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APPLICATION

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SMARTR: An R package for spatial modelling of fisheries and scenario simulation of management strategies

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Abstract

1. Overfishing or exploitation patterns with high juvenile mortalities often negatively impact demersal fish stocks. Meanwhile, the increased availability and diffusion of georeferenced information is propelling a revolution of marine spatial planning.
2. A spatial-explicit approach to the management of fishing effort should protect the Essential Fish Habitats and minimize the impact of trawlers on areas where juveniles of commercial species concentrate.
3. The SMARTR package is a data-driven model that implements the Spatially explicit bio-economic Model for Assessing and managing demeRsal Trawl fisheries to edit and format the raw data; construct and maintain coherent datasets; to numerically and visually inspect the generated metadata; to simulate management scenarios and forecast the possible effects in terms of resources status and economic performances of the fleets.
4. Explicit inclusion of the spatial dimension is essential to improve the understanding of the fishery system, and to enhance the ability of management plans to improve stocks statuses.

KEYWORDS
bio-economic evaluation, decision support, fisheries management, scenario simulation, spatial modelling, management strategy evaluation, species distribution

1 | INTRODUCTION

Increasing impacts on marine ecosystems have raised the need for large-scale responsible management and sustainable exploitation of fisheries resources. Nowadays, a leading strategy guiding human activities relies on globally accepted principles of sustainability known as the Ecosystem Approach to Fishery (EAF; Garcia, Zerbi, & Chi, 2003). EAF principles reveal the proactive will to manage and optimize human activities related to maritime space and they rely upon a deepened understanding of ecosystem function, and of the consequences of short-, medium- and long-term effects. These preconditions demand an improvement of the science of management of the exploited resources towards a more comprehensive and extended representation of the fishery system. In other words, to tame growing management complexity, we need effective models to plan, test and adapt our managing actions, for example with the help of a decision support system to appraise, before deployment, possible management strategies for different configurations of the fishery system. Meanwhile, numerous demersal stocks around the world are affected by over-fishing and detrimental exploitation patterns with substantial juvenile fishing mortality and discarding (Amoroso et al., 2018; Cardinale et al., 2013; Colloca et al., 2013; Damalas, 2015; Vasilakopoulos, Maravelias, & Tserpes, 2014). A classical approach to increase stock productivity and profitability relies upon rebuilding the size- and age-structure of exploited populations by targeting larger sizes (Froese, Stern-Pirlot, Winker, & Gascuel, 2008).

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According to the EU Common Fisheries Policy (https://ec.europa.eu/fisheries/cfp_en), reduction of juvenile mortality rates by protecting sensitive areas/habitats through implementation of Fishery Restricted Areas (FRAs), represents one of the available management tactics. A spatial-explicit approach to the management of fishing effort which (a) minimizes the impact of trawlers on areas where juveniles of commercial species concentrate and (b) protects the habitats that play key roles for recruitment and spawning processes (Essential Fish Habitat—EFH), can achieve similar management targets to those linked to mesh size regulations (Caddy, 1999; Colloca et al., 2015; Russo et al., 2019). Assessing the benefits of closing a fishery area (along with an evaluation of the effects on adjacent areas [e.g. biomass spill-over from FRAs]) becomes of crucial importance for understanding the potential value of spatial-based management of fisheries (Hilborn & Ovando, 2014). Thus, explicit inclusion of the spatial dimension could improve the understanding of the fishery system, and enhance the ability of the management plans to improve stock status. Accordingly, Russo, Parisi, et al. (2014) developed the SMART (Spatial MAnagement of demersal Resources for Trawl fisheries) model to assess the effects of nursery protection on fishing mortality and economic performance of demersal fisheries.

The ultimate goal of the SMART model is to evaluate the effectiveness of different management scenarios, especially spatial closures. Implemented in the smartR package, the model uses multiple data sources, including satellite data of fleet activity. The complete procedure from raw input data to scenario evaluation is described step by step, with particular emphasis on the estimation of some intermediate parameters (e.g. Landings Per Unit of Effort [LPUE], or the demographic structure of the exploited populations) across space-time-scales (e.g. by month and by fishing ground). In addition to the evaluation of user-defined management scenarios, the smartR package provides further advanced modelling of fisheries dynamics, including the reconstruction of biomass fluxes from area of origin (fishing grounds) to their destinations (harbours). Similarities and differences with alike models are discussed.

2 | GUIS AND WORKFLOW

Eight main (and one accessory) Graphical User Interfaces (GUI), or Modules (see Figure 1), guide the smartR workflow: (1) Environment configures the case study area with three environmental layers (grid, bathymetry and seabed); (2) Effort loads the fishing effort database, assigns fishing locations and aggregates the data to the grid (as Fishing Hours); (3) Fishing grounds subdivides the study area into homogeneous regions; (4) Register loads fleet register data (Vessel IDs, length, power and registration port); (5) Production reconstructs the spatial origin of the catches and estimates the Landings (or Catches) per Unit of Effort (i.e. LPUE as Kgs × Fishing Hours × vessel length) for each fishing ground; (6) Mixture and cohorts (cohorts is the accessory GUI) loads length frequency distributions (LFD) from survey and fishery datasets, determines growth parameters, subdivides the studied stocks into cohorts and visualizes the spatial distribution of the cohorts; (7) Simulation estimates costs and revenues, and simulates different management scenarios; (8) Assess evaluates the biological status of the studied stocks. SmartR adopts the object-oriented framework provided by the r6 package (Chang, 2017). Despite having eight functional modules, we have structurally separated the smartR package into a main 'Project' class enclosing three distinct classes: 'Environment', 'Fleet' and 'Resource'. At the beginning of the workflow, these entities are clearly distinct and they blend together in the later steps (i.e. production is a mix of effort data and resource data).

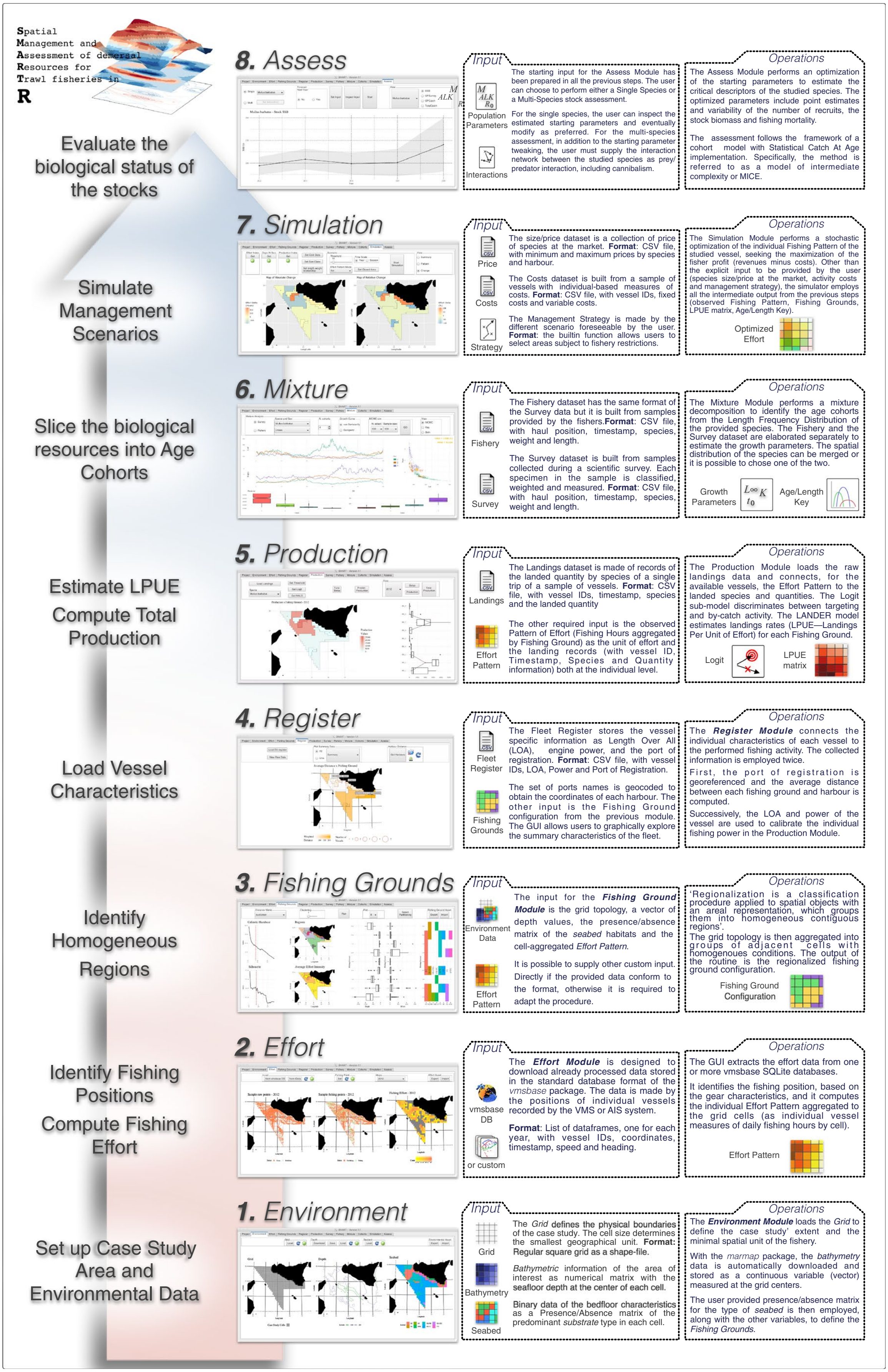
2.1 | Environment

Three main input layers compose the environmental data: a grid topology, a bathymetry matrix and a map of seabed classification (Vignette section 4.1, Supporting Information). They define both the spatial extension of the user's case study and its physical characteristics. Figure 2 shows the main functions included in the toolbox with examples of data. The grid topology defines the physical boundaries of the case study and must be provided in shape-file format. Moreover, the dimension of the cells determines the smallest geographical resolution of the case study.

Given the grid topology, smartR sets up a bounding box encompassing the grid and stores the graphical output. To assign an average depth to each cell, a bathymetry matrix is required. Through the functionalities provided by the marmap package (Pante & Simon-Bouhet, 2013), smartR automatically downloads the bathymetry of the area of interest from the ETOPO1 database (Amante & Eakins, 2009) through the NOAA servers (https://maps.ngdc.noaa.gov/viewers/bathymetry/). The sea bottom characteristic (EUNIS classification scheme for marine habitats by Davies, Moss, & Hill, 2004) of each cell of the topological grid can be loaded as a presence/absence matrix annotated according to the prevalent substrate types.

2.2 | Effort

The fleet dataset required by the smartR package integrates the actual fishing effort (Figure 3) allocated to the area of interest (for VMS/AIS-equipped vessels) and the general characteristics of each vessel (from the Fleet Register) within the working fleet (Vignette section 4.2, Supporting Information). The smartR' algorithm extracts the fishing effort data from one or more vmsbase databases (Russo, D'Andrea, Parisi, & Cataudella, 2014) with a SQL query returning the tracks of ships, under the constraint of user-specified values for the metier and the percentage of points inside the bounding box of the area of interest. The queried pings must have undergone the standard processing within the vmsbase package, including the track's interpolation (Russo, Parisi, & Cataudella, 2011), and bottom depth measurement for each interpolated ping and metier detection (Russo, Parisi, Prorgi, et al., 2011). The successive step of the estimation of the fishing effort dataset consists



8. Assess — Evaluate the biological status of the stocks

Input

The starting input for the Assess Module has been prepared in all the previous steps. The user can choose to perform either a Single Species or a Multi-Species stock assessment.

For the single species, the user can inspect the estimated starting parameters and eventually modify as preferred. For the multi-species assessment, in addition to the starting parameter tweaking, the user must supply the interaction network between the studied species as prey/predator interaction, including cannibalism.

Operations

The Assess Module performs an optimization of the starting parameters to estimate the critical descriptors of the studied species. The optimized parameters include point estimates and variability of the number of recruits, the stock biomass and fishing mortality.

The assessment follows the framework of a cohort model with Statistical Catch At Age implementation. Specifically, the method is referred to as a model of intermediate complexity or MICE.

7. Simulation — Simulate Management Scenarios

Input

The size/price dataset is a collection of price of species at the market. **Format**: CSV file, with minimum and maximum prices by species and harbour.

The Costs dataset is built from a sample of vessels with individual-based measures of costs. **Format**: CSV file, with vessel IDs, fixed costs and variable costs.

The Management Strategy is made by the different scenario foreseeable by the user. **Format**: the builtin function allows users to select areas subject to fishery restrictions.

Operations

The Simulation Module performs a stochastic optimization of the individual Fishing Pattern of the studied vessel, seeking the maximization of the fisher profit (revenues minus costs). Other than the explicit input to be provided by the user (species size/price at the market, activity costs and management strategy), the simulator employs all the intermediate output from the previous steps (observed Fishing Pattern, Fishing Grounds, LPUE matrix, Age/Length Key).

6. Mixture — Slice the biological resources into Age Cohorts

Input

The Fishery dataset has the same format of the Survey data but it is built from samples provided by the fishers.**Format**: CSV file, with haul position, timestamp, species, weight and length.

The Survey dataset is built from samples collected during a scientific survey. Each specimen in the sample is classified, weighted and measured. **Format**: CSV file, with haul position, timestamp, species, weight and length.

Operations

The Mixture Module performs a mixture decomposition to identify the age cohorts from the Length Frequency Distribution of the provided species. The Fishery and the Survey dataset are elaborated separately to estimate the growth parameters. The spatial distribution of the species can be merged or it is possible to chose one of the two.

L_∞ K t_0

5. Production — Estimate LPUE; Compute Total Production

Input

The Landings dataset is made of records of the landed quantity by species of a single trip of a sample of vessels. **Format**: CSV file, with vessel IDs, timestamp, species and the landed quantity

The other required input is the observed Pattern of Effort (Fishing Hours aggregated by Fishing Ground) as the unit of effort and the landing records (with vessel ID, Timestamp, Species and Quantity information) both at the individual level.

Operations

The Production Module loads the raw landings data and connects, for the available vessels, the Effort Pattern to the landed species and quantities. The Logit sub-model discriminates between targeting and by-catch activity. The LANDER model estimates landings rates (LPUE—Landings Per Unit of Effort) for each Fishing Ground.

4. Register — Load Vessel Characteristics

Input

The Fleet Register stores the vessel specific information as Length Over All (LOA), engine power, and the port of registration. **Format**: CSV file, with vessel IDs, LOA, Power and Port of Registration.

The set of ports names is geocoded to obtain the coordinates of each harbour. The other input is the Fishing Ground configuration from the previous module. The GUI allows users to graphically explore the summary characteristics of the fleet.

Operations

The ***Register Module*** connects the individual characteristics of each vessel to the performed fishing activity. The collected information is employed twice.

First, the port of registration is georeferenced and the average distance between each fishing ground and harbour is computed.

Successively, the LOA and power of the vessel are used to calibrate the individual fishing power in the Production Module.

3. Fishing Grounds — Identify Homogeneous Regions

Input

The input for the ***Fishing Ground Module*** is the grid topology, a vector of depth values, the presence/absence matrix of the *seabed* habitats and the cell-aggregated *Effort Pattern*.

It is possible to supply other custom input. Directly if the provided data conform to the format, otherwise it is required to adapt the procedure.

Operations

'Regionalization is a classification procedure applied to spatial objects with an areal representation, which groups them into homogeneous contiguous regions'.

The grid topology is then aggregated into groups of adjacent cells with homogenoues conditions. The output of the routine is the regionalized fishing ground configuration.

2. Effort — Identify Fishing Positions; Compute Fishing Effort

Input

The ***Effort Module*** is designed to download already processed data stored in the standard database format of the *vmsbase* package. The data is made by the positions of individual vessels recorded by the VMS or AIS system.

Format: List of dataframes, one for each year, with vessel IDs, coordinates, timestamp, speed and heading.

Operations

The GUI extracts the effort data from one or more vmsbase SQLite databases.

It identifies the fishing position, based on the gear characteristics, and it computes the individual Effort Pattern aggregated to the grid cells (as individual vessel measures of daily fishing hours by cell).

1. Environment — Set up Case Study Area and Environmental Data

Input

The *Grid* defines the physical boundaries of the case study. The cell size determines the smallest geographical unit. **Format:** Regular square grid as a shape-file.

Bathymetric information of the area of interest as numerical matrix with the seafloor depth at the center of each cell.

Binary data of the bedfloor characteristics as a Presence/Absence matrix of the predominant *substrate* type in each cell.

Operations

The ***Environment Module*** loads the *Grid* to define the case study' extent and the minimal spatial unit of the fishery.

With the *marmap* package, the *bathymetry* data is automatically downloaded and stored as a continuous variable (vector) measured at the grid centers.

The user provided presence/absence matrix for the type of *seabed* is then employed, along with the other variables, to define the *Fishing Grounds*.

FIGURE 1 Architecture and workflow of the SMARTR package

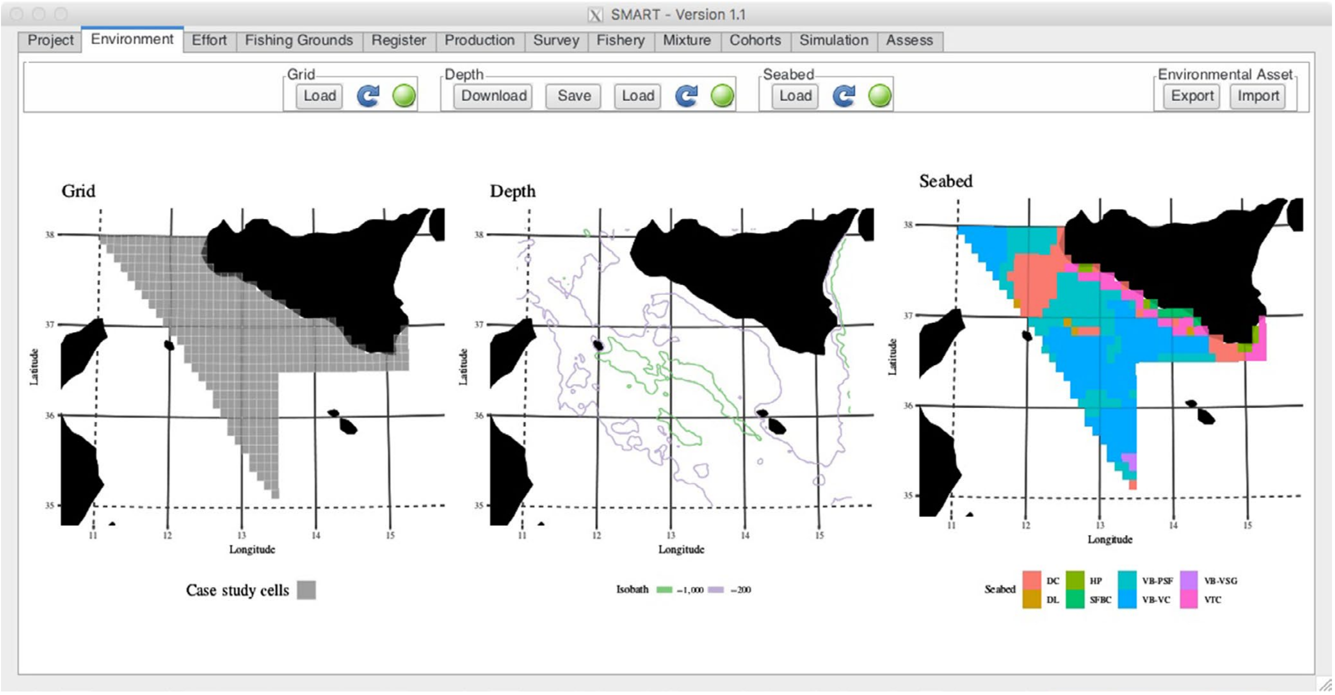


FIGURE 2 Environment panel of the SMARTR package with three plots showing: grid of the case study (left), −1,000 m and −200 m isobaths (centre) and bottom floor substrates (right)

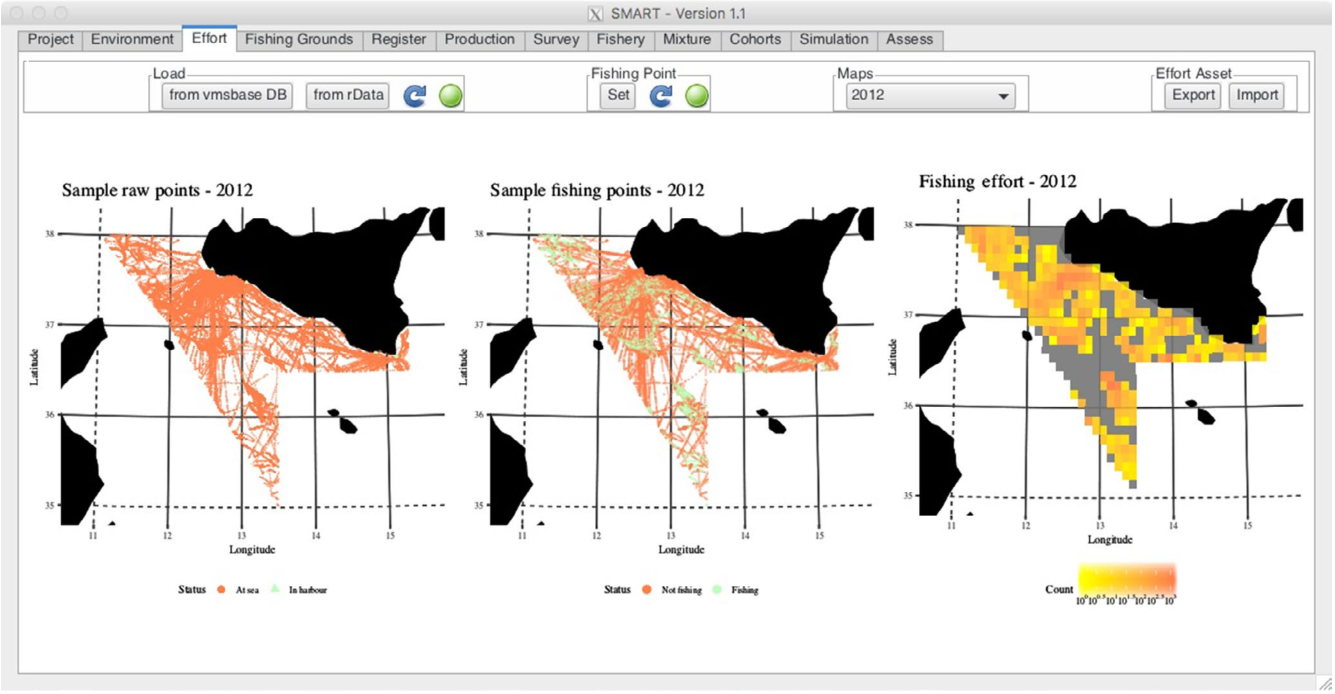


FIGURE 3 Effort panel of the SMARTR package showing three plots with: raw points (left), fishing/steaming points (centre) and gridded fishing effort (right)

of (a) identification of the fishing positions (Russo, D'Andrea, et al., 2014); (b) aggregation of the fishing position into fishing hours and overlay with the environmental grid (number of fishing positions per cell divided by number of points per hour). Thereafter, the spatially aggregated fishing effort (or Fishing Pattern) is expressed in Fishing Hours.

2.3 | Fishing grounds

To analyse the patterns of effort, catches and production at the fishing grounds level (G), data from all cells belonging to that specific fishing ground are aggregated by spatial clustering techniques (Assunção, Neves, Câmara, & Da Costa Freitas, 2006). Specifically, the 'Spatial Kluster Analysis by Tree Edge Removal' (SKATER) procedure (Bivand et al., 2005) of the SPDEP package is employed to identify and merge adjoining areas with similar characteristics (Vignette section 4.3, Supporting Information). This technique of spatial cluster analysis is based on the recursive partitioning of a minimal spanning tree (Lage, Assunção, & Reis, 2001), and it is performed on the grid topology using the seabed category, bathymetry and hours of effort (Figure 4). The different scales of the informative variables prompt a data transformation before any distance/dissimilarity is computed.

2.4 | Register

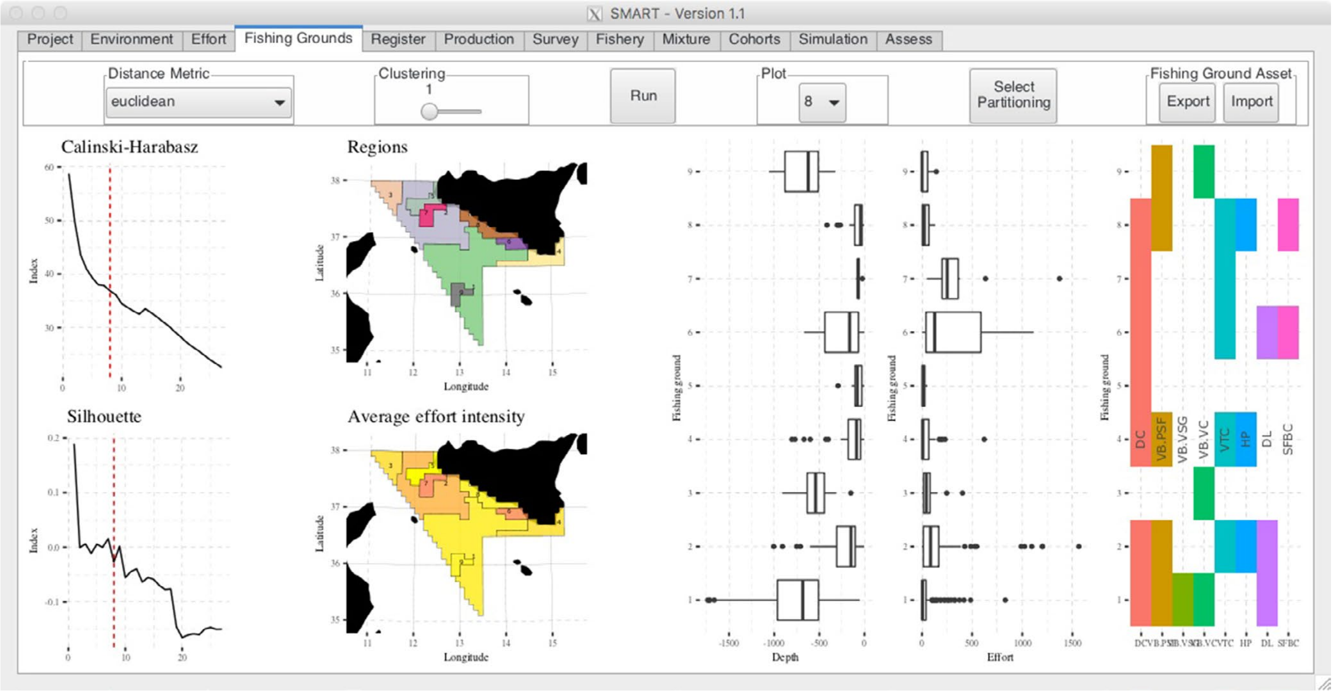
The Register GUI (Figure 5) loads the technical and administrative information of each vessel. The required fields are the vessel ID, length over all (LOA), engine power and the port of registration. This information is usually collected and publicly shared by the local port authorities. For example the EU commission database shares this information through a centralized registry (https://ec.europa.eu/fisheries/cfp/fishing_rules/fishing_fleet_en). The second task of this module is the computation of the average weighted distance between the centroids of the fishing grounds and the harbours of the studied fleet.

2.5 | Production

The landed quantity for a single trip by each vessel is joined to the corresponding Fishing Pattern prepared with the Effort GUI (Vignette section 4.4, Supporting Information). The resulting structure is a matrix where each row contains the vessel identifier, timestamp, hours of fishing in each fishing ground and the landed quantity. A discrimination threshold is set to distinguish the quantity of landed catch obtained from targeted versus non-targeted catch of a species. The records of the vessel *v* during the time interval *t* with a landed quantity of the species *s* above the threshold are classified as targeting the considered species, whereas records with a landed quantity below the threshold are considered by-catch. After training with observed data, the binary choice model is employed to infer the targeting status for Fishing Patterns that lack a direct observation of landings. Thereafter, a non-negative least square (NNLS) model is employed to compute the LPUE (Mullen & van Stokkum, 2012; Russo et al., 2018). The coefficients of the NNLS regression are arranged in the matrix of LPUEs estimates for species *s* on every time interval *t* in every fishing ground *g*. Using the estimated LPUEs matrix as a 'Production Model', which is assumed to be constant within the considered time frame, it is possible to predict the landed quantity of the fishing vessels without landing data.

2.6 | Mixture and cohorts

The information collected, from both scientific surveys and commercial fisheries datasets, is subject to an analogous, but still separate, processing routine. Data from surveys or fisheries (with length measurements for catch samples) are loaded and split into distinct



Distance Metric: euclidean

Clustering: 1

Plot: 8

FIGURE 4 Fishing Ground panel of the SMARTR package with plots of clustering metrics (Calinski-Harabasz and Silhouette), maps of regionalization output and aggregated effort by region, boxplot of the distribution of depth, effort values and binary matrix of seabed floor composition by region

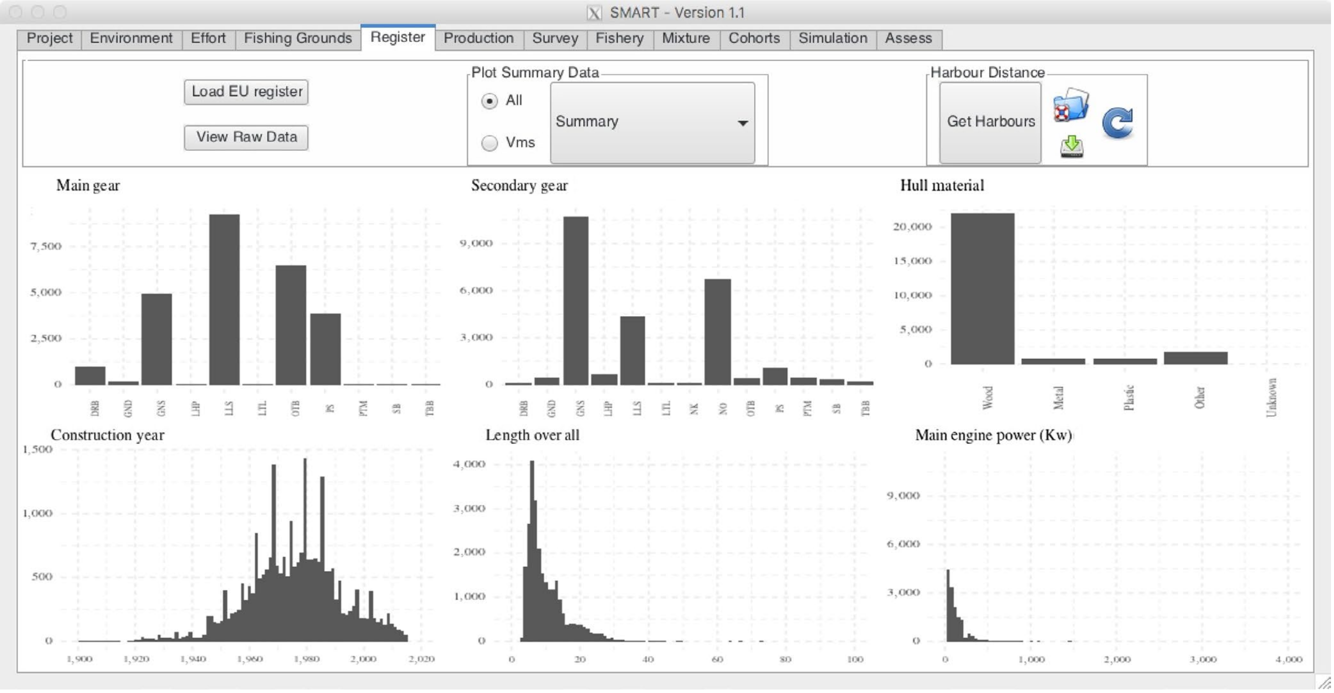


FIGURE 5 Register GUI of the smartR package with a summary plot of the fleet technical characteristics: main gear (top left), secondary gear (top middle), hull material (top right), construction year (bottom left), length over all (bottom middle) and main engine power (bottom right). Note that not all of these information are mandatorily required

subsets for each of the reported species. Then, using the georeferenced information, each LFD record is allocated to its corresponding cell of the grid. To determine the demographic structure of the studied species, the LFD is turned into an age–frequency distribution (Vignette section 4.6, Supporting Information). This mixture decomposition is carried out employing a Bayesian approach with one of the classical growth equations, either the von Bertalanffy (1938) or the Gompertz (1825), within the Markov chain Monte Carlo (MCMC) stochastic simulation engine JAGS (Plummer, 2003). The MCMC outputs are used to split the observed landings by ages, and to slice the LFD characterizing every cohort in each fishing ground for each time frame (Figure 6).

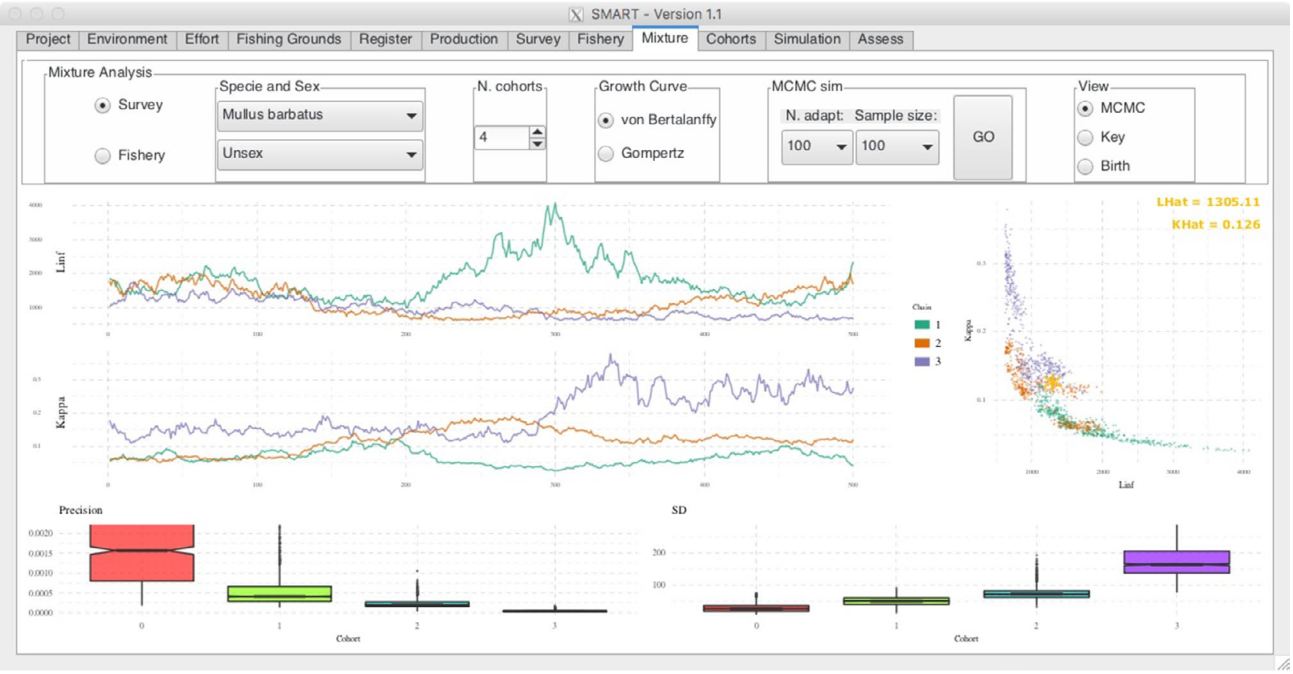
Depth-stratified data collected through a standardized survey are also employed to assess the abundance index of each length class by computation of the average number of individuals at length by depth stratum. The routine implemented in smartR follows the protocol developed for the 'MEDiterranean International bottom Trawl Survey' (MEDITS) campaigns (Bertrand, De Sola, Papaconstantinou, Relini, & Souplet, 2000). Lastly, the length/weight relationship (Cren, 1951) is employed to convert the length observations into weights and to obtain a biomass estimate (Froese, 2006) required by the Assess GUI.

2.7 | Simulation

The 'Scenario Simulation' module of the smartR package (Figure 7) allows the appraisal, before implementation, of potential spatial management measures. The main requirements to run a simulation are:

- the fishing grounds configuration (from the Environment Module);
- the observed spatial effort pattern (from the Effort Module);
- the production model (Logit and LPUEs from the Production Module);
- the growth model (resource spatial distribution from the Mixture Module);
- the economic models (costs and revenues to setup in the Simulation Module);
- the management strategy to experiment.

To gauge the economic performance of the fishing fleet at the single vessel level, we relate the operational cost of each Fishing Pattern with the associated revenues (Vignette section 4.7, Supporting Information). In the first step, smartR computes three economic indicators: Effort Index is a measure of the variable costs associated with the spatial choices of the fisher (arithmetic mean of the cumulative yearly fishing pattern in hours weighted by the average distance of the harbour from the corresponding fishing grounds); Days at Sea is linked to the amount of time spent by a fishing vessel (and its crew) at sea, independently of the fishing location (number of days per month where, for each vessel, the tracking device recorded at least one position outside the harbour); Production Index a proxy for the variable costs tied to the landed quantity of fish from taxes or commercialization costs (total landed quantity of every species by year for each vessel independent of the fishing ground).



Mixture Analysis: ● Survey ○ Fishery

Specie and Sex: Mullus barbatus; Unsex

N. cohorts: 4

Growth Curve: ● von Bertalanffy ○ Gompertz

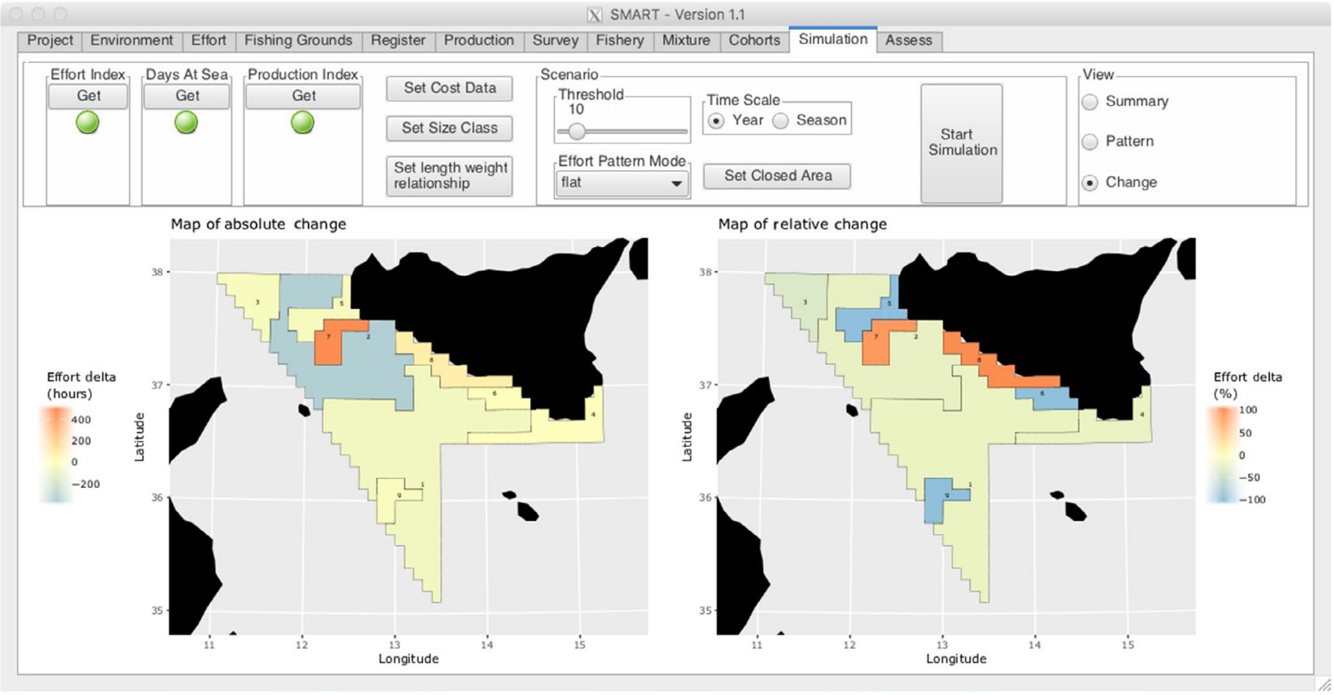
MCMC sim: N. adapt: 100 Sample size: 100

View: ● MCMC ○ Key ○ Birth

LHat = 1305.11

KHat = 0.126

FIGURE 6 Mixture panel of the smartR package with the main diagnostic output: Markov chain Monte Carlo chain' evolution of Linf and *K* values, scatterplot of Linf and *K*, boxplot of precision and standard deviation of cohort slicing



Effort Index: Get; Days At Sea: Get; Production Index: Get

Scenario: Threshold: 10; Effort Pattern Mode: flat

Time Scale: ● Year ○ Season

View: ○ Summary ○ Pattern ● Change

FIGURE 7 Simulation panel of the smartR package with two maps of the absolute (left) and relative (right) change in the simulated fishing effort distribution obtained with the optimization of the spatial displacement

With a dataset of costs disaggregated at the vessel level, smartR performs three separate regressions using the economic indicators and the provided costs. The cost estimate is then expanded to the whole fleet (the fishing units for which direct observations are not available) using the three indexes. The effort-based regression aims at predicting the costs associated with the location choice relative to the spatial index. The days-at-sea regression delivers the fixed costs relative to the fishing activity independently of the location choice. The production-based regression relates the production costs to the production index.

TABLE 1 Models comparison, modified from: Scientific, Technical and Economic Committee for Fisheries (STECF)—Methods for developing fishing effort regimes for demersal fisheries in Western Mediterranean-Part III (STECF-19-01). Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-08330-6, https://doi.org/10.2760/249536, JRC116968

Model	SMART	DISPLACE	InVEST	ISIS-Fish	SIMFISH	TI-FishRent
Age structure	✓	✓	✓	✓	✓	✓
Length structure		✓	✓	✓		
Multiple gears		✓	✓	✓	✓	✓
Multispecies/mixed fisheries	✓	✓		✓	✓	
Connectivity (larval dispersion/adult migration)	Implementation in progress		✓	✓		✓
Prediction of effort displacement	✓	✓			✓	✓
Simulation of management scenario (including temporal and/or spatial closure)	✓	✓	✓	✓	✓	✓
Modelling of trophic relationship among species	✓					
Agent-based modelling (IBM of fishers)	✓	✓			✓	
Reference	Russo, D'Andrea, et al. (2014) and Russo, Parisi, et al. (2014), This paper	Bastardie, Nielsen, and Miethe (2014)	Sharp et al. (2016)	Mahévas and Pelletier (2004) and Pelletier et al. (2009)	Bartelings, Hamon, Berkenhagen, and Buisman (2015)	Simons, Döring, and Temming (2014, 2015)

Lastly, smartR computes the revenues from the landed quantity for each species slicing the individual production pattern (the combination of fishing patterns and LPUEs matrices) by the size/price classes provided by the user employing the spatial distribution and demographic structure of the biological resources (from the Mixture Module).

Once all the inputs are specified, the simulator operates stochastically on the observed pattern, at the single vessel level, seeking the maximization of the fishing activity profits (which, for our purpose, we define as revenues minus costs). The simulated effort patterns, evaluated by profits at each iteration, are obtained slightly altering the observed fishing patterns while minimizing the changes in the probability distribution of fishing effort deployed in each fishing ground.

2.8 | Assessment

The simulated landings, obtained from the optimization of the Effort Pattern according to the selected management strategy, provide the starting parameters for the Assess GUI. For the Stock Assessment, we have chosen the cohort model as the general framework and the statistical catch at age (SCAA) as the numerical method. The stock assessment procedure implemented in smartR is usually referred to as a MICE model (Punt et al., 2016) with a basic population dynamic that follows the classical approach of Doubleday (1976) where the catch-at-age datasets are fitted for multiple cohorts simultaneously and the fishing mortality is split into age and year components (Vignette section 4.8, Supporting Information).

3 | CONCLUSIONS

The smartR package is a spatially-explicit bio-economic model aimed at capturing the spatial dynamics between resources and fishing activities while appraising the performance of fisheries in terms of catches, revenues, costs and ultimately profits. The smartR package was primarily developed to simulate different management scenarios (with particular application to spatial fishing bans) and to forecast their potential effects on demersal resources. The main features of this package, when compared with the analogous software (i.e. spatial suites for modelling of fisheries), are summarized in Table 1. The added value of smartR is that it allows users to model both mixed fisheries and trophic relationships among exploited species. Modelling of fleet behaviour is performed at the vessel-level and prediction of effort displacement is performed through an individual-based model, similar to the approach used in the DISPLACE, the most similar available software. Notably, however, smartR is entirely realized in R. Therefore, it can be customized or further developed by users and all intermediate objects and metadata are fully accessible.

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CONFLICT OF INTEREST

No conflict of interest exists: We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

AUTHORS' CONTRIBUTIONS

S.C., T.R., F.F., A.P. and L.D. conceived the ideas and designed methodology; G.G. and M.G. collected the data; L.D. and T.R. analysed the data; L.D. and T.R. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The stable version of the SMARTR package is hosted at at https://CRAN.R-project.org/package=smartR (D'Andrea, Russo, Parisi, & Cataudella, 2018), whereas the development version is on the github repository at https://github.com/d-lorenz/smartR/. To provide further information for new users, the guided workflow (with the GUI and R script) and description of the input formats is detailed on the package VIGNETTE (Supporting Information). The example data are available in the 'extdata' directory of the SMARTR package. The package is distributed under the terms of a GNU General Public License (GPL ≥ 2, http://www.gnu.org/licenses/).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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