, relative abundance of pollack reached maximum values in March. Recruitment pulses of juvenile individuals as suggested in previous analyses (Alonso-Fernández *et al.*, 2014) would cause this peak. Similarly, catch rates of common octopus showed strong seasonality with a maximum in July corresponding to

the opening of the fishing season and the recruitment of small specimens to the fishery (Bañón *et al.* 2006; Alonso-Fernández *et al.*, 2017). Minimum values occurred in late spring and early summer due to the reproductive cycle and breeding behaviour (Otero *et al.*, 2007; Garci *et al.*, 2016; Alonso-Fernández *et al.*, 2017). Furthermore, the seasonality in catch rates of Atlantic spinous spider crab agreed with previous estimates in the area using beam trawls and traps (Corgos and Freire, 2007). However, the sharp increase during early winter, just at the beginning of the fishing season for this species, could be ascribed to changes in fishing strategies and target species. Overall, our results indicate that the spatio-temporal dimension of the species' life history has a key role in shaping catchability and/or availability and thus affects the estimates of abundance as shown by other authors (Ziegler *et al.*, 2003; Wilberg *et al.*, 2009; Villegas-Ríos *et al.*, 2014).

4.3. Operational and environmental effects on abundance

Operational descriptors of vessel characteristics are frequently used as explanatory variables in standardizing models. For instance, García-Rodríguez *et al.* (2006) showed that catch rates for *Mullus sp.*, *Spardiade* and hake increased with boat length in SSFs operating in the Gulf of Alicante (SE Spain). In our models, vessel size exerted a relatively small effect given that only four out of the 20 species analysed showed a significant relationship with GRT. We found lower abundances of pollack and brill at middle-sized vessel, and catch rates of Senegalese sole and white seabream decreased and increased with GRT, respectively. Therefore, we suggest that relationships with GRT may respond more to different fishing strategies and target species by vessel category rather than fishing efficiency alone; and/or the random effects (vessel and fishing trip within vessel) capture the effect on the response variable at least in part. Apart from tonnage, we accounted for other two measures of effort: gear size and soak

time. Both variables are generally included in the offset term (Baum and Myers, 2004; Ward and Myers, 2005). However, previous works have shown that behavioural interactions in and around passive fishing gears may strongly influence catch rates of target species, for instance inducing gear saturation (Ward *et al.*, 2004; Rodgveller *et al.*, 2008; Li *et al.*, 2011; Bacheler *et al.*, 2013). Thus, catch rates could be biased if average soak time have varied significantly along the time series. To avoid this effect, we treated soak time as an explanatory variable and found species-specific differences in this relationship. Overall, soak time exerted a positive non-linear effect on catch rates suggesting certain gear saturation and/or catch losses for long-lasting hauls particularly in traps catching velvet swimming crab and common octopus. Nonetheless, evaluating the effect of soak time for each species and fishing gear requires further experimental procedures with fishery-independent surveys, which controls other factors that affect yields (Ye and Dennis, 2009).

Fish tend to behave differently in relation to light conditions displaying clear circadian behavioural patterns (Villegas-Ríos *et al.*, 2013; Alós *et al.*, 2017). Thus, it has been suggested that timing of operations could affect catch rates in passive gears likely induced by behavioural patterns as shown for longlines (Ward *et al.*, 2004). The present study found a significant effect of the proportion of nocturnal soak time in specific cases. For instance, we found higher catch rates of European conger during nighttime. This is a carnivore species that leaves its refuge at dusk or during the night to search for food (Saldanha *et al.*, 1995; Pita and Freire, 2011) thus, being more prone to be captured by baited passive fishing gears. By contrast, surmullet was significantly more abundant during daytime, which agrees well with previous observations in the Mediterranean Sea (Azzurro *et al.*, 2007). Catch rates of common cuttlefish and common octopus were higher during daytime; however, circadian rhythms for those

species are more complex. In particular, on the one hand, common cuttlefish in captivity showed different patterns across seasons with clear activity peaks at sunset during summer, while in winter (when we found maximum seasonal catch rates) the higher levels of activity occurred during the afternoon (Oliveira *et al.*, 2017). On the other hand, Meisel *et al.* (2003) found quite a plastic behaviour for common octopus in relation to its circadian rhythms. In experimental conditions though, there was a diurnal activity for this species concurring with our results. Consequently, diel variation in the catchability may influence the reliability of abundance indices (Michalsen *et al.*, 1996; Petrakis *et al.*, 2001), therefore, fish behaviour should be accounted for in order to reduce bias and improve abundance estimates.

Depth of operation is another variable that can affect catch rates likely related to species-specific bathymetric distributions, but also to ontogenic movements with young and adult individuals presenting differing water depth affinities. For instance, the relative abundance of pollack was lower and with higher prevalence of zero catches in deeper operations. Body size of pollack in the area tends to show a spatial gradient where smaller fish used to be associated with inshore waters (Alonso-Fernández *et al.*, 2014). Indeed, most of the species showed a negative correlation with depth, agreeing with their coastal distribution. However, for lesser spotted dogfish the relationship was positive with more relative abundance at deeper waters (down to 150 m). This result agrees with Rodríguez-Cabello *et al.* (2004) that reported maximum abundances in the Cantabrian Sea at depths from 100 to 300 m. Complementary, seafloor type information provided by the fishers revealed that relative abundance had a species-specific relationship with bottom substrate. For instance, catch rates of pollack and ballan wrasse were higher in hard sea bottom agreeing with the known feeding strategy of solitary adult pollack in the wild, which tends to use kelp forests in rocky reefs for

covering (Sarno *et al.*, 1994), or the ballan wrasse inhabiting rocky reefs and kelp beds where they mostly feed on small invertebrates (Figueiredo *et al.*, 2005). As expected, flatfish species were associated (higher index of abundance) to soft bottom substrates (Kottelat and Freyhof, 2007). Other environmental conditions such as temperature are commonly considered in standardization models as indicators for habitat preferences (e.g. Brodziak and Walsh, 2013). This is especially relevant when modelling catch rates of large pelagic migratory species, which might be particularly susceptible to changes in ocean conditions (e.g. Teo and Block, 2010). Sea temperature may also influence the spatial distribution of fish species across a landscape or affect fish activity and hence catchability as suggested for passive gears (e.g. Claireaux *et al.*, 1995; Claireaux *et al.*, 2006). This water temperature effect on catchability would be species-specific (Linløkken and Haugen, 2006; Olin *et al.*, 2016). However, in our models, SST did not show a significant effect on catch rates for most of the species studied here, and only in a few cases (i.e. Atlantic spinous spider crab, undulate ray, common cuttlefish and common octopus) this parameter was positively related to abundance. This suggests that the species may not respond immediately to local environmental conditions and species-specific thermal physiological limits may determine the particular response for each of the species. Furthermore, the SST data used in this study could have a too coarse resolution to detect temperature signals. Nonetheless, the small daily SST effect does not exclude a temperature (or other environmental factor such as the upwelling strength or salinity) influence on abundance at larger temporal scales.

4.4. Trends in effort and landings in the Galician SSFs

Global fishing pressure has steadily risen since 1970s leading to an increase in fish production and posing multiple questions such as which impact this raise in effort and capacity has on marine ecosystems, or which would be the level of effort

underestimation given the countries misreporting (Anticamara *et al.*, 2011). Accurate measures of fishing effort are necessary, among others, to facilitate the assessment and management of marine resources, to monitor the capacity of the fleets, or to interpret the fluctuations in the catch and evaluate the status of the fisheries (Watson *et al.*, 2013). To achieve these aims, recent studies have compiled worldwide data and provided point-estimates and associated uncertainty of global fishing capacity and effort identifying regional differences mostly between developed and developing or undeveloped countries (Bell *et al.*, 2017). However, these global estimates have limitations and gaps probably derived from the quantity and quality of the data that, for instance, may prevent from developing fine-scale spatio-temporal analyses of a particular fishery or fishing sector. This can be even more prevalent in SSFs. The small-scale fleet size and production associated to this sector seems to be in decline since 2000 in many European countries and particularly in Spain (Macfadyen *et al.*, 2011; Lloret *et al.*, In press), though this fact differs among geographical areas. While Gómez *et al.* (2006) showed a decline in Mediterranean coastal areas, García-Rodríguez *et al.* (2006) showed an annual stability in landings in SE Spanish waters. Regarding Galician fisheries, the Spanish national fleet with por of origin in the Galician coast, both artisanal and industrial, has declined by ~20% from 2004 to 2016 (from 5300 to 4527 vessels). However, the relative reduction in SSF vessels was considerably lower (~19%, from 4867 to 3930 vessels) as compared to the industrial counterpart (trawlers decreased by ~38% from 108 to 67 vessels) (<http://www.pescadegalicia.gal/gl/publicacions>). Furthermore, we have observed a steadily decline in fishing effort (number of operational vessels and working days) for the main artisanal gears, however, this reduction was not directly reflected in the landings. In parallel with this, the contribution of SSFs to the total amount of landings in local fish markets of Galicia for

the analysed resources has increased. This finding could be the result of a decrease of the industrial fishing activity and/or an improvement of the statistics by the authorities. Indeed, official statistics in Galicia reveal a clear improvement of the data collection, which nowadays is correctly assigning almost 100% of reported landings to each fishing sector, as revealed by the decrease of the percentage of landings without traceability, i.e. industrial or artisanal. Thus, based on our results, catch rate analyses should be carried out by region and sector to properly estimate the relative contribution of SSF to the commercial fishing activities in the EU. For instance, the present analysis shows that some resources such as common octopus, velvet swimming crab, common cuttlefish and Atlantic spinous spider crab, among the invertebrate species and, ballan wrasse, European sea bass and brill, among the fish species, are basically exploited by the artisanal sector, while the industrial fishery plays a minor role. Obviating such information in these type of studies may lead to underestimate the impact of SSFs in stocks, fishing activities and the contribution to the coastal community development in a particular geographical area.

Our study revealed a generalized lack of correlation between official landings and the estimated relative indices of abundance. This could be attributed to two main facts. First, we selected the most representative fishing gear for each species to develop the standardizing models. However, the official data on landings correspond to the whole multigear SSF fleet without any differentiation among gears, thus probably resulting in an important source of bias to establish direct correlations. Moreover, previous studies have provided evidences of misreporting in Galician fisheries, for instance for common octopus (Bañón *et al.*, 2018), and those levels may vary interannually resulting in a mismatch between reported landings and abundance indices.

776 Therefore, catch/landing data in the case of Galician SSFs would be a poor indicator of
777 population status, and may lead to misinterpretations of population trends.

5. Conclusions

We successfully applied recently developed statistical tools (GLMMs fitted with TMB) to infer the relative abundance of coastal species caught by a SSF in southern European waters accounting for most of the intrinsic complexities ascribed to artisanal fisheries. Using on-board observers catch and effort data we found that temporal trends in relative abundance were species-specific; however, a multivariate analysis revealed an overall decreasing and increasing trend in southern and northern waters, respectively, suggesting some degree of geographical variation at the community level. Seasonal patterns in relative abundance were common for most of the species likely associated to species biological cycles that ultimately affect catchability. Furthermore, fishing operational variables such as vessel size and soak time, and environmental variables such as seafloor type or depth were found to have remarkable effects on catch rates. Finally, we found a pervasive lack of correlation between official landings and the estimated relative indices of abundance. Therefore, the data presented here should serve to increase the general fishery knowledge and to develop assessment models that ultimately would allow implementing future management plans for one of the most important European SSF fleets.

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1153 **Tables**

1154 **Table 1.** Summary information for the set of species of the Galician coast (NE Atlantic) analysed including the selected gear for each species,
1155 sampling details and statistical model type. N = number of individuals; GLMM = generalized linear mixed model; ZINB = zero inflated negative
1156 binomial; NB = negative binomial.¹ Surface; ² Bottom.

Common name	Scientific name	Gear	Gear type	Years	Vessels	Trips	Hauls	N	Model type
Pouting	<i>Trisopterus luscus</i>	Veta	Gill net	2000-2016	276	824	1911	108954	ZINB GLMM
Pollack	<i>Pollachius pollachius</i>	Veta	Gill net	2000-2016	276	824	1911	10362	ZINB GLMM
Surmullet	<i>Mullus surmuletus</i>	Veta	Gill net	2000-2016	276	824	1911	15520	ZINB GLMM
European sea bass	<i>Dicentrarchus labrax</i>	Palangrillo ¹	Longline ¹	2002-2016	49	206	1018	3100	ZINB GLMM
European conger	<i>Conger conger</i>	Palangrillo ²	Longline ²	2005-2016	56	125	311	6800	ZINB GLMM
Ballan wrasse	<i>Labrus bergylta</i>	Miño	Trammel net	2000-2016	417	1352	4479	14066	ZINB GLMM
White sea bream	<i>Diplodus sargus</i>	Miño	Trammel net	2000-2016	417	1352	4479	1081	GLMM NB
Turbot	<i>Scophthalmus maximus</i>	Miño	Trammel net	2000-2016	417	1352	4479	688	ZINB GLMM
Brill	<i>Scophthalmus rhombus</i>	Miño	Trammel net	2000-2016	417	1352	4479	875	ZINB GLMM
Common sole	<i>Solea solea</i>	Miño	Trammel net	2000-2016	417	1352	4479	4465	GLMM NB
Senegalese sole	<i>Solea senegalensis</i>	Miño	Trammel net	2000-2016	417	1352	4479	2083	ZINB GLMM
Sand sole	<i>Pegusa lascaris</i>	Miño	Trammel net	2000-2016	417	1352	4479	6162	GLMM NB
European flounder	<i>Platichthys flesus</i>	Trasmallo	Trammel net	2000-2016	305	1116	3389	1725	GLMM NB
Lesser spotted dogfish	<i>Scyliorhinus canicula</i>	Veta	Gill net	2000-2016	276	1911	15520	5715	ZINB GLMM
Undulate ray	<i>Raja undulata</i>	Miño	Trammel net	2000-2016	417	1352	4479	1062	ZINB GLMM
Common octopus	<i>Octopus vulgaris</i>	Nasa pulpo	Trap	2000-2016	566	1986	13467	141963	ZINB GLMM
European squid	<i>Loligo vulgaris</i>	Boliche	Boat seine	2000-2016	95	276	1568	64117	ZINB GLMM
Common cuttlefish	<i>Sepia officinalis</i>	Trasmallo	Trammel net	2000-2016	305	1116	3389	24101	ZINB GLMM
Atlantic spinous spider crab	<i>Maja brachydactyla</i>	Miño	Trammel net	2000-2016	417	1352	4479	22932	ZINB GLMM
Velvet swimming crab	<i>Necora puber</i>	Nasa nécora	Trap	2001-2016	267	781	4928	78435	GLMM NB

1158 **Table 2.** Summary table of the fitted models to each species of the Galician coast (NE Atlantic) showing the statistical significance for each
1159 covariate (i.e. fixed effects) included in the final formulation based on the Wald test: * < 0.05; ** < 0.005; *** < 0.0005, otherwise non-
1160 significant. “NA” indicates that a given variable was not included in the final model. “+” indicates that the relationship was positive, whereas “–”
1161 indicates that the relationship was negative. Shaded cells indicate significant coefficient.

Species	Fm	GRT	GRT ²	T	T ²	DP	SST	SST ²	SF (mixed)	SF (soft)	ST (25-75%)	ST (>75%)
<i>T. luscus</i>	- (***)	-	-	+	-	+ (***)	+	+	+	+	+ (*)	+
<i>P. pollachius</i>	+	- (*)	+ (**)	+	-	- (***)	+	+	- (***)	- (***)	-	-
<i>M. surmuletus</i>	- (**)	-	-	+ (*)	- (*)	- (***)	+	+	+ (***)	+ (*)	- (*)	- (*)
<i>D. labrax</i>	NA	+	-	-	+	+	+	-	NA	NA	+	-
<i>C. conger</i>	NA	-	+	+ (**)	- (*)	-	-	-	-	- (***)	+ (*)	+ (*)
<i>L. bergylta</i>	NA	+	-	+	-	- (***)	-	+	- (***)	- (***)	-	-
<i>D. sargus</i>	NA	+ (*)	-	-	+	- (***)	-	-	+	- (***)	-	-
<i>S. maximus</i>	NA	+	+	+	-	- (***)	+	-	+ (***)	+ (***)	+	+
<i>S. rhombus</i>	NA	- (*)	+ (*)	+	-	-	+	+	-	+	+	+
<i>S. solea</i>	NA	-	+	+	-	+ (***)	-	+	+ (***)	+ (***)	+	+
<i>S. senegalensis</i>	NA	+	- (*)	+	-	- (***)	+	+	+	+ (***)	+	+
<i>P. lascaris</i>	NA	-	+	+ (**)	- (**)	+	-	+ (*)	+ (***)	+ (***)	+	+
<i>P. flesus</i>	NA	+	-	+	-	- (***)	+	+	+ (**)	+ (***)	- (*)	-
<i>S. canicula</i>	-	-	+	-	+	+ (**)	-	+	+	+	+ (*)	+
<i>R. undulata</i>	NA	-	+	-	+	- (***)	+ (*)	+ (*)	+ (***)	+ (***)	-	-
<i>O. vulgaris</i>	NA	+	-	+ (***)	- (***)	- (***)	+ (***)	-	- (***)	- (***)	- (***)	- (***)
<i>L. vulgaris</i>	NA	-	+	+	-	-	+	-	NA	NA	NA	NA
<i>S. officinalis</i>	NA	-	-	+ (*)	- (*)	- (***)	+ (***)	+	+ (**)	+ (***)	- (**)	- (**)
<i>M. brachydactyla</i>	NA	-	-	+	-	- (***)	+ (***)	+	+	+ (***)	-	+
<i>N. puber</i>	NA	+	-	+ (***)	- (***)	- (***)	+	-	- (*)	- (***)	-	+

Figure captions

Fig. 1. Map of the study area (Galician coast, NE Atlantic) showing the distribution of all analysed hauls during the study period separated according to the two ICES divisions (orange dots 9.a and light blue dots 8.c). A detailed distribution of hauls per fishing gear is provided in Supplementary Figure S28.

Fig. 2. Time series of landings in Galician (NE Atlantic) fishing ports located in ICES division 9.a. Note that *Solea solea* and *Solea senegalensis* and the different species of *Raja* sp. were not identified at the species level. Colour gradient, from dark blue to light blue, represents landings corresponding to: i) the SSF only; ii) the SSF + landings of unknown origin, and iii) total landings (SSF + uncertain + industrial).

Fig. 3. Time series of landings in Galician (NE Atlantic) fishing ports located in ICES division 8.c. Note that *Solea solea* and *Solea senegalensis* and the different species of *Raja* spp. were not identified at the species level. Colour gradient, from dark blue to light blue, represents landings corresponding to: i) the SSF only; ii) the SSF + landings of unknown origin, and iii) total landings (SSF + uncertain + industrial).

Fig. 4. Time series of the estimated indices of abundance for the 20 species analysed from 2000 to 2016 in the Galician coast (NE Atlantic). Light blue line indicates ICES division 8.c, and the orange line shows ICES division 9.a. Shaded areas represent 95% confidence intervals (uncertainty in the random effects was ignored). Values for all explanatory variables used for predictions for each species' model and units of the abundance indices are shown in Supplementary Table S24.

Fig. 5. Estimated (± 95 C.I.) monthly variation in abundance for the 20 species analysed in the Galician coast (NE Atlantic) (uncertainty in the random effects was ignored). The fixed values for all explanatory variables used for predictions for each species' model

and units of the abundance indices are shown in Supplementary Table S24. Note also that for *C. conger* we used season instead of months (Supplementary Table S2).

Fig. 6. Dynamic factor analysis (DFA) of the estimated indices of abundance for the whole set of species studied in the two regions of the Galician coast (NE Atlantic): a) common trend in ICES division 8.c; b) loadings by each species on the common trend in ICES division 8.c; c) common trend in ICES division 9.a; and d) loadings by each species on the common trend in ICES division 9.a.

Fig. 7. Spearman rank correlation coefficient between the abundance indices and the official landings corresponding to the small-scale fisheries of the Galician coast (NE Atlantic) from 2007 onwards in a) ICES division 8.c; and b) ICES division 9.a. Black dots indicate significant correlations ($\alpha=0.05$).

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