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First Maximum Sustainable Yield advice for the *Nephrops norvegicus* stocks of the Northwest Iberian coast using stochastic Surplus Production model in Continuous Time (SPiCT)

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The assessment of the status of fisheries resources is pivotal due to the importance of marine resources in global food security and to halt the ongoing decline in marine biodiversity. Norway lobster (*Nephrops norvegicus*) is one of the most valuable resources in the Northeast Atlantic. However, overfishing has caused the decline of several *Nephrops* stocks over the last decades, particularly in the *Nephrops* Functional Units (FUs) 25 (NW Spain), 26-27 (NW Spain and North Portugal) and 31 (Cantabrian Sea, North Spain). Since 2003, the information provided by the very low level of landings and fishing effort of these three stocks was insufficient to carry out an adequate analytical assessment, so the base of the assessment has been the trends from commercial catch per unit effort (CPUE). The objective of this study was to carry out the first assessment of these three stocks with an analytical MSY-based model. A review of the available data was made and the stochastic Surplus Production Model in Continuous Time (SPiCT) was fitted for each FU. The results indicate an extremely low biomass for FUs 25 and 26-27 since the mid-nineties well below the reference points. For FU 31, on the other hand, estimated biomass is larger. Our findings also identified long-term temporal and spatial changes in the population dynamic of *Nephrops* in the Northwest Iberian coast. The results were compare with those obtained in the same stocks with other data-limited methods. Also the role of abiotic factors on the observed dynamic of the stocks was explored. The results of this study are not only relevant for the sustainable exploitation of Norway lobster stocks off the Northwest Iberian coast but provide valuable insights into the suitability and limitations of production models for the assessment of crustacean stocks in general.

KEYWORDS

fisheries management, stock assessment, Norway lobster, North Galicia, West Galicia and North Portugal, Cantabrian Sea

1 Introduction

There is evidence that the world is moving in the wrong direction, away from the Sustainable Development Goals (SDGs) of ending hunger, food insecurity and malnutrition by 2030, the year until which the SDGs are supposed to be realized (United Nations (UN), 2022). Despite significant previous progress, the percentage of people affected by hunger globally has increased since 2017 (FAO, 2022, UN, 2022). Marine resources are widely recognized for their key role in food security and nutrition, not just as a source of protein, but also as a unique and extremely diverse provider of essential omega-3 fatty acids and bioavailable micronutrients besides being a key part of the marine ecosystem. Global fisheries production will play an increasingly important role in providing food and nutrition in the future, but fishery resources continue to decline due to overfishing, pollution, poor management and other factors (FAO, 2022). In this context, it is necessary to ensure fisheries sustainability through improved resource management.

At the same time, marine biodiversity has been declining in the last decades (FAO, 2022, McQuatters-Gollop et al., 2022). For instance, the Northeast Atlantic shows a widespread degradation in marine ecosystems and biodiversity, particularly for benthic habitats and fish in some regions (McQuatters-Gollop et al., 2022). Therefore, the European Union adopted the Marine Strategy Framework Directive (MSFD) in 2008 in order to effectively protect the marine environment across Europe. The MSFD aims for Good Environmental Status, for the EU's seas and oceans exploited resources. To achieve Good Environmental Status through improved resource management, it is important that as many stocks as possible have an assessment of the stock status and the estimation of the Maximum Sustainable Yield (MSY) reference points (EU, 2021). For instance, 34% of the crustacean stocks in the Northeast Atlantic do not currently have an analytical assessment nor established reference points (ICES, 2023).

Crustaceans account for 23% of the global value of the world fish trade (FAO, 2022) and they are a vital link of the food web between primary producers (algae and aquatic weeds) and higher trophic levels. Among crustaceans there are detritivore, herbivore, omnivore and carnivore species, and they range in size from minute zooplankton with a length of 0.1 mm (Thorp and Rogers, 2011) up to the Japanese spider crab with a leg span of 4 meters (Smithsonian Institution, 2023).

Nephrops norvegicus Linnaeus 1758, (hereafter referred to as "*Nephrops*") is a decapod widely distributed from Iceland to the North of Africa (Johnson et al., 2013) and lives in burrows in muddy sediments at depths from 10 to 600 m. *Nephrops* is one of the commercially most important demersal species in the North Atlantic and across Europe (Sokolova et al., 2021). In 2017, the world production of *Nephrops* reached 59 thousand tons, of which 96% came from European countries (57 thousand tons) (EU, 2019). In Spain, the catches of *Nephrops* were 556 t in 2017, while market pull ranges between 5204 and 10873 t. Spain is one of the three main importers of *Nephrops* in Europe spending around € 65 million per year (EU, 2019). Management of *Nephrops* stocks, just like all other fisheries in the European Union (EU), is performed through a mixture of EU regulations (Common Fisheries Policy, CFP) and National laws. In the Northeast Atlantic, the proposed management measures, such as the minimum conservation reference sizes (MCRS) and total allowable catches (TACs), are established following biological scientific advice based on MSY provided by the International Council for the Exploration of the Sea (ICES; www.ices.dk).

In the Northwest Iberian coast (ICES, divisions 8c and 9a), there are three *Nephrops* Functional Units (FUs) or stocks: FU 25 (North Galicia), FU 26-27 (West Galicia and North Portugal) and FU 31 (Cantabrian Sea) (ICES, 2021a) (Figure 1). Some of the *Nephrops* stock assessments are conducted by sex disaggregated models (ICES, 2001; ICES, 2002; ICES, 2003; ICES, 2004) as females spend more time in the burrows than males (González Herraiz, 2011), so males are more accessible to the fishing gear and suffer a higher fishing mortality (F). Age-based analytical assessments are not feasible for *Nephrops*, as there is no standardized aging method for the species and length-based assessments based on the Length Cohort Analysis (ICES, 1978) were used previously for the three stocks. From 1992 to 2004 the three stocks length distributions were converted to age distributions in order to use Virtual Population Analysis (ICES, 1995; ICES, 2001; ICES, 2002; Fariña and González Herraiz, 2003; ICES, 2003; ICES, 2004). Since the early 2000s, available information provided by the very low level of landings and fishing effort in the three stocks studied was insufficient to carry out an adequate analytical assessment (ICES, 2003; ICES, 2005).

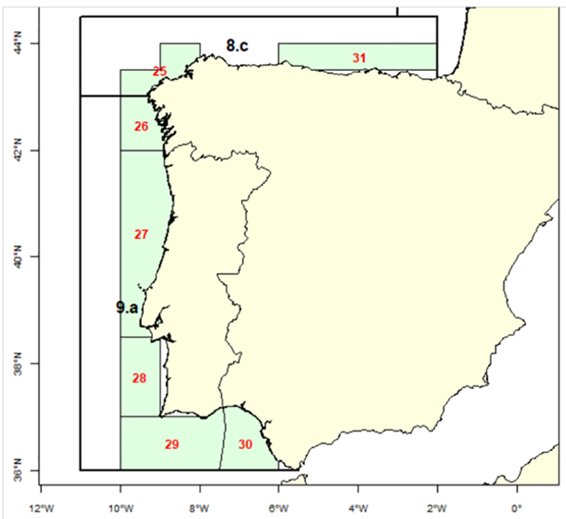

FIGURE 1
Location of *Nephrops* Functional Unit 26-27 (West Galicia and North Portugal, Division 9a), FU 25 (North Galicia) and FU 31 (Cantabrian Sea) (Division 8c) (ICES, 2021a).

Therefore, between 2003 and 2020, advice for the three stocks was based on commercial Catch Per Unit Effort (CPUE) trends (ICES, 2003; ICES, 2005; ICES, 2010a; ICES, 2015). Between 1983 and 2021 the catch of the three stocks decreased by 99% in line with decreasing recruitment. Therefore, the European Union established a zero catch advice for the *Nephrops* FU 25 and 31 in 2017 (EU, 2017). Since 2015, different data-limited stock assessment methods such as Length-Based Indicators (LBI), the Length-Based Spawning Potential Ratio (LB-SPR), the Mean Length-Based Total Mortality Estimators (MLZ), or the Separable Cohort Analysis (SCA) have been applied to the three stocks. However, available data and the stock characteristics did not meet the assumptions of these models(ICES, 2016; ICES, 2018a; ICES, 2020; Cousido-Rocha et al., 2022a).

In recent years, the necessity of estimating stock status and establishing MSY-based reference points has encouraged the use of new assessment methods such as the Stochastic surplus Production model in Continuous Time (SPiCT) (Pedersen and Berg, 2017; ICES, 2018a; ICES, 2021c). SPiCT requires a catch time series, one or more abundance index time series and does not require life history parameters (ICES, 2018a).

Assessing the status of the stocks is the first step towards the design and implementation of effective management measures. The purpose of this manuscript is to obtain MSY-based reference points with an analytical model for the three *Nephrops* stocks studied. The results are the assessments carried out by the ICES *"Working Group for the Bay of Biscay and the Iberian Waters Ecoregion"* (WGBIE) in May 2021 without any modification (ICES, 2021a). These assessments were done using the models fitted *ad hoc* during the ICES *"Benchmark Workshop on the development of MSY advice for category 3 stocks using Surplus Production Model in Continuous Time; SPiCT"* (WKMSYSPiCT) in February 2021 (ICES, 2021c). In this paper, we discuss advantages and limitations, and lessons learned of using production models for *Nephrops* and other crustacean stocks.

2 Materials and methods

2.1 Study area

The study area covers the northern and western continental shelf of the Iberian Peninsula (ICES divisions 8c and 9a), which is divided into three stocks or FUs: FU 25 (North Galicia), FU 26-27 (West Galicia & North Portugal) and FU 31 (Cantabrian Sea) (Figure 1). FU 25 has a *Nephrops* assessment area of 4,500 km^2 from Cape Finisterre to Ría Ortigueira (statistical rectangles 15-16 E0-E1 and 17E1). *Nephrops* in FUs 26-27 are located along the continental shelf and upper slope off the west Galicia and north of Portugal (division 9a) at depths ranging from 80–750 m (Fariña, 1996). More precisely, Functional Unit 26 (West Galicia) extends along the Atlantic area off the northwestern Spanish coast, from Cape Finisterre to mouth of the Miño river (statistical rectangles 14E0, 13E0, 13E1), whereas FU 27 (North Portugal) covers the Atlantic area off northern Portugal from Miño river to Lisbon (statistical rectangles 6E0 - 12E0) covering a surface of approximately 23,300 km^2(Figure 1). FU 31 extends between the mouths of Nalón and Urumea rivers (16E4-E7) and has a *Nephrops* assessment area of 3,800 km^2.

The sea bottom composition of these areas down to 100 m depth is mainly rock or sand sediments. Below 100 m depth, muddy bottoms characterize the Galician waters (FUs 25 and 26) whereas rocky ground and deep canyons are typical in the FU 31 (Abad et al., 2020; Pennino et al., 2022). The *Nephrops* distribution is limited to muddy sediments with more than 40% of silt and clay content, required to excavate burrows (Phillips, 2013).

2.2 Data

2.2.1 Catch

Monthly catch time series were provided by the Instituto Español de Oceanografía (IEO-CSIC) for the FU 25 and FU 26-27 from 1975 to 2020, and for FU 31 from 1983 to 2020 (Table 1). In addition, for North Portugal (FU 27), the Instituto Português do Mar e da Atmosfera (IPMA) also provided yearly catch data landed at Portuguese harbors since 1975.

The trend of FU 25 *Nephrops* catch time series shows a constant decline from 1975 until 2020 (Figure 2A). Since 1990, there has been a marked downward trend of *Nephrops* catches in FU 26-27. Available time series started in 1975 with records of 622 t, while being below 50 t in the period 2005-2011 and below 10 t since 2012. Catches were minimal since that date (mean value of 4 t) (ICES, 2020). *Nephrops* catches in FU 26-27 decreased more than 95% throughout the time series (Figure 2B). Catches from FU 31 decreased from 1989 to 2017 (year in which catch was zero)with a slight increase thereafter (Figure 2C).

TABLE 1 Input data, settings and priors used for the SPiCT models of the three Functional Units.

	FU 25 (North Galicia)	FU 26-27 (West Galicia & North Portugal)	FU 31 (Cantabrian Sea)
Catch data period	Whole time series available (1975-2020)	Whole time series available (1975-2020)	Whole time series available (1983-2020)
Catch data periodicity	Annual	Annual	Annual
Catch for the period with TAC zero (2017-2020)	Registered (no estimated)	Registered (no estimated)	Registered (no estimated)
Biomass index	SP-NSGFS-G2784 Demersales survey (1983-2020) (October) (gram/haul)	Combined survey index (Spanish survey G2784_Portuguese survey G8899) (1983-2020) (gram/haul)	SP-NSGFS-G2784 Demersales survey (1983-2020) (October) (gram/haul)
Biomass index lag	No	No	Yes (Index Year +1)
Biomass index scaling	Normalized to mean 1	Normalized to mean 1	Normalized to mean 1
Sexes	Males and females together	Males and females together	Males and females together
Catch uncertainty scaling	6 times higher catch uncertainty for 2017-2020 (zero TAC period).	Higher catch uncertainty for the first years of the time series (1975-1980).	–
Index uncertainty scaling	–	Higher index uncertainty for the first years of the time series (1983-1990).	Higher index uncertainty for the first years of the time series (1983-1994).
	PRIORS		
Initial stock depletion (B/K)	Medium	Medium	Medium
Shape of the production curve (n)	Fixed to Schaefer (n=2)	Prior mean=2, sd=0.5	Fixed to Schaefer (n=2)
Intrinsic growth rate (r)	$\log(r) = N(\log(0.2), 0.2^2)$	$\log(r) = N(\log(0.2), 0.2^2)$	$\log(r) = N(\log(0.2), 0.2^2)$
Decrease Catch error standard deviation (sdc), observation noise catch	Yes	Yes	Yes
Decrease F error standard deviation (sdf), process noise of F	Yes	Yes	Yes

β: ratio of standard deviation of catch to standard deviation of fishing mortality. bkfrac: Initial depletion of the population, ratio of initial biomass (B) to carrying capacity (K), sd: standard deviation.
α: ratio of standard deviation of index to standard deviation of biomass.

2.2.2 Biomass indices

The biomass index for FU 25 was obtained from the Spanish International Bottom Trawl Survey (IBTS) series (SP-NSGFS-Q4) carried out annually in autumn (September to October) since 1983 by the IEO-CSIC (Table 1). No survey was performed in 1987. The sampling stations consisted of 30 min trawling hauls located randomly within each depth stratum using the baka 44/60 gear and following the protocol of the International Bottom Trawl Survey Working Group (IBTSWG) (ICES, 2017).

In order to obtain an accurate biomass index, the FU 25 *Nephrops* assessment area was defined by reviewing available data of 2598 bottom-trawl hauls from the FU during the period 1983–2020. Among them there were 1117 hauls that caught *Nephrops*. The average geographical coordinates of each one of the 1117 hauls were plotted together and the points distribution was transformed to an area (more details in Supplementary Material Text and Figure S1). The obtained area corresponds to the largest distribution of the species in FU 25. *Nephrops* SP-NSGFS-Q4 survey index each year was expressed as the mean *Nephrops* catch per haul using hauls included in the *Nephrops* assessment area (Figure 2A).

A new depth stratified biomass index in FU 26-27 was estimated (Table 1; Figure 2B) considering hauls included in statistical rectangles that cover FU 26 (Spanish waters) and FU 27 (Portuguese waters) carried out during the Spanish and Portuguese IBTS (ICES, 2017), respectively. The Spanish survey (SP-NSGFS-Q4) covers depths from 70 m to 500 m while the Portuguese survey (PT-GFS-WIBTS-Q4) covers depths from 20 m to 500 m. *Nephrops* catch weight by haul was standardized to one hour. The Portuguese surveys (PT-GFS-WIBTS-Q4) are carried out by IPMA in the 4th quarter of the year. *Nephrops* data were available for the period 1984–2017. No survey was conducted in 2018, 2019 and 2020. A mixed sampling scheme composed of 66 trawl positions distributed over a fixed 5-by-5 miles grid and 30 random trawl positions, with a tow duration of 30 minutes has been carried out since 2005. The fishing gear used was a bottom trawl (type Norwegian Campbell Trawl 1800/96 NCT) with a 20 mm codend mesh size according to the protocol of IBTSWG (ICES, 2010b).

The biomass index for FU 31 was obtained from the hauls carried out in the FU 31 statistical rectangles as part of the Spanish survey SP-NSGFS-Q4 in the period 1983-2020 (Table 1; Figure 2C). *Nephrops* SP-NSGFS-Q4 survey index each year was expressed as the mean *Nephrops* catch per haul. See more information about the survey indices calculation in Supplementary Material Text.

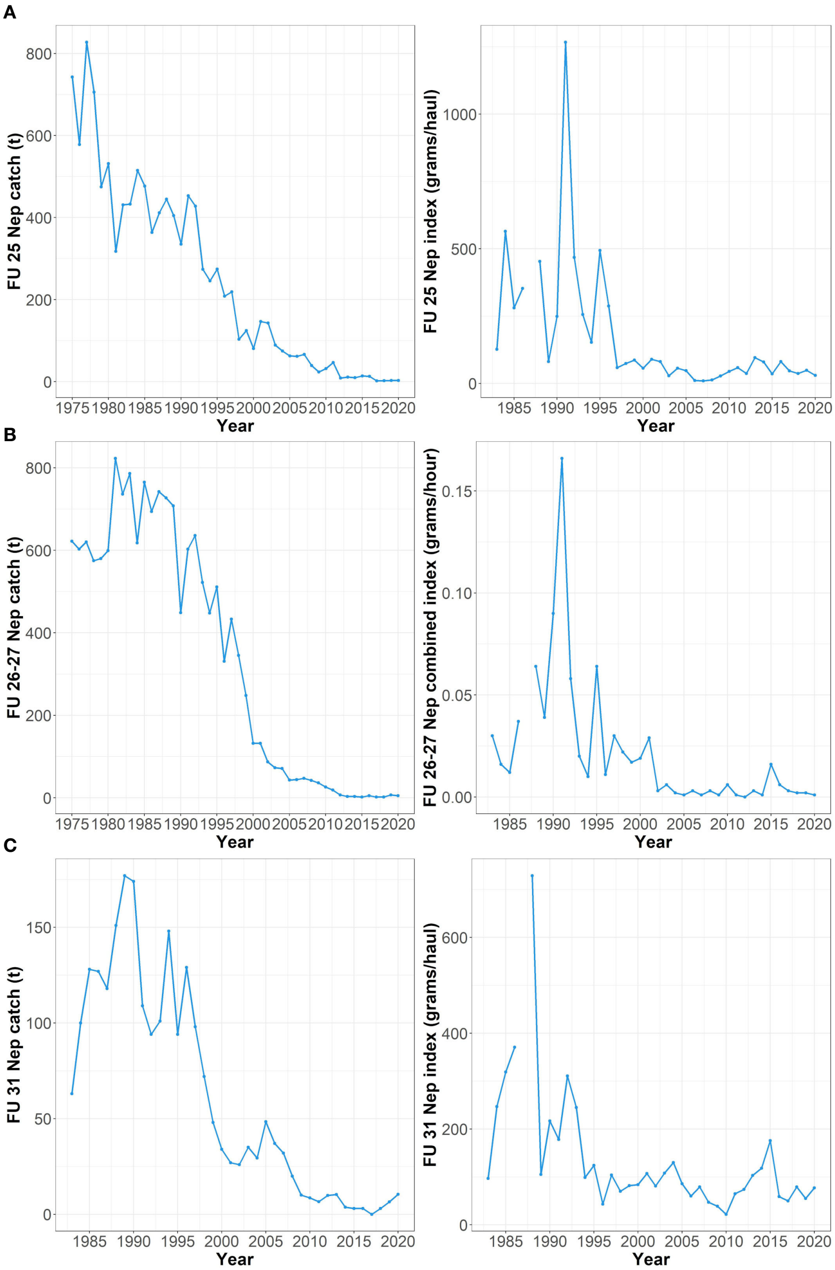

FIGURE 2
Nephrops catches and surveys biomass indices. FU 25 (North Galicia) **(A)**, FU 26-27 (West Galicia and North Portugal) **(B)** and FU 31 (Cantabrian Sea) **(C)**. In 1987 there was no survey. FU 25 (North Galicia) index 1991 data was deleted for the analyses.

Across all stocks, the abundance index drops from higher to lower levels around 1997 (Figures 2A–C). Besides there are small biomass peaks around 2015. The sampling effort and procedures (e.g., number and distribution of hauls) have been similar throughout the time series (ICES, 2021a).

2.2.3 Other data

The average annual temperature below the mixed layer (TBwML) for Galician waters and for the Cantabrian Sea (Polo et al., 2022) was used as an index of environmental conditions of relevant depths. The surface mixed layer depth affected by strong seasonality was excluded in this calculation. The climatological maximum winter mixed layer in the area is within a depth of 250 m, so TBwML is the temperature average between 300 and 600 m depth. Temperature data to calculate these indices were obtained from temperature profiles from the ocean reanalysis (ECMWF Ocean Reanalysis System 4, ORAS4) (Balmaseda et al., 2013). The ORAS4 reanalysis provides monthly temperature, salinity, current, and sea level data at 42 pressure levels from 5 to 5000 m with larger vertical spacing towards the bottom and a spatial resolution of 1×1.

Depth data of hauls with *Nephrops* catch were obtained from different sources of the Spanish Institute of Oceanography data collection. These sources were EU Data Collection Framework

(DCF) Bottom Trawl Survey series SP-NSGFS-Q4 1983-1986 and 1988-2020, data from observers on board of commercial vessels from the DCF Discard Programme 1994, 1997, 1999-2000, 2003-2020 and data from observers on board of commercial vessels in the *Nephrops* Sentinel Fisheries 2017-2020.

Most data were collected through the national fishery sampling programs under the DCF, which is designed to provide evidential support for scientific advice regarding the Common Fisheries Policy.

2.3 Stochastic surplus production model in continuous time

SPiCT explicitly models both biomass and fishing dynamics as stochastic processes in a state-space framework. It is formulated as a continuous-time model to allow for the representation of seasonal fishing patterns and incorporation of sub-annual catch and index data (Pedersen and Berg, 2017).

SPiCT requires a time-series of catches and assumes that catch is observed over a period, e.g. one year for annual data. The observed catches are then equal to the product of instantaneous fishing mortality and stock biomass integrated over the observation period. Fishing mortality is not decomposed into the product of effort and catchability. Therefore, it is not necessary to standardize the catch data based on changes in fishing efficiency: all such changes will be encompassed in the instantaneous fishing mortality. The second time series required by SPiCT is a standardized (exploitable) biomass index, either from the commercial fleet or scientific surveys.

SPiCT quantifies the uncertainty of all parameters estimates (Table S1 in Supplementary Material) and states and is able to propagate uncertainty to all derived quantities of interest, like reference points and relative biomass and fishing mortality. Therefore, all reported quantities are provided with 95% confidence intervals (CI). SPiCT provides stochastic reference points as MSY, F_{MSY} (fishing mortality consistent with achieving MSY) and B_{MSY} (exploitable stock biomass that results from fishing at F_{MSY} for a long time). MSY $B_{trigger}$ (value of exploitable stock biomass that triggers a specific management action) and B_{lim} (limit reference point for exploitable stock biomass) are defined as fractions of B_{MSY} ($B_{trigger}$ = 0.5 x B_{MSY} and B_{lim} = 0.3 x B_{MSY}). F_{lim} (limit reference point for fishing mortality, mean over defined age range) are calculated from F_{MSY} (F_{lim} = 1.7 x F_{MSY}). SPiCT estimates the stock status as relative biomass (B/B_{MSY}) and relative fishing mortality (F/F_{MSY}) for the time series (Table S1). The assessment is done using data for the prior year (in this case, 2020) and do a short-term forecast to the end of the following year (2021) that would be applied for the beginning of the management year (2022). Due to lack of data in the intermediate year (2021), some assumptions need to be made for the short-term forecast. These assumptions were four management scenarios that were defined as (ICES, 2021c): (1) No fishing mortality (F=0), (2) *Status quo* fishing mortality ($F=F_{sq}$), (3) Hockey-stick MSY rule: F = F_{MSY} when biomass is higher than $B_{trigger}$, but F is reduced linearly to zero when the biomass is less than $B_{trigger}$, (4) Hockey-stick MSY rule with the catch fractile: in order to take into account the estimated uncertainties, the 35^{th} percentile of the projected catch distribution is used instead of the median (50^{th} percentile) (Mildenberger et al., 2022). For each scenario the predicted catch, relative F and relative B are estimated for the end of the intermediate year (2021) and apply to the beginning of the management year (2022). MSY advice is in most cases based on scenario 4.

2.3.1 Modeling decisions

Pronounced differences in the mean catch per haul in all areas before 1994-2002 and after could indicate that the stock has declined and/or that productivity of the stocks changed: In FU 25, the average catch per haul changed from 294 g/haul to 51 g/haul before and after 1997; in FUs 26-27, the average changed from 0.032 g/hour to 0.003 g/hour in 2002; and in FU 31, the average changed from 219 g/haul to 83 g/haul in 1994 (Figures 2A–C). The possibilities of carrying out a SPiCT analysis from the point of view of a regime shift (different production curves at fixed time points) or introducing a gradual change in the maximum productivity level over time in the model (mean reverting process, Mildenberger et al., 2020) were rejected since whether regime shift or gradual change, both affect only the height of the production curve (MSY) but not the carrying capacity (K). Another possibility could have been using only the recent period of the time series in each stock. For the three stocks it was decided to keep the whole time series of catch and indices in order to utilize the information about the history of the stocks (Table 1).

According to sensitivity analyses the 1991 value of the FU 25 biomass index was deleted and the values of 1991 in FU 26-27 index and 1988 in FU 31 index were kept. For more specific details on sensitivity analyses please see for FU 25 Tables 9.3 and 9.4, for FU 26-27 Tables 8.3.1.4 and 8.3.1.5 and for FU 31 Tables 10.3 and 10.4 in ICES 2021c. Biomass indices time series were scaled to mean 1 in order to obtain a better numerical stability (Table 1).

SPiCT assumes that the relative biomass index derived from the survey data is representative of the part of the stock that is vulnerable to the commercial fleet. After comparing mean length time series of catch and survey, FU 31 survey biomass index was adjusted shifting forwards in time by one year (Table 1, Figure S2). That was not done in FU 25 and FU 26-27 because the *Nephrops* mean size in these two stocks is the same in the fishery and in the survey along the time series.

Initial runs of the assessment models of the three stocks showed rather large estimates of uncertainty, together with moderate to unsatisfactory model diagnostics. The models estimated a nearly pristine stock in the start of the time series (1975 for FU 25 and FU 26-27 and 1983 for FU31). This means a very low initial depletion of the population, quantified as the ratio of initial biomass to carrying capacity (B/K). Historical catches should encompass earlier periods with relatively low exploitation and ideally the start of the fishery. However, FU 25, FU 26-27 and FU 31 catches are at their highest observed at the beginning of the time series, which most likely implies that the fisheries have started long before the available data. As historical catches were not available, it was suggested to perform an alternative model configuration, using a prior distribution for initial depletion with a mean much lower than 1. This should not have an effect on the trend but could affect the stock status in the terminal year. Accordingly, the sensitivity of the results was evaluated by alternative model runs with a lower B/K prior mean of 0.5. For more specific details on sensitivity analyses see ICES 2021c. Although these produced slightly improved model diagnostics, parameter uncertainty still remained relatively large, the runs showed undesirable retrospective patterns, and the stock at the start of the time series were still estimated to be close to pristine, which does not match the history of the fishery. As a consequence, alternative runs were run with a tighter prior on the B/K ratio (Table 1) and on the shape parameter 'n' (i.e. sd = 0.2).

For data that lack historical catches and show limited contrast in the index, it is recommended to fix the shape of the Schaefer production curve 'n' parameter and to use informative priors for 'r' (e.g. Thorson, 2020). SPiCT has a relatively vague default prior on log n (and on the ratios of process to observation error). Therefore, the shape parameter 'n' was found to be poorly estimated for the three stocks, which resulted in retrospective patterns. Therefore, in FU 25 and FU 31 the shape parameter 'n' was fixed to 2 and in FU 26-27 a prior with mean 2 and sd of 0.5 was used. These changes in the Schaefer model (Schaefer, 1954) improved the retrospective pattern of B/B_{MSY} in the three stocks (Table 1).

In addition, a prior on the intrinsic growth rate parameter 'r' based on a meta analysis with a mean of 0.2 and a CV of 0.2 was used (Table 1). It is important to note that 'r' values from other models might not correspond exactly to 'r' values from SPiCT (ICES, 2021c).

Also priors on the catch observation uncertainty (sdc) and on the F diffusion process uncertainty (sdf) were applied for the three stocks (Table 1).

The effect of priors was evaluated in sensitivity runs, where the robustness of the final year stock status estimates (F/F_{MSY} and B/B_{MSY}) was checked.

From 2016 to 2017, the agreed TAC was reduced from 48 tonnes to zero for division 8c (FUs 25 and 31), and the TAC has remained at zero in the following years (with exception of 2 t and 0.7 t for *Nephrops* sentinel fisheries in FU 25 and FU 31, respectively). Even though there was a TAC zero, *Nephrops* is a bycatch in the bottom trawl fishery and some *Nephrops* catches were expected. Concerns were raised about the uncertainty of the very low reported catches in FU 25 in 2017, which are likely to have a higher CV than the years prior to 2017. This issue was addressed by assuming a higher standard deviation for catches in the years 2017–2020 for this stock (Table 1). The same was done for the initial period 1975-1980 for FUs 26-27 (Table 1). In both FUs 26-27 and 31, extra uncertainty was introduced in the first years of the survey index (Table 1).

The analysis was done in R (R Core Team, 2020) and the 'spict' package available at https://github.com/DTUAqua/spict.

2.4 Other exploratory analysis

Data of TBwML were qualitatively explored with respect to the biomass indices of the three stocks in order to evaluate possible correlation between them. In particular, the Spearman's rank correlation ρ was computed and results were plotted using locally estimated scatterplot smoothing (LOESS) of the "ggplot2" R package (Wickham, 2016).

We calculated the annual average depth of all bottom-trawl hauls that caught *Nephrops* from 1983 to 2021 in order to investigate if the species is caught in increasingly deeper waters. It is worth mentioning that our goal is not to do an environmental analysis, but rather to present these variables qualitatively.

3 Results

3.1 FU 25 (North Galicia)

Results of the model suggest a carrying capacity (K) of 9034 t, a B_{MSY} of 3945 t, F_{MSY}=0.08 $year^{-1}$ and MSY=307 t for this stock (Table 2). The stock biomass at the end of 2020 was 10% of the B_{MSY} and the fishing mortality was 17% of the F_{MSY} (Table 2). Except for 1975, the stock biomass was always below B_{MSY}. Biomass decreased from 1975 to 2009, with a very slight increase since thereafter (Table S2 and Figure 3A), while the fishing mortality was above F_{MSY} until 2011. The default SPiCT plots are shown in Figure S3.

The forecast for 2022 included four scenarios (Table 3). The scenario of F=0 was chosen since the stock biomass is below the limit reference point for B (B_{lim}) since 1996 (Table S2 and Figure 3A) (ICES, 2021b). Therefore there was no change with respect to the anterior advice and a precautionary TAC of zero tons for FU 25 in 2022 was established (EU, 2022).

3.2 FU 26-27 (West Galicia and North Portugal)

Results of the model suggest a carrying capacity (K) of 13030 t, a B_{MSY} of 7309 t, F_{MSY}=0.07 $year^{-1}$ and MSY=506 t for this stock (Table 2). Biomass has been below MSY $B_{trigger}$ since 1989 and fishing mortality below F_{MSY} since 2012 (Table S2; Figure 3B). At the end of 2020 F was 43% of F_{MSY} and B was 2% of B_{MSY}, indicating a depleted stock (Table 2). The default SPiCT plots are shown in Figure S4.

Results for short-term projections (ICES, 2021c) are presented in Table 3. All scenarios recommend zero catch for 2022 except for F_{sq} with projected catches of 5.2 t. The scenario of F=0 was chosen since the stock biomass is below the limit reference point for B (B_{lim}) since 1994 (Table S2 and Figure 3B) (ICES, 2021d). Therefore a precautionary TAC of zero tons for the year 2022 was advised and established for the first time in FU 26-27 (EU, 2022).

3.3 FU 31 (Cantabrian Sea)

The main results of the SPiCT for this stock were a *K* of 1680 t, a B_{MSY} of 707 t, F_{MSY} = 0.08 $year^{-1}$ and MSY = 53 t (Table 2). The stock biomass at the end of 2020 was 44% of B_{MSY} and the fishing mortality was 44% of F_{MSY} (Table 2). The stock biomass has

TABLE 2 SPiCT summary results. 95% IC.

Parameters estimates	FU 25 (North Galicia)			FU 26-27 (West Galicia & North Portugal)			FU 31 (Cantabrian Sea)		
	estimate	cilow	ciupp	estimate	cilow	ciupp	estimate	cilow	ciupp
m (MSY) (t)	405.503	210.0	783.036	507.576	369.12	697.98	76.6562	38.397	153.038
K (t)	9034.28	4567.3	17870.2	13029.56	7913.6	21453	1680.26	801.01	3524.65
n	Fixed (n=2)	–	–	2.757	1.501	5.066	Fixed (n=2)	–	–
$r=m/Kn^{n/(n-1)}$	0.1795	0.124	0.2594	0.191	0.131	0.280	0.1825	0.1250	0.2665
q	0.0010	0.001	0.0019	0.001	0.001	0.002	0.0018	0.0006	0.0050
sdb	0.2037	0.075	0.5563	0.015	0.000	11.098	0.2296	0.1218	0.4328
sdf	0.3982	0.2695	0.5882	0.509	0.388	0.668	0.5113	0.3767	0.6941
sdi	0.5759	0.408	0.8125	0.864	0.685	1.088	0.3226	0.2181	0.4771
sdc	0.1767	0.128	0.2445	0.096	0.065	0.141	0.0952	0.0657	0.1379
Stochastic reference points	**estimate**	**cilow**	**ciupp**	**estimate**	**cilow**	**ciupp**	**estimate**	**cilow**	**ciupp**
B_{MSY} (t)	3945.12	1930	8062.94	7309	3822.4	13977	706.92	329.83	1515.10
F_{MSY} ($year^{-1}$)	0.0794	0.052	0.1204	0.069	0.036	0.132	0.0781	0.052	0.1173
F_{lim} ($year^{-1}$)	0.13498	0.088	0.2047	0.12	0.06	0.23	0.13277	0.088	0.1994
MSYs (t)	307.413	135.6	697.182	506	368.38	696.20	53.455	23.967	119.228
$B_{trigger}$ (t)	1973	965	4031.47	3655	1911	6989	357	164.915	757.55
B_{lim} (t)	1184	579	2418.82	2193	1147	4193	212	98.949	454.53
Estimated states	**estimate**	**cilow**	**ciupp**	**estimate**	**cilow**	**ciupp**	**estimate**	**cilow**	**ciupp**
$B_{2020.9}$	379.224	165.4	869.688	156	70	348	311.235	108.444	893.248
$F_{2020.9}$	0.0136	0.003	0.0649	0.030	0.011	0.079	0.0345	0.0106	0.112
$B_{2020.9}/B_{MSY}$	0.0961	0.0341	0.2706	0.021	0.007	0.061	0.4403	0.1442	1.3444
$F_{2020.9}/F_{MSY}$	0.1707	0.0370	0.7879	0.426	0.132	1.381	0.4416	0.137	1.4237

α: ratio of standard deviation of index to standard deviation of exploitable stock biomass (B_t), β: ratio of standard deviation of catch to standard deviation of fishing mortality (F_t), r: Intrinsic growth rate, m: natural mortality, K(t): carrying capacity in tones, q: catchability, sdb: standard deviation of B, sdf: standard deviation of F, sdi: standard deviation of the index, sdc: catch standard deviation. $B_{trigger}=0.5xB_{MSY}$, $B_{lim}=0.3$ x B_{MSY}, $F_{lim}=1.7$ x F_{MSY}.

decreased since1989 and has been around MSY $B_{trigger}$ since 1997. In the period 2009-2011, biomass was below B_{lim} (Table S2; Figure 3C). Fishing mortality has been below F_{MSY} since 2008 (Table S2; Figure 3C). The default SPiCT plots are shown in Figure S5.

Forecast included four scenarios for the year 2022 (Table 3). As a result of the WKMSYSPiCT 2021 benchmark (ICES, 2021c) and the adoption of SPiCT as the assessment method (ICES, 2021e), scenario 4 was selected for the advice. In this scenario, F is equal to F_{MSY} when biomass is higher than MSY $B_{trigger}$ (=0.5 B_{MSY}), which is the case for 2022 (Table 3), and in order to take into account the estimated uncertainties, the 35th percentile of the catch distribution is used instead of the median (50th percentile; Mildenberger et al., 2022). This resulted in a TAC of 20 t for 2022 terminating the zero catch advice period that started in 2017 (ICES, 2021e; EU, 2022).

For the three stocks, diagnostics and retrospective patterns of the SPiCT models do not show major issues. Indeed, residual diagnostics pass the test for normality, bias and autocorrelation and there are no issues observed in the retrospective analysis (Figures S6–11).

3.4 Biomass indices vs. temperature

TBwML in Galician waters increased during the periods 1983-1986 and 1999-2013 and decreased during the periods 1986-1999 and 2013-2017 (Figure 4). In the Cantabrian Sea TBwML increased during 1983-1994 and 2005-2013 and decreased during 1994-2005 and 2013-2017 (Figure 4). The Spearman correlation coefficient (ρ) between the *Nephrops* biomass index from FU 25 and the annual average TBwML in Galician waters is -0.32 (p-value = 0.06; Figure 5A). The coefficient between stock index of FU 26 and TBwML in Galician waters ρ is -0.52 (p-value < 0.05; Figure 5B). The coefficient between the biomass index of FU 31 and TBwML in the Cantabrian Sea ρ is -0.56 (p-value < 0.05; Figure 5C). These values and the trends shown in the figures do not present a clear correlation among biomass indices and temperature.

3.5 Catch vs. depth

From 1989 to 2021, the depth at which *Nephrops* are caught is increasing (Figure 6).

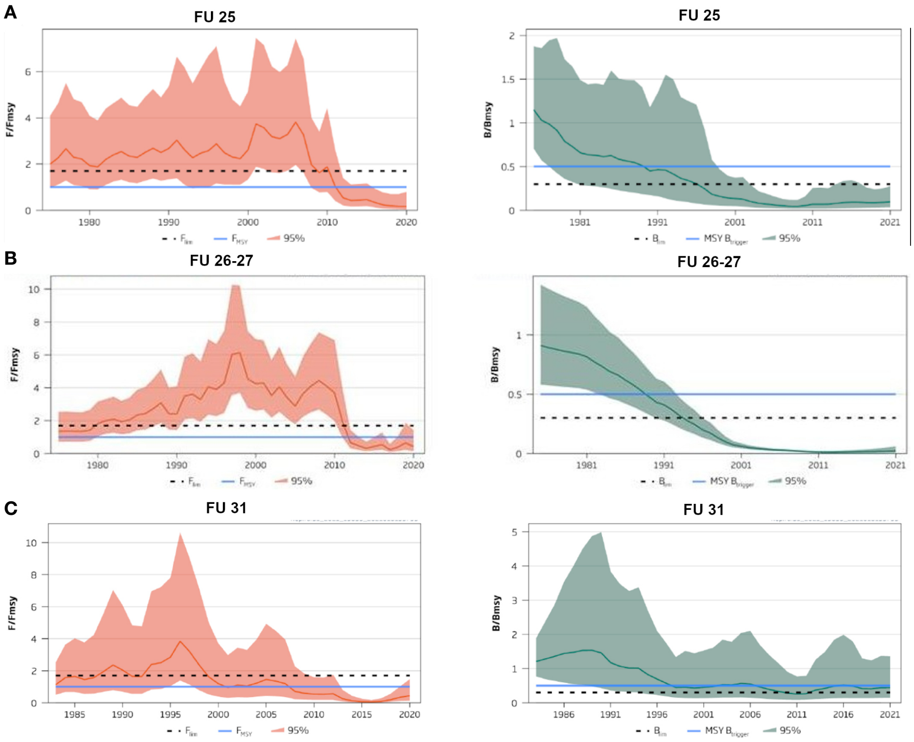

FIGURE 3
Nephrops relative fishing mortalities and biomasses. FU 25 (North Galicia) **(A)**, FU 26-27 (West Galicia and North Portugal) **(B)** and FU 31 (Cantabrian Sea) **(C)** (ICES, 2021b; ICES, 2021c; ICES, 2021d). $B_{trigger}$=0.5 x B_{MSY}, B_{lim}=0.3 x B_{MSY}, F_{lim}=1.7 x F_{MSY}.

4 Discussion

4.1 Procedure, advantages and limitations of the SPiCT assessment for *Nephrops*

The SPiCT model, unlike other methods used for data-limited stocks, takes the history of the fishery into account, does not analyze each year independently (Cousido-Rocha et al., 2022b), and quantifies parameter uncertainty. At the same time, the contrast in the input data is important for a robust SPiCT assessment, i.e. varying levels of abundance and fishing mortality, which was not the case for our three stocks.

Surplus production models do not require life-history parameters, like growth, natural mortality, length-weight parameters, length at which 50% of individuals are mature (Lmat 50), length at which 95% are mature (Lmat 95), M/K, etc., which might be uncertain for crustacean. In fact, growth and natural mortality rates of crustaceans are difficult to estimate due to the fact that their growth is not continuous but stepwise (their exoskeleton is periodically replaced during ecdysis) and age evaluations based

TABLE 3 SPiCT predicted catch and status of the stock for 2022.

FU	FU 25 (North Galicia)				FU 26-27 (West Galicia & North Portugal)				FU 31 (Cantabrian Sea)			
Scenarios	F=0	$F=F_{sq}$	$F=F_{MSY}$	$F=F_{MSY}$ C fractile	F=0	$F=F_{sq}$	$F=F_{MSY}$	$F=F_{MSY}$ C fractile	F=0	$F=F_{sq}$	$F=F_{MSY}$	$F=F_{MSY}$ C fractile
Catch (t)	0.0	6.4	0.0	0.0	0.0	5.2	0.0	0.0	0.0	12.2	26.3	20.2
B/B_{MSY}	0.13	0.13	0.13	0.13	0.03	0.03	0.03	0.03	0.54	0.53	0.50	0.51
B/B_{MSY}.lo	0.04	0.04	0.04	0.04	0.01	0.01	0.01	0.01	0.16	0.15	0.14	0.14
B/B_{MSY}.hi	0.42	0.42	0.42	0.42	0.09	0.09	0.09	0.09	1.87	1.85	1.84	1.84
F/F_{MSY}	0.00	0.17	0.00	0.00	0.00	0.43	0.00	0.00	0.00	0.44	0.97	0.74
F/F_{MSY}.lo	0.00	0.03	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.07	0.15	0.11
F/F_{MSY}.hi	0.00	1.14	0.00	0.00	0.00	2.72	0.00	0.00	0.00	2.84	6.22	4.73

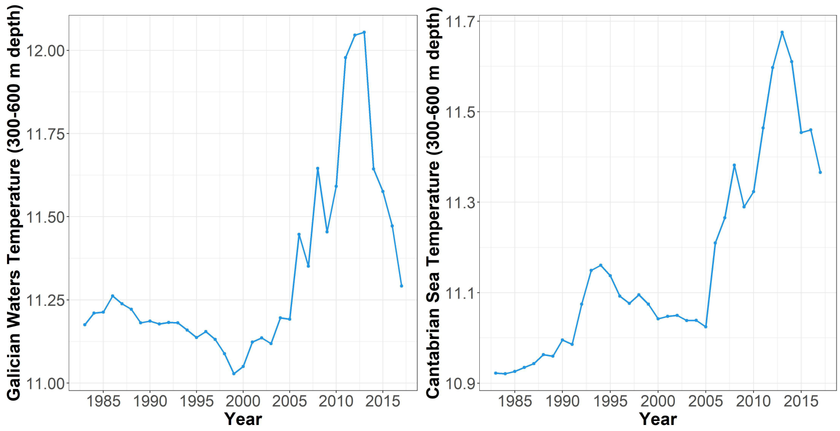

FIGURE 4
Temperature TBwML (300-600 m depth) (1983-2017) in Galician waters (left) and Cantabrian Sea (right).

on periodic markings on the body surface impossible (Hartnoll, 2001; Kilada, 2017; Mariella Canales et al., 2019). The size at maturity of females could be estimated by several methods (eggs presence, macroscopic or microscopic ovary stages, presence of spermatophores, etc.) (Mente, 2008), thus the results of different stocks may not be comparable if different methods were used. In the case of male *Nephrops*, identifying the carapace length at which the slope changes in the relation of male appendage length to carapace length seems to be the only standard method to obtain the size at maturity (ICES, 2006; González Herraiz, 2011), but requires to have samples with very small individuals.

Ideally, the catch time series for production models includes landings and discards. Historical catches should encompass earlier periods with relatively low exploitation and ideally the start of the fishery (ICES, 2021c). Catch time series will then be calibrated in the model by one or several biomass indices. This is one of the advantages of SPiCT, the model can handle several indices, successive or simultaneous, with different sampling frequency (monthly, quarterly, annually, etc.). This is very useful for example for introducing annual or sporadic survey data. The index time series should not be too short (at least 10 years as a rule of thumb but ideally longer time series are preferable) and can correspond to CPUE indices from the commercial fleets or from scientific surveys.

The indices should be representative of the stock in terms of area and time of the year in order to avoid hyperstability or hyperdepletion. Hyperstability in catch rates signifies that CPUE values can remain high even when stocks are rapidly depleted. This can happen if catch rates are derived from fishing activities that remain concentrated in areas or periods of relatively higher abundance. On the contrary, hyperdepletion in catch rates implies that CPUE values can remain low even when the stocks have high biomass. This can occur if the fishery is conducted over areas or periods of relatively lower densities (ICES, 2019).

In general, it is preferable to use survey indices rather than commercial CPUE indices. Surveys are scientifically designed to take into account previous knowledge in order to achieve objectives avoiding as much as possible sampling bias. Instead, CPUE indices from the commercial fishery are influenced by several factors, such as targeting, and their standardization is often more difficult.

In the case of *Nephrops*, biomass indices from scientific surveys that were not designed specifically for the species, a reference (assessment) area could be identified (see Material and methods). Then, only data from hauls inside the reference area are used in order to obtain a more accurate index (e.g. excludes areas with rock or gravel bottoms where *Nephrops* cannot dig its burrows). Regardless of this, throughout the time series the survey must have the same characteristics and level of sampling and cover the same area and the index must be calculated in the same way. Thus, the index, and therefore the SPiCT analysis, would take into account the absence of *Nephrops* in some zones due to a possible contraction of the stock area as is the case of two of the stocks examined in this study, FU 25 and FU 26-27 (ICES, 2021a). Survey indices standardization is necessary, especially when information from several surveys are combined.

The use of monthly time series as input data the SPiCT assessment is useful for carrying out an in-depth exploration of the fishery and identifying high fluctuations of stock biomass or fishing mortality that could be indicators of the dynamics of the fishery. There is indeed seasonality of the *Nephrops* fisheries in these latitudes, with the higher catches per unit effort being observed between May and September (ICES, 2018b). Low catches during these months over several years could indicate issues in the data, the fishery, or the population and would require special attention. At the same time, monthly time series could introduce high uncertainty and noise in the model that could prevent the achievement of good diagnostics (ICES, 2021c).

Something similar occurs with the assessment by sex. As it was aforementioned males are more available to the trawl gear than females since females, especially during the incubation period, remain inside the burrows for longer periods than males. In the worst case, a high fishing mortality could cause a decrease of males in the stock and prevent the mating for females (sperm limitation) (ICES, 2013). Therefore, an assessment by sex, or at least for the weakest fraction of the stock (normally males), would be suitable but it is necessary to have a high quality and representative sex ratio

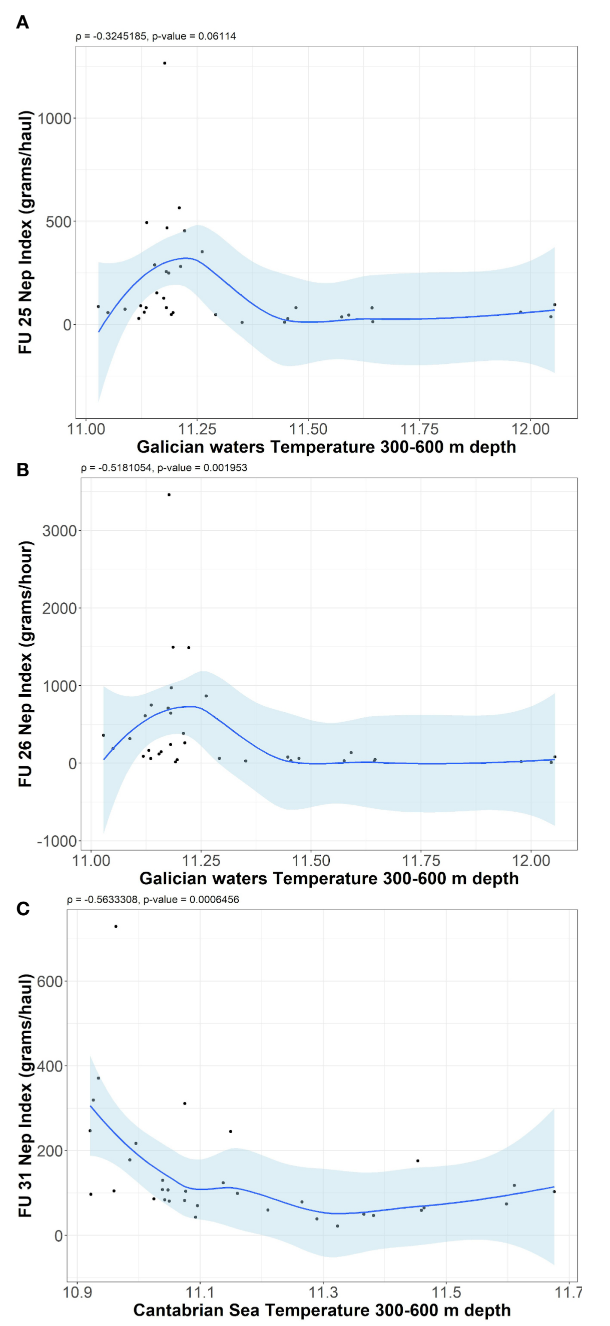

FIGURE 5
Annual *Nephrops* biomass indices vs. annual average temperature below mixed layer (TBwML), 1983-2017: FU 25 (North Galicia) (grams/haul) in Galician waters, **(A)**, FU 26 (West Galicia) (grams/hour) in Galician waters **(B)** and FU 31 (Cantabrian Sea) (grams/haul) in Cantabrian Sea **(C)**, ρ is the Spearman correlation coefficient.

estimation, normally based on the length composition sampling. Otherwise it could introduce noise in the catch and index data and affect the quality of the obtained results (ICES, 2021c).

A period in the catch time series with catch limitations due to management could imply some misreporting in some cases. The catch time series cannot be corrected or estimated without additional assumptions about discarding and misreporting that are difficult to make. The input time series of catch and index can be supplemented in SPiCT with uncertainty scaling time series, which inform the model about the relative uncertainty of observed time series. Therefore, an increased scaling factor can be used for the catches where misreporting could be higher. If we compare the analysis of these stocks with SPiCT with the use in FU 25 and FU 26-27 females stocks of other data limited stocks methods as Length Based Indicators (LBI) (see Cousido-Rocha et al., 2022a) we found that FU 25 females stock in 2019 was not exploited at the MSY level, albeit closer to it. Length Based Spawning Potential Ratio (LBSPR) method applied suggested that FU 25 females stock were below MSY levels above collapse in the last years (Cousido-Rocha et al., 2022a). The SPiCT result for FU 25 in 2019 was that the biomass was 9% of the B_{MSY}.

LBI and LBSPR indicators estimate a healthy stock status for FU 26-27 females. The SPiCT result for FU 26-27 in 2019 was that the biomass was 19% of the B_{MSY} and the survey index has been decreasing since the 1990s.

The results of LBI and LBSPR methods lead to a more optimistic stock status than the status according to the previous knowledge and to the SPiCT results. That is because those stocks did not meet the assumptions of LBI and LBSPR (constant total mortality and recruitment, life history parameters not uncertain). The lack of recruitment in FU 25 increased the LBI indicators L_c (length at first catch, length at 50% of the mode) vs. L_{50} (length at which the 50% of the females are mature) and L_{mean} (mean length of females $>L_c$) vs. L_{opt} ($3L_\infty/3+(M/k)$) plus 10%. LBSPR method converted the decreases of recruitment along the time series in increasing SPR.

Besides, LBI and LBSPR models analyze each year regardless of the other years, do not take into account the spatial component, are very sensitive to different values of the input parameters (Cousido-Rocha et al., 2022a) and provide very simple results. SPiCT takes the history of the fishery into account and the input data are only catch and biomass index time series. Also SPiCT provides a very complete set of results that have confidence intervals, provides several diagnostics tools and allows to estimate the status of the stock compared to both the MSY reference points and the carrying capacity of the stock. Also, SPiCT can provide biomass and fishing mortality estimates by month of the whole time series of the stock. As a result of the use of SPiCT in 2021 and 2022 in the three stocks studied, FU 25 and FU 26-27 have a TAC zero and the *Nephrops* fishery in FU 31 was reopened in 2022. If the stocks had been managed according to LBI and LBSRP probably the management measures would have been different in FU 25 and FU 26-27 and there has not been a tool to accurately estimate the catch options for each stock and year. Therefore, knowing the bases of the model and taking into account its assumptions are key issues when a model is applied.

4.2 Stocks status

Our findings show that in recent years both catches and biomass indices of *Nephrops* derived from surveys have strongly declined in the three stocks analyzed. Similar patterns of decreasing total fish production since the mid-nineties have been observed at

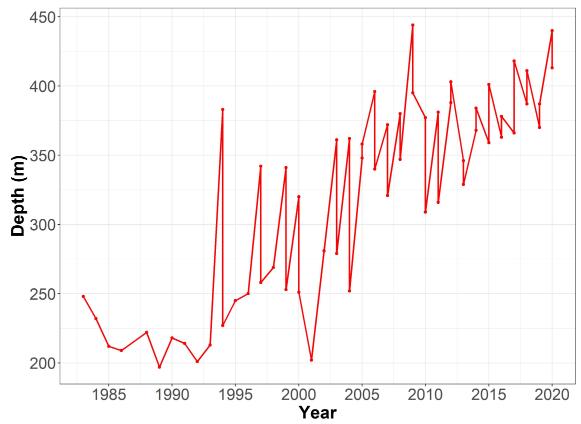

FIGURE 6
Depth annual average (m) of the hauls with *Nephrops* catch in FU 25 (North Galicia), FU 26-27 (West Galicia and North Portugal) and FU 31 (Cantabrian Sea), 1983-2020 (source: DCF Bottom Trawl Survey series SP-NSGFS-Q4 1983-2020 and observers onboard in commercial vessels 1994-2020).

different levels (marine captures in Northwest Atlantic, Europe and Spain and landings of the world upwelling areas; FAO, 2020, FAO, 2022).

Nephrops catches in FU 25, FU 26-27 and FU 31 show a decreasing trend throughout the time series (Figures 2A–C). In accordance, the model estimated that fishing mortality has been over F_{lim} between 1975 and 2010 in FU 25, from 1980 to 2011 in FU 26-27 and between 1988 and 1999 in FU 31 (Table S2, Figures 3A–C). As a result of the biomass collapse (Figures 3A–C), fishing mortality started to decrease in 2007 in FU 25, in 1999 in FU 26-27 and in 1997 in FU 31 (Table S2, Figures 3A–C).

As the *Nephrops* zero TAC was only recently enforced (the most recent since 2017), the reduced fishing mortalities cannot be attributed to a reduction in allowable catch. The reduction of fishing mortalities estimated by the models could be a reflection of a reduction of effort (Figure S12) or a reduction in catch greater than the reduction in biomass. This could be an effect of reduced catchability as the stocks are becoming less and less available and/or have contracted their range. The decline of the fishing effort in the three stocks (Figure S12) could suggest possible effects of environmental conditions in the development of the stocks catches and biomasses. With respect to a possible contraction of the FU 25 stock area, *Nephrops* has been absent in 53% of the *Nephrops* reference area in the *Nephrops* Sentinel Fishery carried out in FU 25 in August (2017-2021). In addition, in the SP-NSGFS-Q4 survey, *Nephrops* passed from being absent in the 22% of the hauls in the *Nephrops* reference area in 1983 to being absent in 84% of the hauls in 2021 (ICES, 2021a). Data suggest that the FU 25 stock area has decreased by 63% from 1983 to 2020 (ICES, 2021a). Spatial information shows a contraction in the historical distribution of *Nephrops* in FU 26-27 since 1983 (ICES 2021a).

Other changes in the spatial distribution have been recorded in FU 25 and FU 26. *Nephrops* have disappeared from the shallower waters of their traditional distribution (Figure 6), which may have a direct effect on their catchability from the commercial fleets. The depth associated with positive catch rates of *Nephrops* has been increasing since 1989 in all three stock areas. *Nephrops* movement capacity is low (Chapman and Rice, 1971) and limited by the type of sediment, so these changes could be attributed to the disappearance of *Nephrops* from the shallow waters more than to *Nephrops* displacements. Fishing effort and CPUE have been decreasing throughout the time series in the three stocks (Figure S12; ICES, 2021a).

Other kind of factors apart from fishing could also be involved in the observed dynamics of the *Nephrops* biomass. Thus, the decrease of *Nephrops* CPUE in Porcupine Bank has been related to an increase in temperature and frequency of storms (González Herraiz et al., 2009) but that was not the case in FU 25 (González Herraiz et al., 2015). The comparison of the temperature at the depth ranges that *Nephrops* inhabit (around 300-600 m) (Lavín et al., 2006; Punzón et al., 2016; Punzón et al., 2021) with the FU 25, FU 26 and FU 31 *Nephrops* biomass indices have not provided conclusive results (Figures 5A–C). Environmental conditions could have amplified the biomass collapse but fishing itself seems to be the main cause of the observed biomass development.

On the other hand, Northwest Iberian *Nephrops* fishery affects the abundance of large individuals in the three stocks analyzed (ICES, 2020; Cousido-Rocha et al., 2022a). This could cause a genetic overfishing because there could be a selection of genetic characters that slowed down growth, reproduction would carry out at smaller sizes and thus there would be less fecundity (Fariña, 1996; González Herraiz, 2011). Besides NW Iberian *Nephrops* fishery affects especially male individuals since they are bigger than females and also because females spend most of the year in the burrows (González Herraiz, 2011). The effect of the high fishing mortality could lead up to the point where females do not find males for mating (sperm limitation). In the worst case, low quantities of males could have decreased the reproduction potential of the population (ICES, 2013) and could therefore affect recruitment in subsequent years (González Herraiz et al., 2015).

Taking into account the biomass collapse in the three stocks, a basic recommendation that could be given about how to manage FU 25, FU 26-27 and FU 31 under a possible climate change impact is to apply the precautionary approach in the assessment and management processes.

In order to improve the tools for more robust stock assessments and to provide better insights into the management and conservation of *Nephrops* fisheries, more focused research is required in the future. Efforts should be directed towards better understanding of the life-cycle of the species on a local and regional scale, as well as improving the available tools for data collecting.

5 Conclusions

MSY assessments of marine stocks are essential due to the key role marine resources play in global food security and to curb the marine biodiversity decline. SPiCT can be a useful tool for assessing data-limited stocks when long time series of catch and biomass indices are available. The first MSY analytical assessments of FU 25, FU 26-27 and FU 31 *Nephrops* are presented in this manuscript.

Since the mid nineties the estimated biomassess of FU 25 and FU 26-27 remained below B_{lim} and the estimated biomass of FU 31 below MSY $B_{trigger}$. The declining trends in catches and survey indices of all three stocks are robust and consistent with the contraction of the stock area in FU 25 and FU 26-27 in the period 1983-2020 and with depleted stocks. The comparison of the biomass indices time series with the temperature time series at the depth at *Nephrops* live did not provide conclusive results. The average depth at which *Nephrops* is caught shows an increasing trend in the period 1989-2021 which might be indicative of an effect of changes in temperature but also due to the contraction of the stock following depletion. In future work, a model with different regimes or time-variant parameters should be explored. New studies should integrate new technologies and non-destructive methods such as underwater TV surveys in the area to assist in the assessment of these stocks.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://ices-library.figshare.com/articles/report/Working_Group_for_the_Bay_of_Biscay_and_the_Iberian_waters_Ecoregion_WGBIE_/18621449 See WGBIE 2021 Full_report.pdf, see FU 25 Catch in Table 12.1.1 (page 427), FU 25 index in Table 12.1.3 (page 430), FU 26-27 catch and index in Table 13.1.6 (page 488), FU 31 catch in Table 12.2.1 (page 455) and index in Table 12.2.2 (page 456).

Author contributions

IG: conceptualization, data curation, visualization, writing-original draft, formal analysis, and writing – review & editing. YV: data curation, writing- original draft, formal analysis, and writing – review & editing. MC: methodology and writing – review & editing. CB: methodology, software, and writing – review & editing. HW: methodology, software, and writing – review & editing. MA: methodology, software, and writing – review & editing. TM: methodology and writing – review & editing. AK: software and writing – review & editing. AV: data curation. RM: data curation. RS: data curation and writing – review & editing. MP: supervision, software, visualization, and writing – review & editing. All authors contributed to the article and approved the submitted version.

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Conflict of 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.

The reviewer ND declared a past co-authorship with the author HW to the handling editor.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1062078/full#supplementary-material

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