Annex 1: Spatial model

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The DISPLACE model project (Bastardie et al. 2014) is developing a research- and advisory platform to transform fishermen's detailed knowledge and micro-decision-making into simulation and management evaluation tools (Figure 1). This involves advanced methods to assess and provide advice on the bio-economic consequences for the fisheries and fish stocks of different fishermen decisions and management options. DISPLACE is an agent-based simulation model developed to fisheries, habitat conservation, maritime spatial planning and management issues, especially from the perspective of the fisheries. A particular feature of the approach is to model processes at the spatial (2 × 2 km) and the time scale (hourly time steps) closer to the spatial and time dynamics occurring in human decision-making and fish populations dynamics. It is also closer to the appropriate scale for dealing with spatial management issues. The model integrates process-based mechanistic relationships that should give the advantage of being able to better predict in novel conditions and incorporate the spatial and temporal details. DISPLACE models fleet/skipper decision facing changing catch rates and limited by fisheries management including quotas or effort harvest control rule (overall capacity reduction, limits in days at sea, temporal & spatial closure to fisheries) embedded in multi-annual management plans in a CFP context (i.e. FMSY). The overall pattern of effort allocation between fisheries, space and time, and eventually the differential catchabilities and partial fishing mortalities, emerge from all of the individual fisher's decisions and the displacement of fishing vessels with varying catching powers.

So far, important progress has been made in a row of applications including the Adriatic Sea, the Ionian Sea, the Black Sea, the Baltic Sea and the Irish Celtic Sea. Regional scale applications are currently being developed for the North Sea and the Baltic Sea fisheries. On the Mediterranean side, DISPLACE is applied to the north Adriatic (GSA 17) to the Italian demersal fisheries (Bastardie et al. 2017). We applied the fish and fisheries model to assess the impact of a suite of spatial plans suggested by practitioners that could reduce the pressure on the four demersal stocks of high commercial interest in the GSA 17, and that could promote space sharing between mutually exclusive activities. The 2017 Adriatic Sea application has been recently updated with most recent fish stock assessment data, extended to include the Croatian fisheries. One major shortcoming in the current Adriatic application (resulting from the nature of the scientific survey data used to parameterize the current application) is the assumption of stationary in the spatial distribution of the harvest stocks over the projected years. The model, however, accounts for different distributions along the growth of a stock.

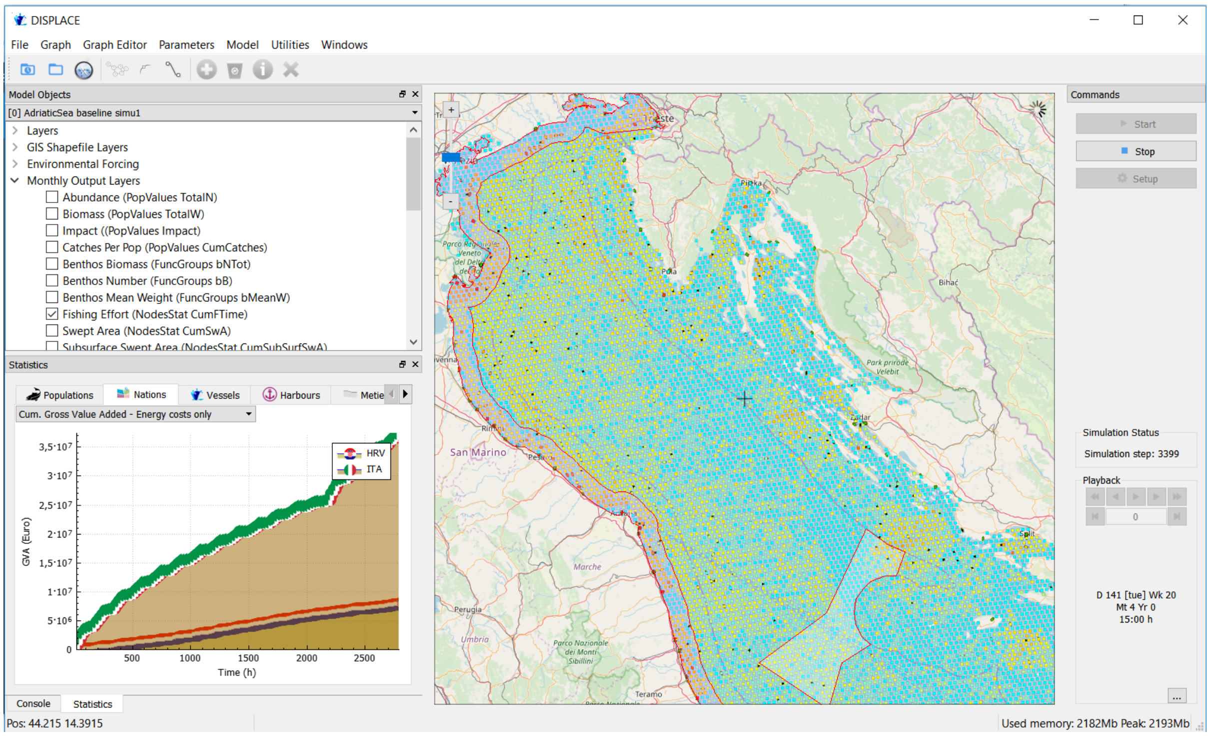

Figure 1. Random snapshot of the DISPLACE User Interface for the Demersal Italian & Croatian demersal fisheries in the northern Adriatic (GSA17). Movement and catches of individual fishing vessels are simulated at hourly time steps on a 6y time horizon. DISPLACE projects EU MSFD and AER bioeconomic indicators which can then be aggregated at various levels (Vessels, to Metiers, to Harbours, to Nations) and simultaneously mapped in a unified framework

Fleet dynamics

We obtained average values for Italian and Croatian fishing vessels using trawl or set nets in the GSA 17 and targeting demersal fish. For larger vessels, the relative spatial fishing effort distributions per activity were obtained from the Automatic Identification System (AIS), which is a an automatic tracking system that uses transponders on ships and is used by vessel traffic services (VTS), in use in all the fishing vessels with a length over all ≥15 m LOA (EC No. 2009/17/CE; EC No. 1224/2009; EC No. 2011/15/UE). Information on the fishing grounds of the small-scale gillnet fishery, for which AIS data are not available, was obtained from index suitability maps; these maps were defined by the relative likelihood of the fleet to visit the potential fishing grounds based on the suitability of these areas (according to bathymetry, distance to coast, etc.; Kavadas et al. 2015). The simulation assuming that fishing vessels land only in their home harbor. A geographical range was assumed around each home harbor

(80 km for trawlers and 15 km for set netters), and each vessel distributed its effort within this range and per zone relative to the frequencies given by the relative effort data layer that was given as input at the initial stage.

Fishing gear-specific selectivity ogives and fixed, stock-specific, spatial catch rates were applied per type of activity and vessels. Considering the differences among the body shape of the four species, selectivity was assumed to be species-specific (Fabi et al. 2002). The mesh sizes considered to define selectivity curves were 68 mm stretched for gillnets and 50 mm diamonds for otter and rapido trawlers, with these mesh dimensions being the most used in the GSA 17. The vessels considered in this simulation usually do not change gear during the year. However, exceptions were made by some gillnetters, who in some rare cases switched to bottom trawling; this modification never occurred during a trip. Each trawler vessel was assumed to work from Monday to Thursday, leaving the harbor each day at 4 a.m. and returning at 10 p.m., in agreement with the regulation that allows a vessel to spend a maximum of 72 h at sea per week (Regulation 03/07/2015). Thus, in the model, these vessels were considered to work 5 d/week, with an average daily fishing time of 12 h. Catch rate of each vessels were assumed to increase by 3% a year to account for a so-called "technological creeping" effect. In total, 797 "agent" vessels were simulated, comprising 351 set netters, 432 otter trawlers, and 19 rapido trawlers. For practical reasons, such as to speed up the simulations and reduce the overall size of output, we assumed that each agent represented four vessels. These groups of vessels were defined as "super-individuals." The specifications for each agent, which included the individual catch rates, hourly fuel consumption rate (deduced from the vessel engine power), fuel tank capacity, and fish storage capacity, were therefore multiplied by four to obtain values for each of the "super-individuals."

Stock dynamics

Species

The model was designed to handle the spatial population dynamics of six important commercial species in the area: hake (Merluccius merluccius), common sole (Solea solea), red mullet (Mullus barbatus), Norway lobster (Nephrops norvegicus) and the spottail mantis shrimp (Squilla mantis) and cuttlefish. These species have been assessed by the FAO-GFCM management and STECF for estimating the stock levels.

Parameters

The fish body size-population structure (using total length for fish) was discretized into 3-cm bins for all species (3 mm carapace length for Norway lobster and spottail mantis shrimp); growth parameters were the same used in the last stock assessments developed for these species, from which population estimates are derived.

Scientific survey

The population spatial distributions were obtained from data collected during scientific surveys. In particular, the SoleMon survey is being conducted by the National Research Council (CNR-IRBIM, Italy) in cooperation with the National Institute for Environmental Protection and Research (ISPRA, Italy), the Institute of Oceanography and Fisheries of Split IOF (Croatia), and the Fisheries Research Institute of Slovenia FRIS (Slovenia) using rapido trawls (width = 3.69 m, weight = 200 kg, and codend stretched mesh size = 40 mm; Grati et al. 2013).

Abundance and spatial distribution

By applying geostatistics to the survey data, interpolated levels of stock abundance can be obtained by the categories of fish sizes. For each species, the spatial distribution was described according to three size groups on the basis of commercial categories (small, medium, and large individuals) to accommodate the variation along the growth of the individuals relative to where they locate themselves in the marine environment during the life cycle: hake: 0–20 cm Total Length (TL), 20–25 cm TL, and >25 cm TL; common sole: 0–20 cm TL, 20–25 cm TL, and >25 cm TL; red mullet: 0–9cm TL, 9–12 cm TL, and >12 cm TL; Norway lobster: 0-26 mm Carapace Length (CL), 26–31 mm CL, and >31 mm CL and spottail mantis shrimp: 0-26 mm Carapace Length (CL), 26–31 mm CL, and >31 mm CL. The spatial distribution of the species (variable: kg/km2) was estimated by means of Ordinary Kriging, a geostatistical method of interpolation, which is the procedure for predicting the value of attributes at unsampled sites from measurements made at point locations within the same area or region.

Intertwined stock and fleet dynamics

The harvest (in kilos) from each active vessel at sea in DISPLACE depletes the underlying stocks, as the individual catch rates are specific to the species and affect the size structures of the population according to the varying selectivity for body size of the fishing vessel gear. This size- structured depletion dynamically links back to the underlying population models as detailed in Bastardie et al. (2016). Contrary to that, the catch rates were not assumed to depend on the available biomass by locality (unless the catch is greater than the total available biomass). Therefore, the difference in the amount and price of the catch from a vessel or from one trip to the next mainly arises from the varying duration of the fishing event, the specific selectivity of the various gears being used, and the variation in the mixture of species and abundance per size on the localities where the vessel is fishing. Hence, an assumption is made of hyperstability in catch rates (e.g., Harley et al. 2001) that are in agreement with the best data because we do not have data on spatial catch rates that will allow us to index catch rates according to the various levels of stock abun- dance. Rapido and otter trawlers are assumed to target the five species, whereas the set netters are assumed to target common sole and spottail mantis shrimp, as the hake is very rare in the set netters' fishing grounds and the red mullet is not retained by the mesh sizes used in gillnets. After each trip, simulated fishing vessels return to port and earn money from the landings in harbor where the fish prices were informed per marketable category. These fish prices were assumed not depending on the demand conditions for seafood. In an additional step, the revenue from the landings from the previous trip was determined using the amount of the catch represented by species other than the five studied species in the total revenue (revenue times 2.5, 3.3, and 2 for the otter trawlers, gillnetters, and rapido trawlers, respectively). For each vessel, the probability of visiting a certain fishing ground is updated over time from information obtained at the end of each trip concerning the expected profit the vessel could make on each ground and the expected profit according to the catch rates during this last trip. Finally, estimated depletions in the stock numbers in each of the localities, obtained mainly from other countries active in the Northern Adriatic and other catches from Croatia and Slovenia were applied evenly over the spatial distribution of the stocks inside their respective exclusive economic zones.

Fleet economy

Fish prices per marketable category (small, medium and large fish) per harbor from Bastardie et al. (2017). Fish prices evolve from a year to the next according to a price flexibility equation with parameter at 25%. The vessel cost structure additional to the operating costs that are directly simulated were informed from economic Indicators collected in STECF AER 17-12 Table 5.53 for the Italian fleet and Table 5.12 for the Croatian fleet.

Management and population scenarios

The effects of the spatial management scenarios on the five considered stocks were analyzed. Considering the Italian regulation foresees a ban for trawlers inside the 3 nm from the coast, set gears are used almost exclusively inside the 3-nm strip, avoiding conflicts with active/mobile gears outside this limit. The scenarios tested referred to:

- The 6-nm trawling ban along the Italian coasts, which is supposed to reduce fishing pressure on this vulnerable area; it represents one of the most relevant nursery area for many species, especially for common sole;
- Increase the selectivity of gillnet through the adoption of a 72mm stretched mesh size;
- A permanent closure of the “sole sanctuary” area for all fishing activities (both Italian and Croatian fleets). Again, the closure of this area highlights the importance of reducing the fishing pressure on vulnerable areas (e.g., spawning and nursery areas) that are considered of biological interests for commercial species.
- A permanent closure of the high persistency area for common sole juveniles in the Northern part of Italian coast identified in Grati et al. 2013 and Scarcella et al. 2014.
- A combination of the previous two scenarios, means the permanent closure both the “sole sanctuary” scenario plus the high persistency coastal area of sole juveniles.
- A combination of a permanent closure both 6 nautical miles from the Italian coast plus the “sole sanctuary”

Considering this information, the following scenarios were tested:

1. sceallyear6nm - trawling ban within 6 nm from the Italian GSA17 coast;
2. scesoleselectivity - increase the gillnet selectivity;
3. scesoleadulsanctallyallmet - permanent closure of “sole sanctuary”;
4. scesolejuvsanctallyallmet - permanent closure of high persistency area of common sole juveniles
5. scesolesanctallyallmet - a combination of scenarios 3 + 4
6. scesolesanctallyallmet6nm - a combination of scenarios 1 + 3

We obtained a quantification of the changes provoked by the implementation of alternative plans by running Monte Carlo simulations that projected the scenarios with varying spatial harvest patterns (from the activity of individual vessels), comparing them against the baseline situation where the current management was applied. A total of 20 stochastic runs were conducted per scenario and provide quantified changes to the activity-specific impacts on the economic return, on the sustainability of the harvesting strategies for the species considered in this study, and on the fraction of underlying seafloor habitats enduring the fishing pressure.

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