Aquat. Living Resour. 2023, 36, 23
© S. A. V. Akia et al., Published by EDP Sciences 2023
https://doi.org/10.1051/alr/2023018

Aquatic Living Resources
Available online at:
www.alr-journal.org

Research Article

Open Access

Towards "glocalised" management of tuna stocks based on causation between a stock and its component belonging temporally to local Exclusive Economic Zones

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Received 27 December 2022 / Accepted 20 June 2023

Abstract – The creation of Exclusive Economic Zones (EEZs) in 1982 gave coastal countries sovereignty over their local tuna resources, whereas the migratory nature of tuna calls for regional management. However, as regional tuna management by Regional Fisheries Management Organisations (RFMOs) does not always facilitate optimal management of local resources by coastal countries, there is a need for an approach that ensures both the achievement of regional management objectives and optimisation of local benefits, i.e., "glocalised" management. To promote "glocal" management measures for the local populations of highly migratory species, (1) the spatio-temporal VAST model was used to estimate abundance indices for the adult regional Eastern Atlantic yellowfin tuna population and its local component in Ivorian waters using catch and effort data and (2) convergent cross mapping was used to examine the causal relationship between changes in abundance at these different spatial scales over time. Convergent cross-mapping detected a causal relationship between general stock dynamics and local dynamics, in the direction from global stock abundances to local resource abundances. This implies that the success of local fishing was closely linked to the general state of the stock. Conversely, we found no evidence of a causal relationship in the direction from local resources to the regional stock. This suggests that local adult dynamics had little or no influence on overall stock dynamics. Based on these results, we propose several criteria to ensure fairer distribution of tuna resources between coastal states and distant water fleets (DWFs).

Keywords: Glocalisation / local fisheries / causal relationship / convergent cross mapping / abundance index / yellowfin tuna

1 Introduction

With an estimated annual production of 7 million tons, tuna and tuna-like species account for 20% of the market value of all marine catches and more than 8% of global seafood production.[1] Fishing for tuna plays a vital role in the economic development (Gillett et al., 2001; Sun et al., 2017), sustainable development (Bretherton and Vogler, 2008; Parris and Grafton, 2006) and food security of several countries and territories around the world (Gilman et al., 2017; McCluney et al., 2019).

It was difficult to apply an equitable sharing of tuna resources between countries until the 1982 United Nations Convention on the Law of the Sea (UNCLOS), which established the coastal State concept: a maritime space extending from the State's baseline to 200 nautical miles from its coastline over which it exercises sovereign and economic rights for the exploration and use of natural resources (United Nations, 1994). The creation of Exclusive Economic Zones (EEZs) gave coastal countries sovereignty (local scale) over natural resources (fish, offshore oil and gas). This convention has conferred a special regime on highly migratory species (HMS) such as tuna.

Due to their highly migratory nature, tuna stocks are managed at the stock scale which can be oceanic or regional, and which does not favour local management by each individual country. Indeed, no nation can unilaterally manage the tuna resources temporarily available in the waters under its jurisdiction (we will call this 'national resource' in the paper) because tuna pass through waters under the jurisdiction of many different nations as well as the high seas during their migrations. Bearing this in mind, the law of the sea has fostered cooperation among countries by establishing regional fisheries

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[1] Cf https://www.un.org/en/observances/tuna-day.

management organisations (RFMOs) to ensure the conservation of tuna and tuna-like species.[2] The objective of these organisations is to maintain populations at levels of abundance equal to or greater than those that will produce maximum sustainable yield (MSY) on a sustainable basis (United Nations, 1995). For several Tuna Regional Fisheries Management Organization (tRFMOs), this has evolved so as to maintain stocks in the green quadrant of the Kobe plot[3] (a plot common to all tuna RFMOs, showing the trajectory of a stock's status over time as a function of the ratios of annual biomass and fishing mortality to their respective reference levels) with high probability (ICCAT, 2013).

Tuna management at the regional scale favours the production of fishery indicators such as abundance indices, population growth rates, mortality, and movement rates at the stock scale, which are used as inputs for stock assessments. Attempts to optimise the management of local tuna resources by coastal States are sometimes limited or non-existent, thereby favouring regional management, which does not always consider local particularities. Regional management decisions sometimes require local measures, such as establishing marine protected areas or time-area moratoria. Conversely, each country's economic benefits derive from the national resources at its disposal depend on its choices and on the optimisation of management policies that complement regional recommendations. This issue highlights the need to promote tuna management methods that account for both local and regional interests. However, it is not always easy to find a balance between the simultaneous presence of global (i.e., considering the entire stock at regional scale) and local dimensions in managing and exploiting marine species like tuna (Gulland, 1980). The search for a perfect balance between regional and local interests is usually fraught with pitfalls due to the egotistical nature of organisations (Gordon, 1954; Colebatch and Larmour, 1993).

Taking the local and global dimensions into account in the assessment of facts is known as "glocalisation". Invented in the 1980s and popularised by sociologist Roland Robertson in the 1990s, glocalisation, a neologism derived from the fusion of "globalisation" and "localisation", refers to the notion of thinking globally and acting locally.[4] The Oxford dictionary defines glocalisation as adapting products or services available worldwide to make them suitable for local needs. The term originates from a Japanese expression, "dochakuka" (originally "dochaku"), expressing the local adaptation of foreign agricultural techniques (Robertson, 1994). As mentioned above, any glocalised tuna management approach would require a study of the interactions between the regional and local dimensions of the stock of the species under consideration. To this end, four relationships between the local and global dynamics of the stock of the study species are possible. (1) A situation in which the availability of the local resource depends on overall stock dynamics; (2) a situation in which the future of the global stock is affected by local operations; (3) a situation in which the two dynamics affect each other and, conversely, (4) the situation where they do not affect each other.

Relationships between biological phenomena such as interactions between species abundances can be analysed from a causal perspective (Borregaard and Rahbek, 2010). Furthermore, causality analysis makes it possible to determine whether global stock dynamics affect local abundance or vice versa. Convergent Cross Mapping (CCM) makes it possible to investigate nonlinear causal interactions between two time series by using a nonlinear state space reconstruction (Sugihara et al., 2012). This approach specifically aims to identify causation in ecological time series that are generally non-linear and non-stationary (Sugihara et al., 2012).

The development of glocalised management measures depends partly on the results of the interaction between the global dimension of the stock and the local dimension specific to the particular EEZ. In this paper, we address the case of yellowfin tuna in the Eastern Atlantic Ocean and its local resource in the Ivorian EEZ. This case study aims to inspire similar analyses with a view to promoting glocalised management approaches within RFMOs. We use the term "global" when talking about the regional dimension because the regional dimension represents the entire stock area and includes the local dimension.

The aim of this paper is to analyse the causal relationship between the local mature yellowfin resources in the EEZ of Côte d'Ivoire and the abundance index of the mature yellowfin population in the Eastern Atlantic. To achieve this aim, we (1) used abundance indices derived from catch-per-unit of effort (CPUE) data which were standardised applying a Vector-Autoregressive Spatio-Temporal (VAST) model to both the resources in the EEZ of Côte d'Ivoire (local scale) and the Eastern Atlantic Ocean (global scale) population, and (2) analysed the causal relationship between the two abundance indices with convergent cross mapping analysis. We conclude with a discussion of the different types of possible relationships between global stocks and their local components and how these relationships can be taken into account within RFMOs to improve regional fisheries management.

2 Materials and methods

2.1 Study area

The study area comprises the Eastern Tropical Atlantic. The global fishing area where purse seiners operate extends between latitudes 20°S and 20°N and longitude 35°W and 15°E (Fig. 1A). The local study area extends between latitudes 1°N and 6°N and longitude 2°W and 8°W (Fig. 1B). It is the smallest area that includes the 1° squares that make up the Ivorian EEZ. This area was selected to facilitate future comparisons with data collected by 1° square degrees and to avoid boundary effects. In the local area, on average 7.8% of total mature yellowfin tuna catches from this stock by purse seiners are taken annually (estimate made by the authors based on study data). A strong seasonal surface temperature signal characterises this EEZ because of two cold seasons, each associated with the coastal upwelling (Morlière, 1970). The main cold season occurs in austral winter between July and September. Winter cooling is then intensified on the coast by upwelling that brings nutrient-rich water to the surface. A second cooling occurs along the coast in

[2] See article 64 of the UNCLOS.

[3] Find a much more detailed explanation of the Kobe plot here https://www.iss-foundation.org/glossary/kobe-plot/.

[4] Cf https://www.investopedia.com/terms/g/glocalization.

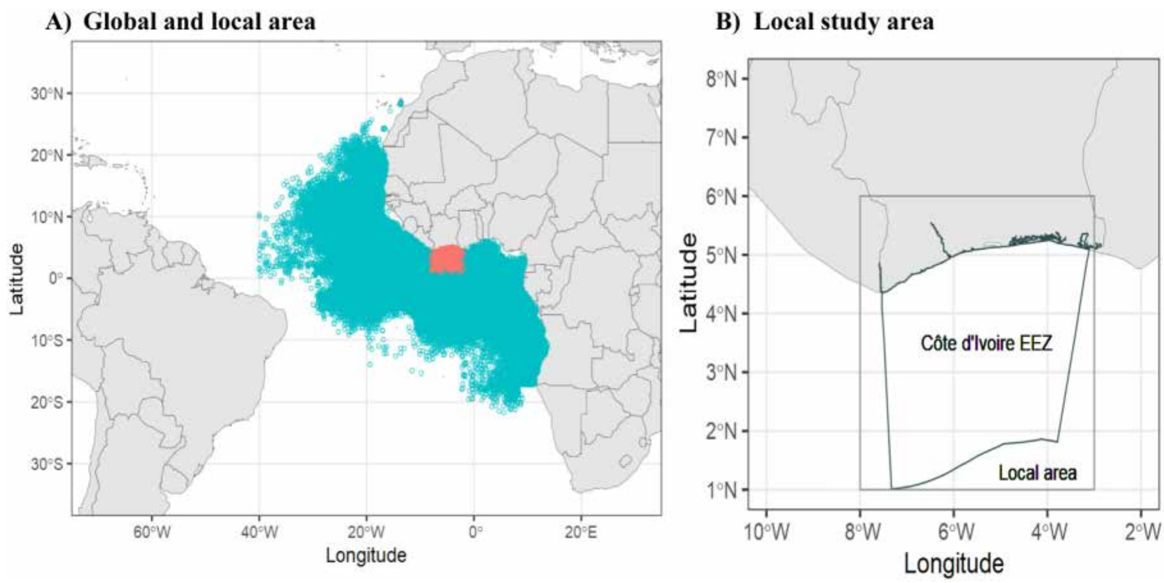

Fig. 1. (A) The global (Eastern Atlantic in blue) and the local (Côte d'Ivoire in pink) fishing areas for the purse seine fishery. (B) The local study area is used as a proxy of the EEZ of Côte d'Ivoire (i.e., the square area defined in this figure). We used only data from the blue area in Figure A to estimate the global abundance indices in this paper.

January-February. This second cold season is low-amplitude and short-lived (i.e., between one and two months, Cury and Roy, 1987).

2.2 Catch and effort data used for abundance indices

Catch and effort data concerning EU purse seiners operating in the Eastern Atlantic Ocean from 1993 to 2018 were compiled and managed by the Tuna Observatory (Ob7) of the French National Research Institute for Sustainable Development (IRD) for the French fleet, and by the Spanish Institute of Oceanography (IEO) for the Spanish fleet.

Logbook data for the French and Spanish purse seine fleets targeting tropical tuna in the Atlantic Ocean from 1993 to 2018 were analysed to derive standardised CPUE indices. The T3 methodology was used to correct the raw logbook data reported by the skippers regarding the total catch and species composition per set based on size and species sampling at landing to generate the level 1 logbook database used in this paper (see Pallarés and Hallier, 1997; Duparc *et al.*, 2020 for more details on the T3 method and the level 1 logbook database). The commercial size category was used to select mature yellowfin tuna. Commercial categories 2 and 3 (tuna $\geq$ 10 kg) were used as a proxy for mature tuna catches, while landings for category 1 (tuna $<$ 10 kg) were classified as immature tuna. The ICCAT manual (chapter 2.1.1: description of yellowfin tuna; item 3.d) https://www.iccat.int/en/iccatmanual.html) specifies that 50% of yellowfin individuals are mature at around 100 cm fork length (around 20 kg). However, for simplicity, we used the conventional commercial "size" categories reported in purse seiner logbooks by European skippers. Indeed, purse seiners commercial category 1 is composed of young fishes ($<$10 kg) caught under drifting fish aggregation devices (dFADs), while categories 2 and 3 (10 kg–30 kg and $>$30 kg, respectively) characterise free school sets and are dominated by large yellowfins and a few bigeyes (Ruiz et al., 2020).

All sets per boat and per day were combined and assigned to the centroids of the set locations. The total number of sets per day per boat was then filtered, and days with unrealistic data (over five sets per day per boat) were removed. The study area was defined by all grid cells where yellowfin tuna of category 2 and 3 had been fished for at least 5 years over a period of no less than 15 years, to avoid areas that were not routinely fished. Vessels with fewer activities than the 5th percentile of the cumulative number of days per boat (all activities combined) were removed. Given that free schools (FSC) are detected randomly at the sea surface, the unit of effort associated with this fishing mode is expressed as the search time (i.e., the time spent on the fishing ground minus the length of time required for all setting operations). Only catch and effort data from sets of mature yellowfin tuna ($>$10 kg) on FSC carried out in the local study area were used to calculate the local abundance indices, while all sets of mature yellowfin tuna ($>$10 kg) on FSC carried out in the global study area were used to estimate the global abundance indices, except the sets used for the local abundances indices to ensure the two time series were independent.

2.3 Methods

2.3.1 Spatio-temporal model for abundance indices

We applied a vector-autoregressive spatio-temporal delta-generalised linear mixed model to catch and effort data using the R package VAST (Thorson, 2019). The fact that VAST has recently been extended to take account of seasonal and interannual variability (Thorson et al., 2020) provides insights into how species distribution and abundance varies across seasons in one year, and also within one season across different years. The model performs reasonably well, even when not all the data are available for one or more combinations of years and seasons, which is common in commercial catch data. It should be noted that for these reasons, interest in VAST is growing for

CPUE standardisation in tuna RFMOs (Kitakado et al., 2021; Vidal, 2020; Vidal et al., 2020). To work at a finer temporal resolution (monthly, bi-monthly, quarterly), the estimates for year-season t are shrunk towards predicted densities in adjacent year-seasons ($t-1$ and $t+1$), as well as towards estimating density in other seasons in a given year and density in other years for a given season. This specification implies that the model includes a "main effect" for season and year, as well as an autocorrelated "interaction" of season and year. Below, we present a brief summary of the main parameters, the philosophy of the model, and some technical details, but readers are encouraged to refer to the Thorson et al. (2020) paper for more technical details.

The VAST model implemented in this paper is the "Poisson-link delta model" using a log-link function and a gamma distribution for the positive component (ObsModel = c (2, 1) in the R packages VAST). The Poisson-link delta model specifies a probability distribution for catches B, with b_i the catch for purse seine observation i (in our case, a purse seine observation is a set). The Poisson-link delta model includes the probability p_i that observation i encountered a given species [i.e., $\Pr(B>0)$], and the expected catch r_i given that the species was encountered, $\Pr(B\ B>0)$:

$$\Pr(B=b_i)=\begin{cases}1-p_i & \text{if} B=0\\ p_i \mathrm{G}\{B\, r_i,\sigma_m^2\} & \text{if} B>0\end{cases} \tag{1}$$

where we specify a gamma distribution G for the distribution of positive catches (i.e., successful sets with a catch greater than 1 ton). This delta model predicts encounter probability p_i and positive catch rate r_i by modelling two log-linked linear predictors, $\log(n_i)$ and $\log(w_i)$ for each observation i detailed below; n_i and w_i were then transformed to yield p_i and r_i:

$$p_i=1-\exp(-a_i n_i), r_i=\frac{a_i n_i}{p_i}w_i, \tag{2}$$

where a_i is an offset variable (units of effort: the time spent on the fishing ground minus the length of time required for all setting operations) for i. This model structure is designed so that expected catch density $d_i=b_i/a_i$ is the product of encounter probability and positive catch rate (i.e., $d_i=p_i r_i/a_i=n_i w_i$). Predictor n_i can be interpreted as density in numbers (i.e., number of individuals per fished area) and predictor w_i as average weight of an individual (in unit biomass). Compared to delta models with logit or log-link functions, the Poisson-link delta model has the advantage that both linear predictors use a log-link function so that all effects are additive in their impact on predicted log-density (the expected catch density). We model the linear predictors as:

The spatial correlation structure of both the spatial random effects (spatial main effect, season spatial effect, year spatial effect) and the spatiotemporal random effects (year-season spatial effect) was governed by a multivariate noal random field with a Matérn spatial covariance function. For the spatiotemporal random effects, a correlation structure was assumed for the temporal component of variation to account for seasonal variation within years. Model coefficient $V_n(v_i)$ represents random variation in catchability among individual vessels. It should be noted that the French purse seiners were targeting mainly free schools while the Spanish purse seiners were targeting dFADs. This difference in fishing strategy was less pronounced in recent years as the use of dFADs has increased in both fleets. There is likely also a vessel-size category component in the choice of the fishing strategy. To account for this, fleet country and vessel storage capacity (carrying capacity) were introduced in the analysis as catchability covariates. Modelling the impacts on encounter probability and positive catch-rate of different catchability covariates k was accomplished by estimating parameters $\lambda(k)$ (the estimated impact of catchability covariates for this linear predictor n and w) and the definition of the catchability covariate basis-matrix $Q(i,k)$ (see Thorson, 2019). For the estimation of global and local abundance indices in this study, the expected catchability for observation i corresponding to vessel v and fishing set s was composed of two additive factors: both fleet_country and storage_capacity were modelled as fixed effects, the latter using a three-degree polynomial spline implemented using the bs function in R package "splines" (R Core Team, 2021). Key model results for abundance indices are predicted density and area-weighted sum of density (i.e., total abundance). Combining eq. 3 and 4, annual densities for each extrapolation grid cell are estimated as follows:

$$d(s,t)=n(s,t)w(s,t) \tag{5}$$

Total abundance for the entire domain was estimated as the area-weighted sum of density $d(s,t)$ predicted at a fine spatial resolution:

$$I(t)=\sum_{s=1}^{n_s}a(s)d(s,t), \tag{6}$$

where n_s is the number of extrapolation grid cell and a_s is the spatial area associated. We defined 625 (25*25) km^2 as the spatial area of each fine scale grid for the local zone and of 2500 (50*50) km^2 as the spatial area for the global zone. We defined 150 knots for the global zone and 50 knots for the local

$$\log(n_i)=\underbrace{\beta_n^*(t_i)}_{\text{Year - Season intercept}}+\underbrace{\omega_n^*(s_i)}_{\text{Spatial maineffect}}+\underbrace{\xi_{nu}^*(s_i,u_i)}_{\text{Season spatialeffect}}+\underbrace{\xi_{ny}^*(s_i,y_i)}_{\text{Year spatialeffect}}+\underbrace{\epsilon_n^*(s_i,t_i)}_{\text{Year - Season spatialeffect}}+\underbrace{\xi_n^*(i)}_{\text{Catchability covariates}}+\underbrace{V_n(\upsilon_i)}_{\text{Vessel effect}} \tag{3}$$

$$\log(w_i)=\underbrace{\beta_w^*(t_i)}_{\text{Year - Season intercept}}+\underbrace{\omega_w^*(s_i)}_{\text{Spatial maineffect}}+\underbrace{\xi_{wu}^*(s_i,u_i)}_{\text{Season spatialeffect}}+\underbrace{\xi_{wy}^*(s_i,y_i)}_{\text{Year spatialeffect}}+\underbrace{\epsilon_w^*(s_i,t_i)}_{\text{Year - Season spatialeffect}}+\underbrace{\xi_w^*(i)}_{\text{Catchability covariates}}+\underbrace{\mathrm{V}_w(\upsilon_i)}_{\text{Vessel effect}} \tag{4}$$

zone, and used quarters as seasonal dimension. Abundance indices were calculated as a spatial average of the predicted density across the model extrapolation grid. Uncertainty around the index was derived using a generalisation of the delta-method (Kass and Steffey, 1989). The spatiotemporal models converged if the gradient of the marginal log-likelihood was less than 0.0001 for all fixed effects, and that the Hessian matrix of second partial derivatives of the negative log-likelihood was positive definite (Grüss et al., 2020). The framework of the models is presented in supplementary material.

2.3.2 Convergent cross mapping

Convergent cross mapping (CCM) is a statistical test for a cause-and-effect relationship between two variables (Sugihara et al., 2012). CCM is based on the theory of dynamical systems and can be applied to systems where causal variables have synergistic effects. As such, CCM is specifically intended to identify linkage between variables that can appear uncorrelated with each other. It has been used to demonstrate that the apparent correlation between sardine and anchovy in the California Current is due to shared climate forcing and not direct interaction (Sugihara et al., 2012).

The convergent cross mapping algorithm is based on Takens' embedding theorem (Takens, 1981). CCM can detect and help quantify the relative strength of unidirectional and bidirectional causal relationships between variables X and Y in coupled complex systems. Takens' theorem generically proves that the state space of a dynamical system can be reconstructed from a single observed time series of the system, X. This reconstructed or shadow manifold M_X is diffeomorphic to the true manifold, M, preserving instrinsic state space properties of M in M_X.CCM leverages a corollary to the Generalized Takens Theorem (Deyle and Sugihara, 2011) that says that it should be possible to cross predict between two variables X and Y observed from the same system. If X causes Y, X leaves its signature on Y, and consequently, the reconstructed states based on Y can be used to cross predict values of X. CCM leverages this property to infer causality by predicting X using M_Y libraries based on increasing number of points (library size L) (or vice-versa for the other direction of causality). If the prediction skill of X increases and saturates as the entire M_Y is used, this provides evidence that X is causally influencing Y. Cross mapping is generally asymmetric. If X forces Y unidirectionally, variable Y will contain information about X, but not vice versa. Consequently, the state of X can be predicted from M_Y, but Y will not be predictable from M_X.

Multi-spatial CCM was developed for use with short time series (Clark et al., 2015). It introduced a parametric test to evaluate the causal significance. Causality analysed in this paper through the multi-spatial CCM approach does not claim to deal with causality in its strictest sense, which would mean that X is the leading cause of the existence of Y. This causality approach is about causal influence, i.e., the dynamics of the caused variable Y are directly influenced to some measurable extent by the causal variable X. Time series X_i and Y_i are the local abundance indices and the global abundance indices derived from the local zone catch and effort data and the stock zone without the local area, respectively. The multi-spatial CCM used a bootstrapping method to leverage information. We drew n_s samples (with replacement) among all library size vectors (L) and repeated the test to identify for the optimal embedding dimension (E) value. This provided estimates for uncertainty around the predictive power estimated in each test. In this paper, we used 100 iterations per test and for each iteration calculated the Pearson correlation coefficient ρ for each library length. We then tested whether these predictions indicated a significant causal relationship by testing if the calculated ρ was significantly greater than zero and whether it increased significantly with L. We interpreted CCM results for which ρ was greater at the longest L available than at the shortest L available, and where ρ at the longest L was greater than zero as indicating causal forcing. For this analysis, we used 10 library size vectors L ranging from 10 to 100 (steps of 10). To test for statistical significance of this signal, we used the nonparametric bootstrapping conducted above to leverage information to determine whether the ρ vs. L relationship passed both of these criteria for at least 95% of bootstrapped iterations. All statistical analyses were conducted with R 4.1.2 (R Core Team, 2021), and the R packages VAST (Thorson, 2019). and multi-spatial CCM (Clark et al., 2015).

3 Results

3.1 Abundances indices

For each catch and effort data set (global and local), a spatio-temporal delta-generalised linear mixed model was implemented using R package VAST release number 3.8 (Thorson, 2019) to estimate abundance indices. We checked convergence by checking that the gradient of the marginal log-likelihood was less than 0.0001 for all fixed effects, and that the Hessian matrix of second derivatives of the negative log-likelihood was positive definite. Both the spatiotemporal models meet these criteria (Table S1).

For the global area, temporal patterns in the VAST standardised and nominal (raw data) CPUEs were generally in accordance, while the magnitude of variations was larger for nominal CPUEs compared to standardised CPUE (Fig. 2). Similar results were found for the local area (Fig. 3). The comparison of quarterly variations in standardised CPUEs of local and global resources showed good agreement, with local maxima and minima often in the same quarters (Fig. 4). Model outputs confirming convergence and summaries for the models are shown in supplementary material (Figs. S1–S7 and Tab. S1). Outputs include the spatial locations of knots determined by the K-means algorithm (Fig. S1), abundance indices for the global and local zone, the effective areas occupied and the centre-of-gravity of the adult yellowfin tuna distributions (Figs. S2 and Figs. S2 and S3), anisotropies (Figs. S4 and S5), spatial distributions of residual quantiles and quantile-quantile residual plots for the two models (Figs. S6 and S7), and parameter estimates and maximum gradient components (Tab. S1). The abundance indices obtained at this stage were used as input in the following analysis.

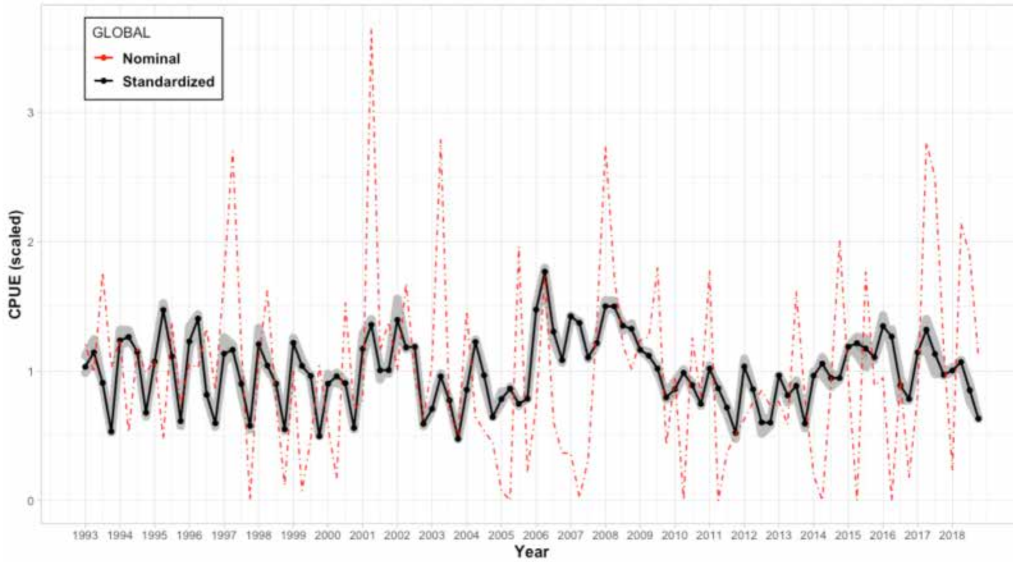

Fig. 2. VAST standardised Catch per unit effort (CPUE, interpreted as abundance index) for free school sets of mature yellowfin tuna of the global zone (black line), with 97.5 CIs (grey) and compared to nominal CPUEs (red). Time series are quarterly (inspired from Guéry et al., 2020). To scale values, annual values of the indices were divided by the average of the whole period.

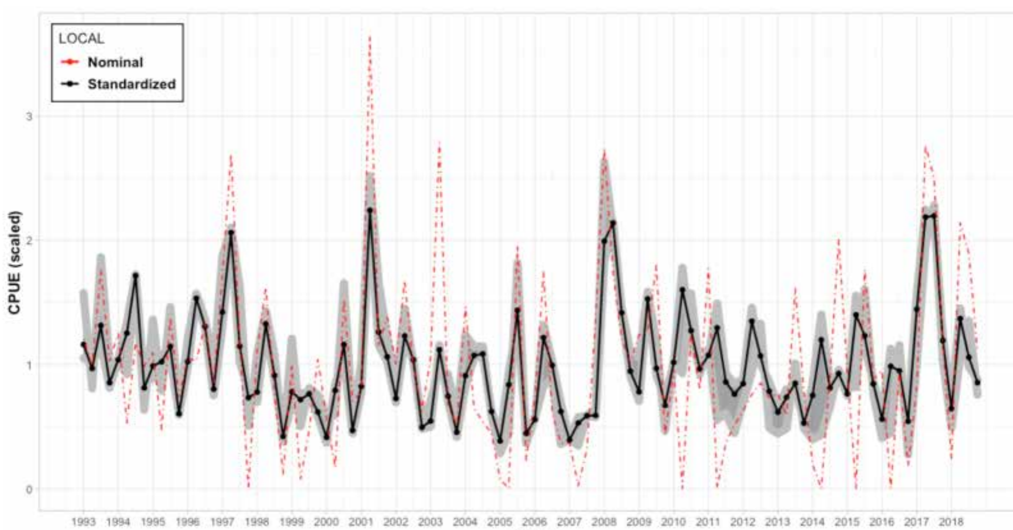

Fig. 3. VAST standardised CPUE for free school sets of mature yellowfin tuna of the local zone (black line), with 97.5 CIs (grey) and compared to nominal CPUE (red). Time series are quarterly. To scale values, annual values of the indices were divided by the average of the whole period.

3.2 Convergent cross mapping

Applying CCM starts by identifying the maximum embedding dimension of each variable. The optimal embedding dimension was estimated as 10 for the global abundance indices and 6 for the local abundance indices (Fig. 5). The causal relationship was significant where rho (the cross-map skill) was greater at the longest available library subset size than at the shortest library size, with rho at the longest library size beings greater than zero (Fig. 6). Bootstrapping conducted in the multi-spatial CCM made it possible to test the null hypothesis of no causal relationship. Our results suggested that the variations of the global scale resource significantly causally influenced the abundance indices at the local scale, whereas the local scale did not causally influence global scale abundance indices.

4 Discussion

This study analysed the causal relationship between temporal changes in standardised CPUE of the adult Eastern Atlantic yellowfin tuna population and its local component in the EEZ of Côte d'Ivoire. The noticeable differences between the nominal CPUEs and the standardised CPUEs underlines the importance of standardising CPUE to construct abundance

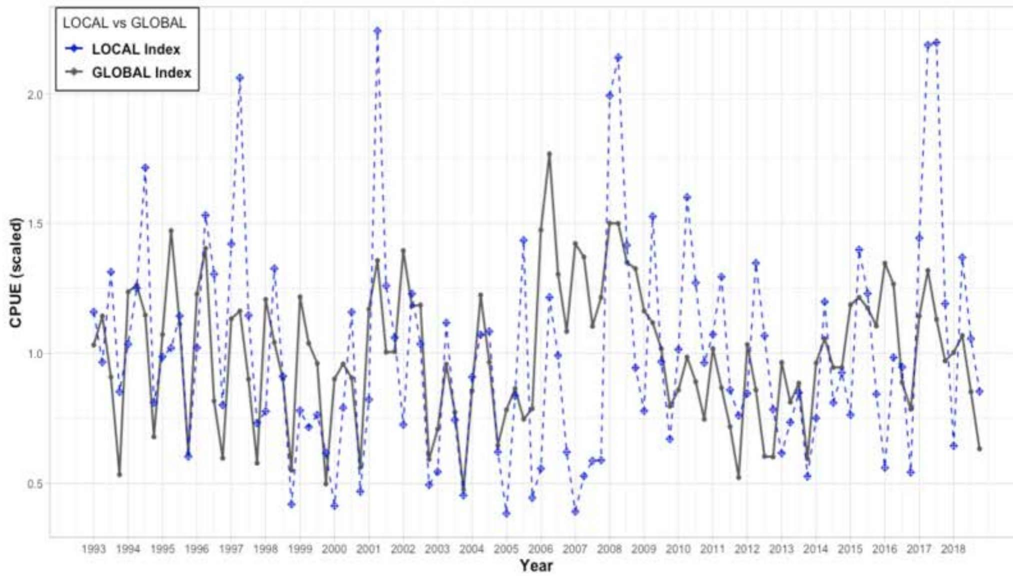

Fig. 4. VAST standardised CPUE for free school sets of mature yellowfin tuna of the global zone (black line) compared to standardised CPUE for free school sets of mature yellowfin tuna of the local zone (blue). Time series are quarterly.

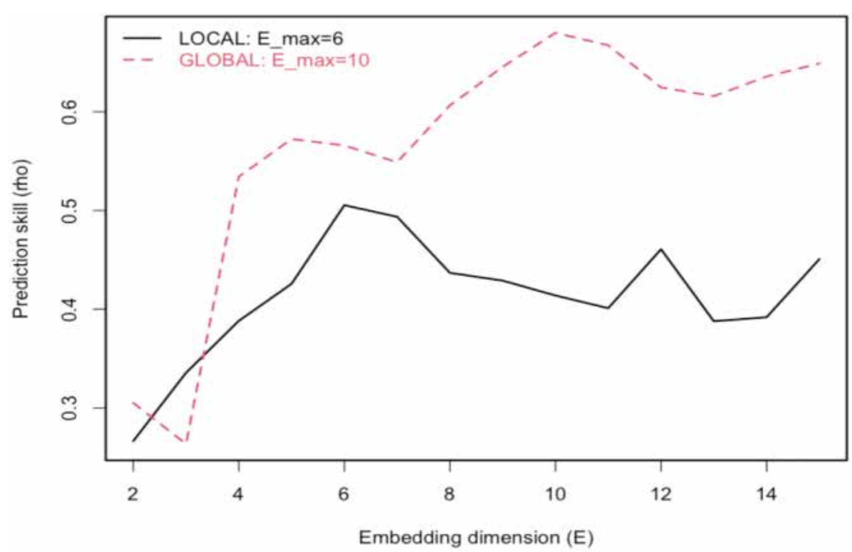

Fig. 5. The optimal embedding dimensions E of the two series of abundance indices (VAST standardised CPUEs).

indices. Once this precaution has been taken, we can conclude that there was no evidence of a causal relationship in the direction from local abundance to global stock abundance (Fig. 6).

This result is not trivial as a large harvest of a few age classes (e.g., spawners) in a reduced area might affect the whole stock, but we found no evidence of this in our study. On average, 7.8% of total mature yellowfin tuna catches from this stock by purse seiners are taken in the local area (estimate made by the authors based on study data). Conversely, our findings showed that abundance variations in the adult yellowfin tuna resource transiting Ivorian waters were directly linked to abundance variations of this component in the overall population of the Eastern Atlantic Ocean, suggesting that the dynamics of the abundance of the local resource was causally driving by the dynamics of the abundance of the regional stock. Thus, this study showed that the local and global dimensions are not always disconnected in terms of yellowfin tuna abundance. In such a case, a coastal country with sovereignty over the local adult yellowfin tuna resource needs to be involved in the global management of this species at the regional scale. Thus, the effectiveness of local management of this species depends on the achievement of global management objectives, as it has a direct impact on the availability of the local resource in the Ivorian EEZ. This stresses the need to establish a glocalised management approach to this resource.

Causality in the sense of CCM is based on the intuition that X causes Y, if part of the temporal history of X can reliably estimate the states of Y. This means that possible shocks (negative: over exploitation, stock collapse, etc., or positive:

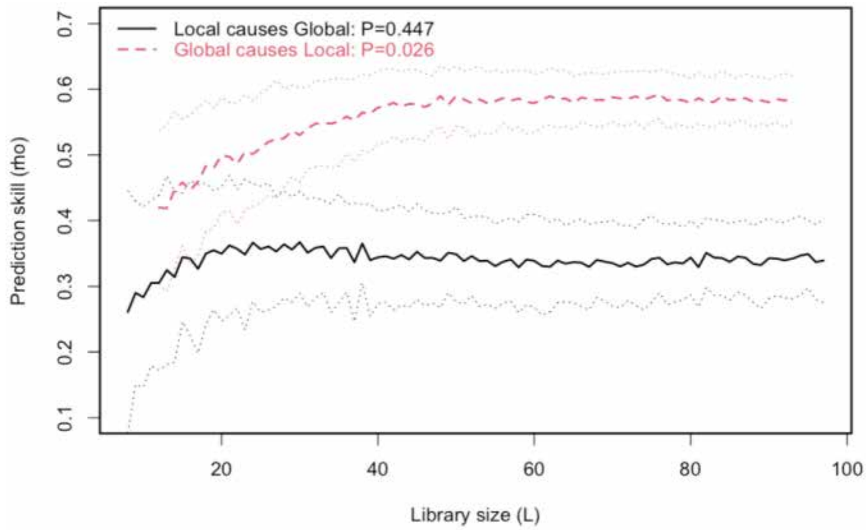

Fig. 6. Results of Convergent Cross Mapping applied to the global and the local abundance indices of the Eastern Atlantic yellowfin tuna. The red and black lines represent the effect of Global on Local and conversely. Thin colour lines show mean ± SD from bootstrapping. The figure presents predictability (rho) as a function of library size (L). The *p* value is for the significance of each causation direction. Causal forcing is indicated when rho is significantly greater than zero for large library length L and that rho increases significantly with increasing L.

stock rebuilding following the application of good management policies, strong recruitment) occurring at the global level would affect the local resource in the Ivorian EEZ. However, the CCM did not enable complete modelling of all factors external to the studied system-couple likely to affect it, as would be the case of the Granger causality method. Unfortunately, the Granger causality method is not appropriate for the analysis of systems with non-linear and interdependent dynamics like ecological phenomena. Thus, it should be stressed that the results of the causal relationship as analysed in this paper do not mean that the local resource is solely dependent on the global resource. The abundance of the local resource could also depend on factors such as environmental conditions whose effects would combine with the global abundance level.

The significant relationship between the global and the local abundance indices can be explained by the biology of the yellowfin population in the Eastern Atlantic Ocean. Several studies have shown that a large population of mature yellowfin generally congregates in the Gulf of Guinea in the first quarter of the year to spawn (Albaret, 1977; Kitchens, 2017). This phenomenon generates high densities followed by an increase in catchability of adult yellowfin tuna in free schools which contribute most of the catches of yellowfin by purse seiners in the Eastern Atlantic Ocean (see **Figs. S8** and **S9** in supplementary material). While studying the exploitation of large yellowfin tuna caught in free school concentrations in the 2013 spawning season, Fonteneau et al. (2017), highlighted a sort of cyclic pathway that links the zones of latitude covering the local study area (see **Fig. S9** in supplementary material). The Fonteneau et al. (2017) study partly explained the relationship between the local resource of this species and the rest of the overall Atlantic Ocean population and corroborated the sense of causality we established. Schematically, we can say that the local abundance of the Ivorian EEZ is nourished by seasonal migrations of local concentrations of this regional resource. Hence the impact of regional exploitation level on the seasonal availability of the local resource.

The analyses in this paper were based on several working assumptions and choices that should be mentioned. Several fleets and gear types exploit the tuna resources of the Ivorian EEZ and the Atlantic Ocean stock, but our study was limited to European purse seiners. This choice guaranteed the consistency of the results due to the better quality of the data and data availability, but interpretations may be affected by the selectivity of purse seiners. It is important to keep this in mind when considering the conclusions of this research.

The causal analysis in this paper was based on the concept of glocalisation. As we have seen for the Ivorian case, global management may influence the profitability of coastal fisheries if the causality proceeds in the direction of global to local. Conversely, the opposite direction would mean that local resource management should be managed with caution as local exploitation (abuse) could significantly influence the state of the global population as a whole. Due to spatial disparities, local factors (e.g., environmental conditions, the level of exploitation) and the regional nature of their management, it is essential that RFMOs and their coastal contracting parties promote glocalised management approaches for their tuna resources. This implies that in addition to the local and regional knowledge available on tuna, consideration should be given to assessing the nature of the interactions between stock and local resources, as analysed in this paper.

From a theoretical point of view, we can distinguish four types of causal relationships between the global and local scale. In the next section, we will discuss these four scenarios, illustrate them with real-life examples and suggest ways to consider the implementation of glocalised management approaches for each scenario. Although this goes far beyond the results presented for the Côte d'Ivoire EEZ, we would like to lay the foundations for an approach taking into account the analysis of the relationships between global and local abundances in the development of glocalised management strategies for migratory species whose management has been entrusted to regional organisations. The four scenarios are as follow:

(1) *The local causally influences the global*. In this case, the health of the global stock is, to some extent, a function of the level of exploitation of the local level. This situation assumes control of local exploitation and may lead to global management decisions aimed at regulating local exploitation. This kind of situation is sometimes at the heart of global decisions such as establishing spatio-temporal moratoria or other local Marine Protected Area (MPA) to protect and ensure the rebuilding of a stock. Moratoria are usually implemented to control fishing effort, improve spawning potential by protecting adults during the spawning season, or by protecting juveniles from depletion before recruitment to the fishery (Gulland, 1977). When the level of exploitation of a local area or a region including the local area has a proven capacity to influence the status of the global stock, the local area is included in the regulation of fishing activities by RFMOs.

An example for this case is the inclusion of several EEZs of countries bordering the African coast in establishing the ICCAT FAD moratorium area (**Fig. S10**;ICCAT, 2020). The application of measures such as a moratorium has a negative impact on the immediate benefits from local EEZ resources whose areas are affected by the decision. The majority of developing coastal countries with few or no industrial commercial fishing boats favour access agreements with distant water fleets (DWFs) to achieve better use of their local resources. According to the FAO (2022) typology, access arrangements covering a high percentage of global fisheries can be classified as either first-generation access arrangements or second-generation access arrangements. First-generation access arrangements involve allocating fishing access in return for financial payment. They can have different formats, such as bilateral or plurilateral, government-to-government, industry association-to-government, and firm-to-government (FAO, 2022). Second-generation access arrangements involve one or two broad mechanisms. They can include allocating access and/or reduced licensing costs for foreign vessels to register locally. They can also include the agreement to use local goods and services through transhipment and/or land the fish domestically. Alternatively, they can require onshore investments in return for fishing access, such as processing facilities. Commitments to onshore investments can take the form of joint venture enterprises and involve direct and indirect employment generation, spin-offs in ancillary industries, exports, and technology transfer, among others (FAO, 2022).

When global management decisions aim at regulating local exploitation by measures such as establishing spatio-temporal moratoria, the coastal countries are deprived of fishing for the component of the resource concerned or could see their fishing agreement with foreign fleets negatively affected. It should be recalled that the dependency of coastal contracting parties and co-operating non-contracting parties (CPCs) concerns not only nutritional aspects but also employment and access to foreign currency. In the case of Côte d'Ivoire, the by-product of the purse seine fishery landed in the local market of Abidjan (i.e., the "Faux-poisson") represents an average of 22,500 tons per year (Shep, 2016). The tuna processing industry in Côte d'Ivoire generates about 15% of total export earnings, creates 3500 jobs with a high predominance of women in canneries and another 35,000 jobs in various upstream and downstream services and goods businesses (Caillart et al., 2014). Employment generated by ancillary activities related to port calls (e.g., landings, canneries, bunkering [refuelling] facilities, gear repair, port taxes, etc.) may be significantly influenced by the implementation of spatio-temporal regulations of fishing. However, it should be kept in mind that when dealing with issues like differentiated responsibilities, demonstrating disproportionate or adverse impacts requires data, and for tuna fisheries, the small-scale sector, and catch destined for local markets, continues to be under-represented in the available data (Sinan et al., 2021).

Any such management decisions must therefore include a compensation factor for affected EEZs. When establishing conservation and management measures (CMMs), compensation plans should be developed within RFMOs through discussion between scientists, politicians and stakeholder managers. This could generate some win-win commitments of the RFMOs towards the coastal countries and a commitment of the coastal countries to ensure compliance with the management measures by providing quality data. Convergence towards glocalised management that considers both the local interest and the achievement of the regional objectives of RFMOs will make it possible to ensure, on the one hand, the proper application of regional measures to ensure their efficiency and, on the other, to compensate the coastal CPCs, favour their effective involvement in the RFMOs and obtain their collaboration in the achievement of its future objectives.

(2) *The global causally influences the local.* This means that the local resources depend on the level of exploitation at the global scale. In this case, local resources would be influenced by a decrease in abundance at the global level due to periods of over-exploitation. Therefore, a glocalised management approach for local tuna resources cannot be complete without reference to fluctuations in the state of the global stock. In such situations, the management objectives at the global scale must include maximising the local countries' benefits to avoid disengagement from cooperation objectives.

The best example is the case of the coastal countries in the Western and Central Pacific oceans. This region accounts for 60% of the world's annual tuna production (Harley et al., 2014), has large EEZs and fisheries, and is of greater economic importance than the Eastern Atlantic Ocean coastal countries. However, the coastal countries in the Western and Central Pacific oceans face difficulties implementing sustainable tuna stocks on a global (regional) scale. This (global) management inefficiency is due to the Pacific Island member states' divergent political and economic interests (Hanich et al., 2010). As a result, there are three levels for any management agreement for tuna fisheries in this area: national, sub-regional and regional (Hampton, 2010). The Pacific Islands Forum Fisheries Agency (FFA) members prioritised national fisheries management for the different fisheries operating in their EEZs (Hampton, 2010). However, with the aim of negotiating with DWF CPCs, some FFA members have formed coalition groups to develop coordinated management measures at the sub-regional level (Davis and Hanich, 2022). The first, known as the Parties to the Nauru Agreement (PNA), envision ecologically sustainable fisheries, tightly controlled and managed through PNA cooperation, generating diverse maximum economic and social benefits.

It is clear from these examples that the best tuna fisheries management must seek to achieve global (regional) management objectives and maximise local profit. Miller et al. (2014) explore the extent to which a sub-regional (with mostly local decisions) and an RFMO interact in managing regional tuna fisheries by examining the interplay between the regional Western and Central Pacific Fisheries Commission (WCPFC) (global scale) and the Parties to the Nauru Agreement (local scale). They concluded that unilateral management at the global or sub-regional level cannot effectively manage the tuna fisheries in this area. However, the combined work of the PNA and the WCPFC may offer a testing ground for functional multilateralism based on shared resources and using both regional and sub-regional governance platforms.

When the level of exploitation of a local area or an adjacent area is affected by the overall level of exploitation, coastal countries are directly concerned by the sanctions against the flags that do not respect the quotas. The resources legally belonging to the coastal countries are reduced without compensation. These countries, which sometimes establish fishing agreements with other DWF CPCs, could see their reference tonnage influenced over the years because of the impact of possible over-exploitation of the rest of the stock on the local resource. It would be more appropriate to propose financial compensation to make up for the shortfall of the latter by levying fines imposed on CPCs that exceed their quotas.

(3*) Lack of causality between the local and the global.* In this case, the management of local resources is independent of the level of exploitation of the stock at the global scale. Management would consequently focus more, for example, on the local level of exploitation of the resource and on regulating local fishing effort.

Finally (4) *Bidirectional causality between the local and the global* is a combination of the first two cases.

In view of the results of this study, its implications and the above discussion, we recommend a glocalised management approach that depends on the nature of the causal relationship between the entire stock and the resources of the coastal countries' EEZs. Regardless of the direction of causality, the existence of a causal relationship between the global stock and local resources influences the profits of coastal countries. The profits of coastal countries are either affected by over-exploitation of the rest of the stock, or by global management measures that promote spatio-temporal based closures. These factors are not frankly addressed, but the tensions that flow from them are perceptible and sometimes fuel discussions within RFMOs. Unilateral management either based on global decisions or sometimes monopolised at the local level, like the case of the Western and Central Pacific countries, reveals its flaws and risks dislocating unity within RFMOs in the long term.

By comparing the resource allocation approaches of the five tuna Regional Fisheries Management Organisations, Seto et al. (2021) showed that all tRFMOs except one had defined resources for allocation and outlined principles to guide allocation based on equity, citizenship, and legitimacy, but all fell short of applying these principles in assigning fish resources. Most tRFMOs rely on historical catch or effort, while equity principles rarely determine dedicated rights. In practice this leads to favourable treatment in allocation to states that have been active in the fisheries for some time (Henriksen and Hoel, 2011). Although the United Nations Fish Stocks Agreement (UNFSA) clearly identified the concept of allocation as a substantive matter and provides guidance, distribution and equity only emerged in tRFMOs in the mid-1990s (Seto et al., 2021). For example, in the Eastern Pacific, the limit in fleet capacity allocated to each state includes not only the historic catches over a period of reference, but also the catch historically taken within the zones where each state exercises sovereignty or national jurisdiction, tuna landings in each nation as well as the contribution of each state to the IATTC conservation programme (IATTC, 1998). In ICCAT, the tuna RFMO considered in this study, the status of participants (i.e., various needs and requirements) is one of the four criteria considered for allocation (Henriksen and Hoel, 2011; ICCAT, 2003). Note that this does not disengage the coastal CPCs with respect to compliance with ICCAT CMMs and responsibilities concerning data submission and research.

Furthermore, the current system of annual negotiations reduces certainty, trust, and transparency, counteracting many benefits asserted by rights-based management proponents (Seto et al., 2021). In contrast, it is assumed that more equitable CMM are more effectively implemented. Greater transparency is likely to engender greater trust in CMM negotiations and outcomes, and greater support for their implementation (Davis and Hanich, 2022).

Allocation mechanisms have been established by CPC in the majority of tRFMOs. However, the exploitation of tuna takes place at a range of spatial scales and the impact of fishing on the species depends on their distribution, which favours imbalances in the distribution of resources when making overall management decisions. We suggest that approaches for the allocation of tuna resources should be part of a glocalised management approach. This involves combining several parameters to find a satisfactory compromise between the benefits of coastal countries and the achievement of the overall objectives of the tRFMOs without disadvantaging foreign flags (countries without EEZs in the area of distribution of the stock concerned) which exploit the resources. The quotas of coastal countries should therefore be upgraded taking into account the areas of the EEZs and/or the catch taken in this EEZ (even if this assumes a greater financial contribution of the coastal CPC to the annual budget of the tRFMO), the quality and the adequacy of the data produced by coastal countries, a spatialised approach to the redistribution of quotas to account for the distribution of species according to their biology and the capacity of the coastal country to exploit its resource.

From all these discussions, it emerges that the need to adopt glocalised management approaches is now urgent and important and requires that this issue be openly addressed within the tRFMOs to ensure better management of tuna.

5 Conclusion

This paper showed that although tuna populations are generally analysed at the stock level, a causal relationship between standardised CPUEs of the whole population and the abundance of the resources of coastal countries may exist. Hence, the need to bear in mind that tuna fishing has two dimensions at two different scales: global in terms of how stocks are assessed and managed, and local in terms of their temporary belonging to a coastal country's EEZ. The global management by RFMOs prioritised in the 1982 United Nations Convention on the Law of the Sea can be reinforced by components aimed at optimising how coastal countries benefit from their local resources. In return, optimising the local benefit of coastal states would promote their active involvement and full participation in the programmes of tRFMOs. This active involvement would ensure that research and knowledge on tuna resources advance through the collection and sharing of good quality data, knowledge, and local experience. The advancement of research and knowledge will facilitate good decision-making to ensure sustainable and profitable exploitation of these resources. Our paper does not call into question the current management of tuna fisheries by RFMOs, but proposes guidelines to optimise current management by ensuring maximisation of benefits derived from their local resources by coastal countries. All these proposals can be summarised as the promotion of glocalised management approaches to tuna fisheries. This requires additional consensus-building efforts and a higher level of commitment from coastal countries. Further, it requires case studies such as those conducted in this study to evaluate the state of local resources and their degrees of dependence on the global stock.

Acknowledgements. This project was co-funded by IRD (ARTS funding) and the "Observatoire des Ecosystèmes Pélagiques Tropicaux exploités" (Ob7) from IRD/MARBEC. We sincerely thank the staff of the Ob7 for providing data on the French fleet, and the staff of the IEO (Instituto Español de Oceanografía) especially Pedro Pascual Alayon for providing data on the Spanish fleet. The authors also thank Lorelei Guery (IRD-MARBEC) for many helpful suggestions and advice regarding our analyses.

Our gratitude also goes to the reviewers of this manuscript for their comments, corrections and suggestions for its improvement.

Competing interests statement

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

Author contribution statement (CRediT)

S. AKIA: Conceptualisation, Methodology, Data curation, Formal analysis, Software, Validation, Visualisation, Investigation, Writing −original draft.

M. Amandè: Conceptualisation, Supervision, Writing −review & editing, Supervision.

D. Gaertner: Conceptualisation, Resources, Validation, Writing −review & editing, Supervision, Funding acquisition, Project administration.

Funding statement

This research was co-supported by IRD (ARTS funding) and the "Observatoire des Ecosystèmes Pélagiques Tropicaux exploités (Ob7) from IRD/MARBEC.

Data availability statement

The data were provided by Ob7 staff for the French fleet and IEO (Instituto Español de Oceanografía) staff for the Spanish fleet and can be obtained from these two institutes, on request.

Supplementary Material

Figure S1. Visualisation of the spatial structure used to approximate the spatial variation in each case-study (after projecting Latitude/Longitude to UTM coordinates measured in eastings (x-axis) and northings (y-axis). Red circles show the location of interior knots (50 for the local zone and 150 for the global zone) where this dots was chosen a priori and knots were then allocated using a k-means algorithm in proportion to the available sampling data. Black dots represent the extrapolation-grid ($\simeq 0.227°$ for local zone and $\simeq 0.45°$ for the global zone) used when approximating the integral across the fishing location.

Figure S2. Abundance indices (A; representing total biomass at the chosen spatial domain, in metric tons), effective area occupied (B; representing area needed to contain the population at average biomass-density, in km2), and northward (C) - eastward (D) center-of-gravity (C and D; representing the centroid of the population) each showing bias-corrected maximum likelihood estimate (ovals) and +/- one standard error (whisker) for each quarterly index of the adult yellowfin tuna resource in the global area; the period is from 1993 to 2018 (26 years * 4 =104 quarters).

Figure S3. Abundance indices (A; representing total biomass at the chosen spatial domain, in metric tonnes), effective area occupied (B; representing area needed to contain the population at average biomass-density, in km2), and northward (C) - eastward (D) center-of-gravity (C and D; representing centroid of the population) each showing bias-corrected maximum likelihood estimate (ovals) and +/- one standard error (whisker) for each quarterly index of the adult yellowfin tuna resource in the EEZ of Côte d'Ivoire; the period is from 1993 to 2018 (26 years *4 =104 quarters).

Figure S4. The predicted geometric anisotropy for the GLOBAL model. The ellipses give the 10% decorrelation distance for each of the two model components (delta model).

Figure S5. The predicted geometric anisotropy for the LOCAL model. The ellipses give the 10% decorrelation distance for each of the two model components (delta model).

Figure S6. A)The quantile-quantile plot of residuals (left) and plot of how residuals vary with magnitude of the prediction (right). B) Spatial map of quantile residuals by quarter. Results for the GLOBAL area.

Figure S7. A)The quantile-quantile plot of residuals (left) and plot of how residuals vary with the magnitude of the prediction (right). B) Spatial map of quantile residuals per quarter. Results for the LOCAL area.

Figure S8. Geographical distribution of yellowfin tuna total catches by major gears in the Atlantic Ocean (ICCAT zone) from 2010 to 2016 (Source: ICCAT, 2019).

Figure S9. Overview of a hypothetical spawning migration pattern of adult yellowfin, from the North Central Atlantic Ocean in summer, to the Gulf of Guinea before, during and after each 1st quarter (from Fonteneau et al., 2017).

Figure S10. ICCAT recommendations since their introduction in 1999. FAD stands for fish aggregating devices. (figure from (Stephan et al. 2022)).

Table S1 Summary details of the models used in this application. For each model, the following information is given: number of fixed effects, number of random effects, total estimated parameters and maximum gradient component.

Table S2 Abundance indices per year-quarter

The Supplementary Material is available at https://www.alr.fr//10.1051/alr/2023018/olm.

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Cite this article as: Akia SAV, Amandè MJ, Gaertner D. 2023. Towards "glocalised" management of tuna stocks based on causation between a stock and its component belonging temporally to local Exclusive Economic Zones. *Aquat. Living Resour.* 36: 23