CHAPTER 26

Operational Oceanography and the Management of Marine Living Resources: The Mediterranean Sea as a Case Study

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This chapter provides examples demonstrating the relevance of integrating operational oceanography data from ocean observing systems and ecological and fisheries assessment models to improve the management of marine living resources. Commercial fisheries exploit coastal, demersal, and pelagic marine resources. Many marine organisms merge in the water column and most of them occupy the pelagic habitat as planktonic organisms (egg and larval stages), during which time they are subjected to the highest mortalities of their life cycle as they are transported by oceanic currents. Hence, it is important to determine how environmental processes control survival rates and dispersal patterns of the early life stages of the species. We offer a general view of a multidisciplinary research field that aims at the protection and exploitation/management of marine living resources by documenting some current strategies and recent advances in the Mediterranean Sea. We include a short introduction of the current strategies for the protection and exploitation of living resources and the recent advances of the field and present four practical examples, which show how the integration of operational oceanography into the management of living resources has improved our knowledge of: 1) the spatial distribution of adult fish, 2) the connection among management areas, 3) the redefinition of management areas, and 4) the use of marine protected areas for the conservation of coastal ecosystems.

Marine Living Resources

Since life first appeared on the Earth, the oceans have been a first home for living organisms. A wide variety of creatures, from primitive bacteria to complex forms of life, inhabit the sea. Their survival depends very much upon their relationship with the surrounding environment, their capacity to respond and adapt to environmental variability, and their relationship with other players in the ocean ecosystem. Feeding, settling in their preferential habitats, using currents for dispersal and migrations, limiting their spatial distribution, and timing their migrations and reproductive events are only some of the biological processes that can be influenced by the abiotic and biotic environment in which marine organisms live.

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Humans have been using the sea for goods (living and mineral resources) and services, especially as a source of food (fishing and shellfish), since immemorial time. Living marine resources are renewable, but not unlimited, and their exploitation must ensure the preservation of habitats, with fishing activities subjected to management systems aimed at safeguarding their sustainability. Therefore, effective management strategies that lead to sustainable development must be implemented.

Practically all marine habitats are currently being exploited, from intertidal areas to deep-banked bottoms and the open ocean. We can distinguish three main types of commercial fisheries (Fig. 26.1, note that recreational fisheries are becoming more and more important in some areas):

- The artisanal fisheries that exploit the **coastal resources** with a great diversity of gears, fixed nets, or hand lines. This type of fisheries is also the most diverse in the number of species captured, targeting a huge variety of taxa, from shellfishes (clams…) or crustaceans (crabs, lobsters…) to shore fishes (sea-breams, mullets, soles, groupers…).
- The industrial or semi-industrial fisheries, as trawl fleets, that exploit **demersal resources** - the organisms that preferentially inhabit or are in close association with the seabed (cod, hake, flatfish ...) - in shelf or slope areas.
- The fleets exploiting the **pelagic resources** – those that inhabit the water column including both species in neritic (sardines, anchovies ...) and oceanic areas (tunas, swordfish ...) which are captured mainly by purse seines, trawl lines or longlines.

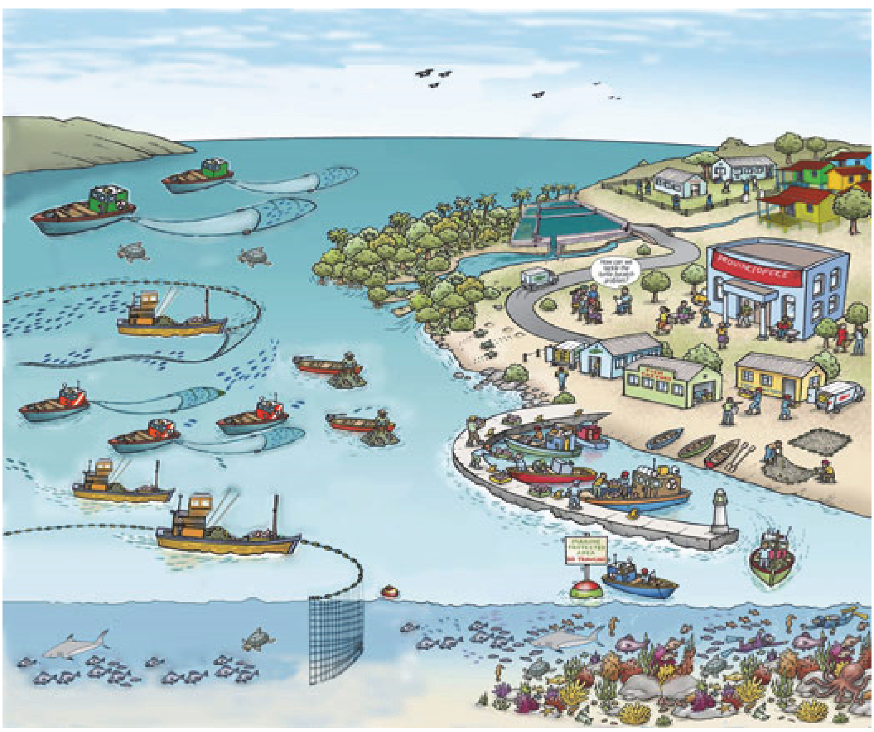

Figure 26.1. Illustration showing how living resources are being exploited in most marine habitats. Source: image adapted from FAO EAF Nansen Project in Staples et al. (2014).

All living resources, regardless of their habitat—coastal or offshore, pelagic or demersal—merge in the water column at some stage of their life cycle. This is because most marine organisms pass through a planktonic egg and larval stage, typically lasting from weeks to few months. Pelagic species live their entire life cycle in the water column. For example, Atlantic bluefin tuna, a pelagic top predator, release their 1 mm size eggs at the surface, which hatch into larvae (around 2-3 mm long) after few hours and continue growing several days to attain juvenile size. All of these developmental stages take place in the upper water column (around 20 m depth in the Mediterranean, Fig. 26.2). Even at the adult stage, this species will conduct large migrations within their habitat range and will perform extensive movements throughout the water column.

In contrast to pelagic species, demersal or sessile benthic species (those living fixed to the substrate) only spend the early stages of their life cycle in the water column. For many of these species most of the mid- or large-scale displacements will occur while they occupy the pelagic habitat as planktonic organisms (during the egg and larval stages), at which time they are transported by oceanic currents from their natal place to distant habitats where they may settle and continue living as juveniles and adults. Larvae from most exploited species inhabit surface waters, where light and food resources are abundant. Nevertheless, some larvae from demersal species such as deep lobsters can also take advantage of resources at deeper layers where there is less light (Fig. 26.3). Among marine invertebrates, decapod crustaceans have relatively long larval stages during which they can be especially sensitive to any environmental factors (Giménez, 2010).

In general, the survival rates during the planktonic stages of different exploited resources (fish or invertebrates) are very low and highly variable depending on environmental conditions. this means that planktonic stages are not only important for the spatial dynamics of many marine living resources serving as the dispersive phase of the life cycle, but also constitute a critical period in which the success of the recruitment process is determined.

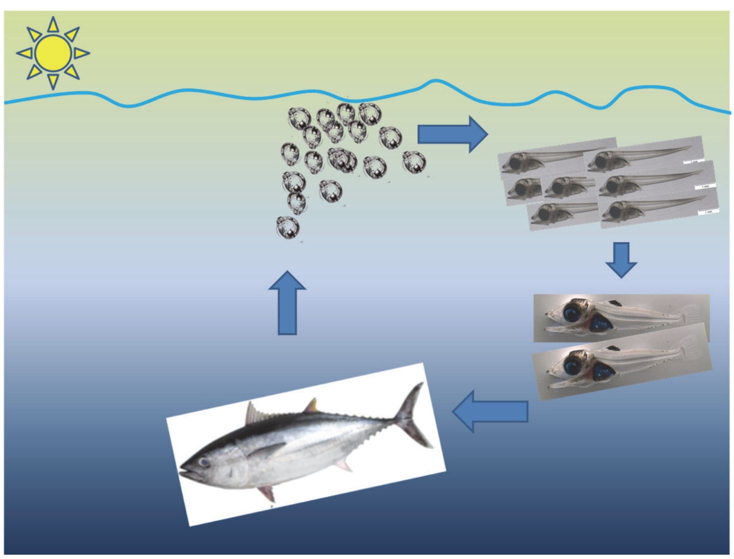

Figure 26.2. The life cycle of a pelagic species. Example of Atlantic bluefin tuna (*Thunnus thynnus*) from eggs, then larvae (urostile pre-flexion and post-flexion), juvenile, and finally pelagic adult phases. All of the developmental stages of this species take place in the water column.

In the context of fisheries, recruitment is defined as the number of juveniles that survive and grow long enough that they can be caught by a specific fishery. Recruitment is the result of complex physical and ecological processes that act at various spatial and temporal scales and throughout the life stages (both larvae and juvenile) leading up to the recruitment itself. As a result, it is important to determine the impacts of environmental processes on survival rates and movements during the early life stages of a species. Therefore, knowledge of the pelagic environment and the characteristics and dynamics of water masses, is crucial for the understanding the processes driving marine population dynamics, and hence for evaluation and planning of management measures aimed at ensuring the sustainability of pelagic and demersal living resources.

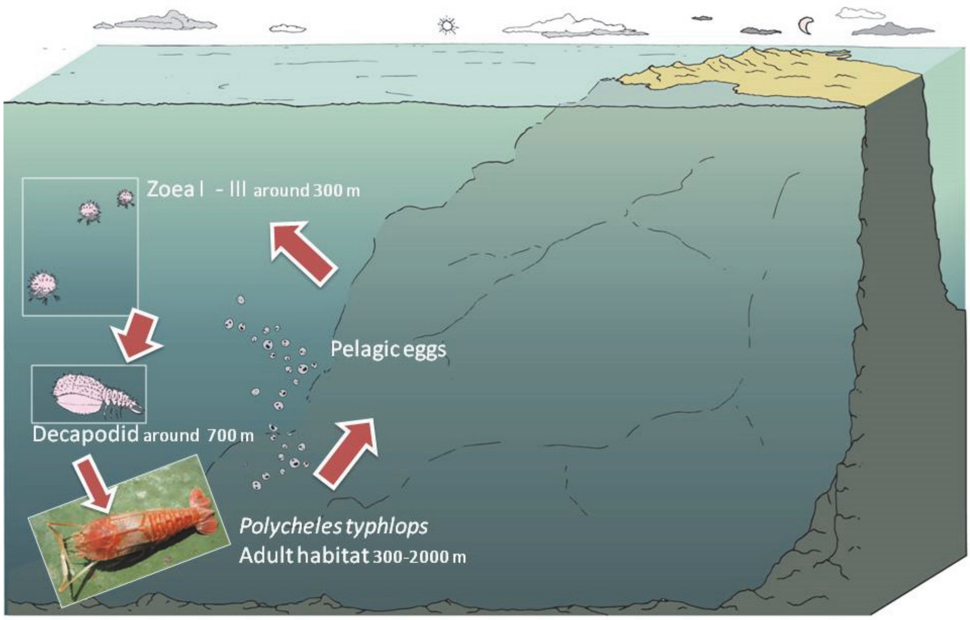

Figure 26.3. Life cycle for a demersal decapod as exemplified by the deep sea lobster *Polycheles typhlops*. Larval stages (from zoea to decapodid) are represented as function of depth (Torres et al., 2014), with adults living around 300 to 2000 m depth in Mediterranean Sea.

Current Strategies for the Protection, Exploitation, and Maintenance of Living Resources

Methodologies for the formal evaluation of the "state of the stocks" (i.e., the population of a certain species occupying a certain geographic area considered as management unit) was initially applied in the 1950s. Within this framework, fisheries are managed as populations isolated from the surrounding environment in order to maximize production of the targeted species. This is based on models that allow determining the biomass of the stock from fishery data alone, such as catches and effort (production models), or using a combination of fishery data (fishing mortality) and biological/ecological parameters (growth rates, natural mortality, survival to the adult population or recruitment). In addition, these models provide projections of how the biomass of the stock will change in relation to fishing efforts in order to estimate the suitable harvest levels for sustainable exploration. Following this approach, stocks have been managed through the control of fishing effort, quotas of capture, and technical measures such as minimum sizes, based mostly on fishery-dependent data and with a focus on maximizing production of the targeted species irrespective of the type of fisheries, either coastal, benthic, or pelagic (Fig. 26.4). In this context, they are still considered isolated from the environment, without taking into account environmental condition variations or spatially explicit issues.

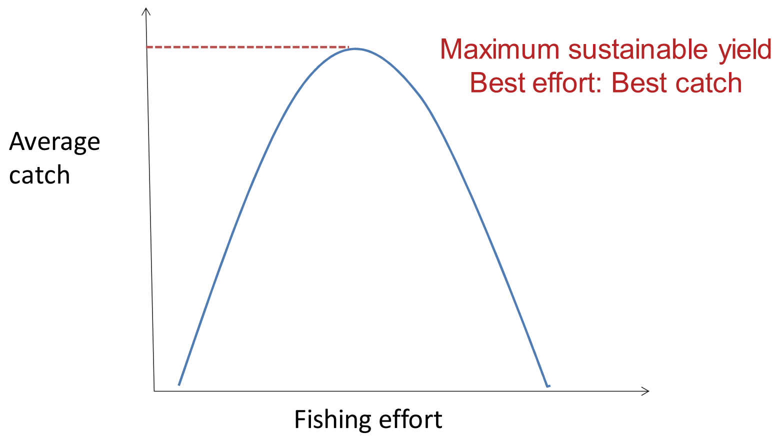

Figure 26.4. The maximization of production of a targeted species. The maximum sustainable yield is estimated from the best relationship between fishing effort and average catch.

Let us take, as an example, the Atlantic bluefin tuna in the Eastern Atlantic and the Mediterranean Sea. After single population models suggested an important decrease in the biomass of the stock, the European Commission established a 15-year recovery plan for Atlantic bluefin tuna starting in 2007 that included, as management measures, decreasing the total allowable catch limit, restricting the fishing seasons for certain types of fishing vessels, prohibiting the use of airplanes and helicopters to search for Atlantic bluefin tuna, and establishing a minimum size of 115 cm and minimum weight of 30 kg (except for juveniles of 8 kg in the Adriatic Sea). Using this approach, the assessment of the eastern Atlantic bluefin tuna does not take into consideration natural fluctuations in abundance due to environmental factors' impact the survival of the early life stages, although inter-annual variability is expected (Fig. 26.5).

Over time and after some failures by fisheries management systems based on reductionist approaches—perhaps because of their intrinsic shortcomings or failures in governance or enforcement issues or as a result of the growing social awareness on environmental protection issues—a new paradigm, the *ecosystem approach,* has been proposed. This approach, which emerged in the early 1980s and was accepted internationally at the Rio Earth Summit in 1992, began to be incorporated into fisheries management at the 24th session of the Food and Agriculture Organization of the United Nations (FAO) Fisheries Committee and at the World Conference on Responsible Fisheries in Reykjavik (2001). Its implementation is now an obligation in some areas, such as the European seas, having been formally adopted by the European Commission's Common Fisheries Policy.

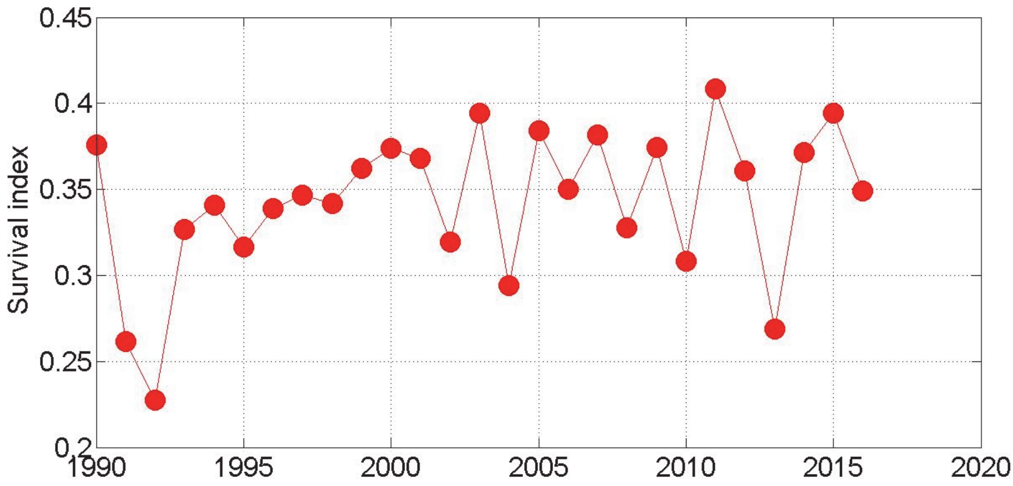

Figure 26.5. Natural fluctuations in larval survival probability due to the effect of temperature on growth.

Applying the ecosystem approach involves promoting multidisciplinary scientific research that provides quality scientific information and advice on fisheries, associated ecosystems taken as a whole and their relevant environmental factors, as well as their interactions. Besides fishing activity, variations in the Earth's climate, such as warming, heat waves or increasing sea level, are expected to affect marine ecosystems. While it is difficult to know exactly the systems' responses to climate warming, a broad range of observations during the past decades as well as modeling exercises predict that species can change their distribution, migration routes, or their reproductive timing and location. One example is the "tropicalization" of ecosystems, or the immigration of exotic species from warmer neighboring areas, when species change their distribution area along with changes of ecological niches (usually northward migration). Improved medium- to long-term projections based on understanding the physiology of organisms and the ecosystem functioning is important if climate change drives the environment out of the scenarios for which historical datasets are available (Fox and Aldridge, 2008).

The application of the ecosystem approach to the evaluation and management of living marine resources inevitably requires information on the characteristics and dynamics of the bodies of water provided by studies of physical oceanography. Also, in order to assess the vulnerability of fisheries to climate change, it is necessary to properly forecast future scenarios of environmental conditions. The incorporation of environmental information into models for the assessment of fishery resources is an emerging field of research, but there are already relevant examples of products based on operational oceanography data directly applicable to fishery management. Some of these applications are described below to demonstrate how they relate to each other to improve the management of living resources in a dynamic context. One of the current and future challenges is the need to work toward integration of oceanography into the assessment of marine living resources, allowing designing management actions to take into account environmental variability and climatic trends and, thus, ensure the sustainability of resources.

From a practical perspective there is a need to better link the knowledge of physical oceanography to fisheries assessments. Future research and development of data tools by oceanographers will have a higher impact on the sustainability of living resources if they are designed in multidisciplinary working groups. In fact, different international bodies are starting to establish collaborative networks with this in mind (e.g., http://www.imber.info/science/regional-programmes/cliotop/task-teams). To facilitate a better understanding of how operational oceanography is being linked in practice with pelagic, demersal, and coastal fisheries assessments, below are a number of study cases.

Current Advances and Challenges Integrating Operational Oceanography in the Management of Living Resources: Applied Examples.

The spatial distribution of adult fish

The fisheries of tuna species in the Mediterranean Sea mainly target adults during their reproductive season. Mature fish are captured in areas where they go to mate and reproduce. The spatial location for tuna species to reproduce can be linked to a certain spatially-fixed recurrent feature in a specific region (geographically-driven spawning) or it can be strongly influenced by oceanographic features that vary in their position from year to year, such as fronts (environmentally-driven spawning) (Reglero et al., 2012; Ciannelli et al., 2014). Thus, tuna species may be able to change their spawning distribution between years in relation to environmental changes within the ecological limits for the offspring success imposed by larval survival (Ciannelli et al., 2014).

Worldwide, tuna spawning grounds are usually found in areas with mesoscale oceanographic features such as fronts and eddies (Bakun, 2006; Reglero et al., 2014). There are several tuna species that reproduce in the Western Mediterranean (Fig. 26.6). The bullet tuna (*Auxis rochei*) is a small-size tuna that inhabits the coastal areas year-round. The albacore tuna (*Thunnus alalunga*) is a medium-size tuna that inhabits the open waters, and the Atlantic bluefin tuna (*Thunnus thynnus*) is a large-size tuna that undertakes far-reaching seasonal migrations in spring-summer from their feeding grounds in the Atlantic Sea into the Mediterranean Sea to reproduce. These three tuna species select their reproductive habitats based on different environmental signals (Reglero et al., 2012).

The location of reproduction habitats for Atlantic bluefin tuna shows two distribution patterns depending on the position of the salinity front that recurrently occurs and persists during the summer off Balearic Islands (Fig. 26.7a-b). Albacore reproductive locations are geographically fixed and linked to a quasi-permanent eddy (Fig. 26.7c), whereas bullet tuna reproduce mainly in the coastal areas (Fig. 26.7d).

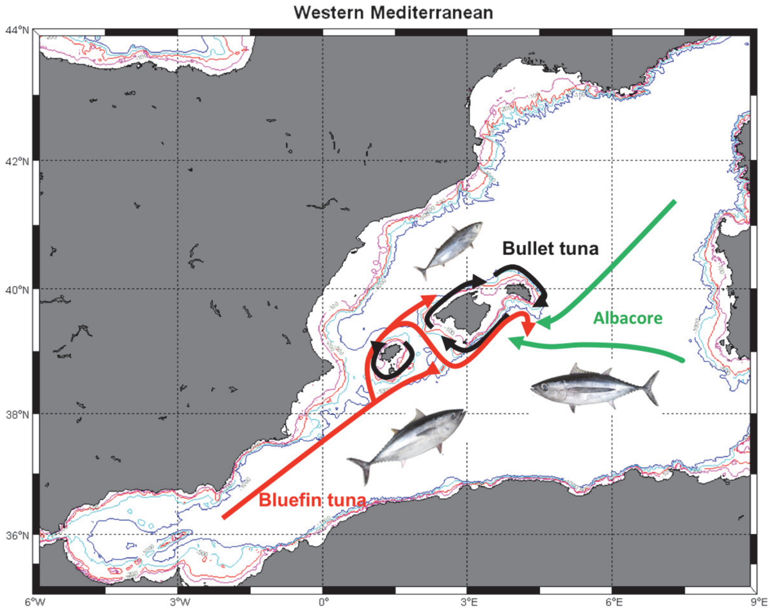

Figure 26.6. Conceptual figure summarizing the spawning geography of the three species of tuna—the large migratory Atlantic bluefin tuna (red), the Mediterranean albacore (green), and the coastal bullet tuna (dark blue)—and their plausible migration pattern around the Balearic Islands (Mediterranean Sea) from Reglero et al. (2012). Tuna pictures from S. P. Iglésias.

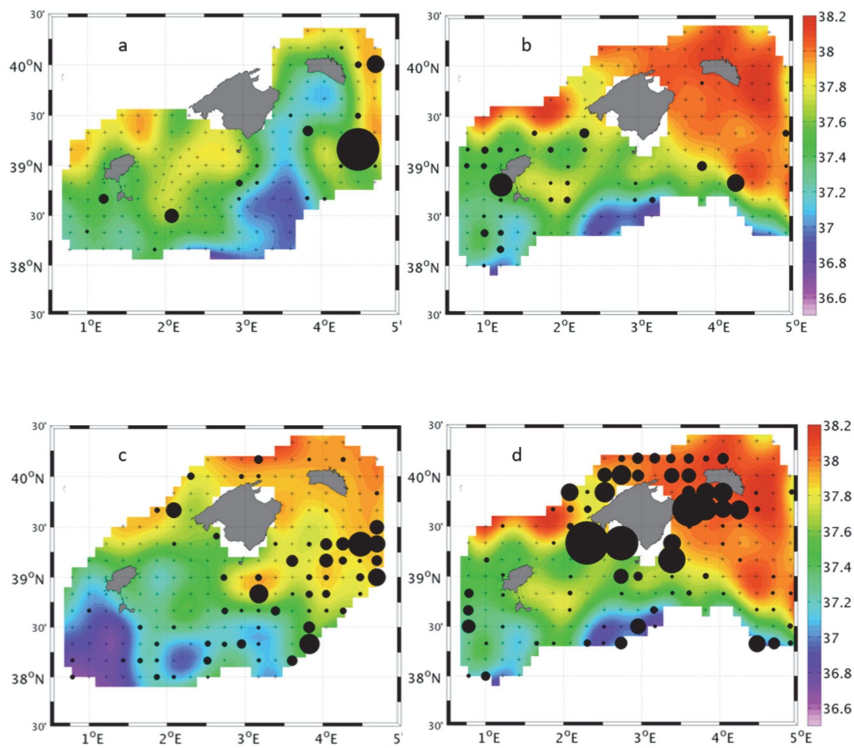

Figure 26.7. Spatial distribution of tuna larvae (black dots size represent larval density in larvae m^{-3}) in relation to salinity. a-b) Atlantic bluefin tuna spatial distribution varies with the position of the salinity front. c) Albacore spatial distribution is associated to a fixed mesoscale structure south of Menorca. d) Bullet tuna spawning in mostly in coastal areas. From Reglero et al. (2012).

Spawning locations can be estimated from models developed from data on spatial distributions of egg and larval abundances in relation to oceanographic operational data. Forecasting oceanographic summer situations, based on a long-term data series of environmental data from periodic research vessels surveys and new oceanography products based on the knowledge of environmental variability and ecological process, can help in the development of decision support tools for the spatial conservation and management of tuna species (Alvarez-Berastegui et al., 2016).

Management areas in the NW Mediterranean: Connectivity among subpopulations

One the most illuminating examples of the paramount need for oceanographic modeling (both hindcast and forecast) in fisheries research is the current challenge of embracing the spatial pattern of commercially-exploited populations to their temporal assessment. Indeed, better understanding the complex dynamics of large marine fish stocks is a critical need in fisheries science, as it is essential to know how many fish are in a given area and at a given time. Marine populations are often structured as a set of sub-populations connected through the exchange of individuals and whose spatial boundaries rarely coincide with management units. This is the case in the Mediterranean Sea (Fig. 26.8) where more than 90% of the stocks are considered over-exploited, with the European hake (*Merluccius merluccius*) being the most representative example.

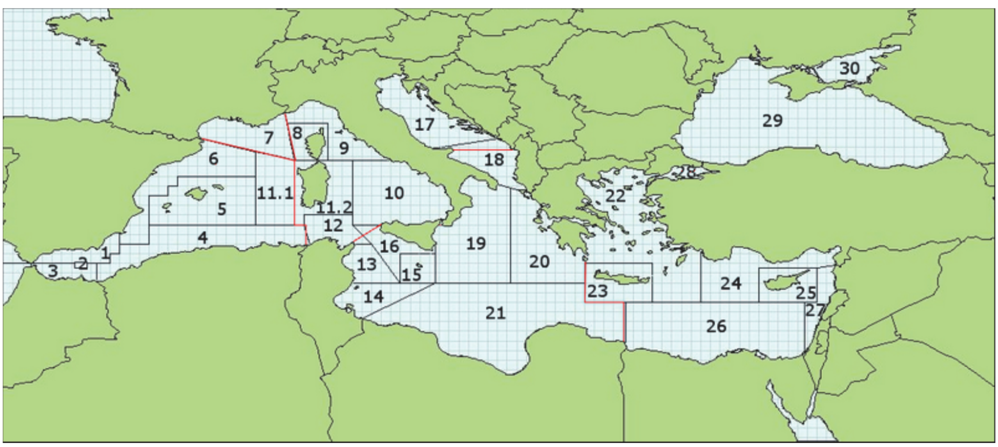

Figure 26.8. Geographical subareas used in the Mediterranean Sea as data collection and management frameworks (FAO).

Although fisheries models are increasingly considering adults' movement estimated from tagging experiments (i.e., marked-recaptured individuals), they still overlook the dynamics of early-life stages (eggs and larvae) potentially connecting subpopulations. Connectivity during early life stages is largely driven by physical dispersion due to multi-scale oceanic currents (Fig. 26.9) and has a profound impact on fish recruitment (e.g., the smallest fish or juveniles being captured by fisheries). Estimates of connectivity among subpopulations in the northwestern Mediterranean can be compared using ocean circulations models, with the recruitment estimates (number of young fish at sea per year) from the commercial fishery.

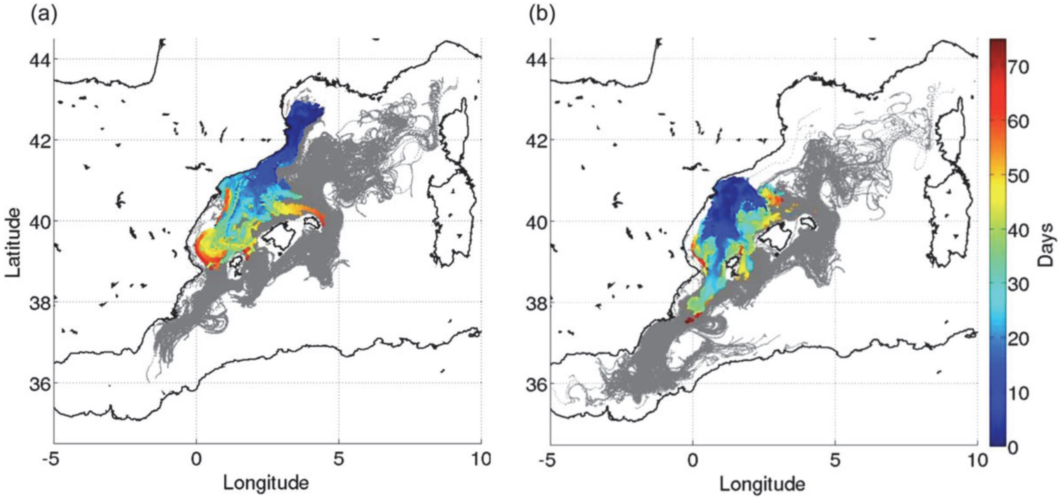

Figure 26.9. Lagrangian trajectories of Winter Intermediate Water (WIW) particles from the Gulf of Lion (a) and (b) the Ebro Delta regions. Color indicates time for particles with WIW that could simulate ELS in this habitat. Trajectories indicated in gray lost WIW properties (adapted from Juza et al., 2013)

A recent study demonstrated for the first time that the inter-annual variability of recruitment of large fish stocks can be modeled in relation to physical pattern of currents, calculating spatio-temporal connectivity estimates derived from high-resolution circulation models (Fig. 26.10). Fisheries science would benefit from efficient ways to include physics and fisheries assessment to improve management of large and complex populations, integrating the analysis of a limited number of controlling ecological and environmental processes that are critical to understanding and reproducing the dynamics of marine fish populations. This research provides a considerable step in that direction by acknowledging the complexity of marine populations and ecosystems in a relatively simple manner, as opposed to the development of overly complex ecosystem models (e.g., end-to-end modeling). This study opens broad opportunities to improve fisheries management by including short-term projections of physical oceanography.

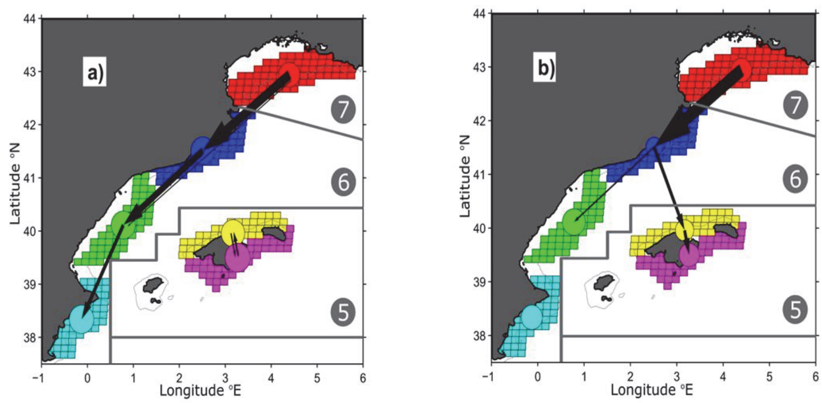

Figure 26.10. Spatial variability of the connectivity processes (export as arrows and retention as bubbles) between hake (*Merluccius merluccius*) subpopulations for two contrasting years. (a) Year 1989 shows the main south-westward transport pattern along the mainland with almost no import into the Balearic archipelago. (b) Year 2005 exhibits a reduced southwestward transport and stronger connections with the Balearic Islands (adapted from Rossi et al. in review).

Characterizing the dispersion potential of the seascape for a better informed marine spatial planning

As dispersion and connectivity are expected to affect both genetic structures and demographic rates of local populations, a careful evaluation of these bio-physical processes is crucial to understanding and modelling population dynamics. Thus, characterizing the connectivity regimes of all location of the ocean provides useful information for ecosystem management. Through the direct incorporation of population genetic concepts into a basin-scale biophysical model (i.e., Lagrangian module coupled with state-of-the-art operational ocean model), Dubois et al. (2016) proposed a common platform for geneticists, marine ecologists, and oceanographers to evaluate connectivity for management applications. By manipulating connectivity matrices with network theory tools, Dubois et al. (2016) analyzed complementary connectivity metrics: local retention (the ratio of locally produced settlement to local larval release), self-recruitment (the ratio of locally produced settlement to the overall settlement), and the source/sink proxy (relative importance of larval export versus import) (Botsford et al., 2009; Bode et al., 2006). The model predicts that retention processes are favored along certain coastlines due to specific oceanographic features, such as a sluggish circulation and extended continental shelves (Fig. 26.11b). Moreover, wind-driven divergent (convergent, respectively) oceanic regions are systematically characterized by larval sources (sinks, respectively) (Fig. 26.11a).

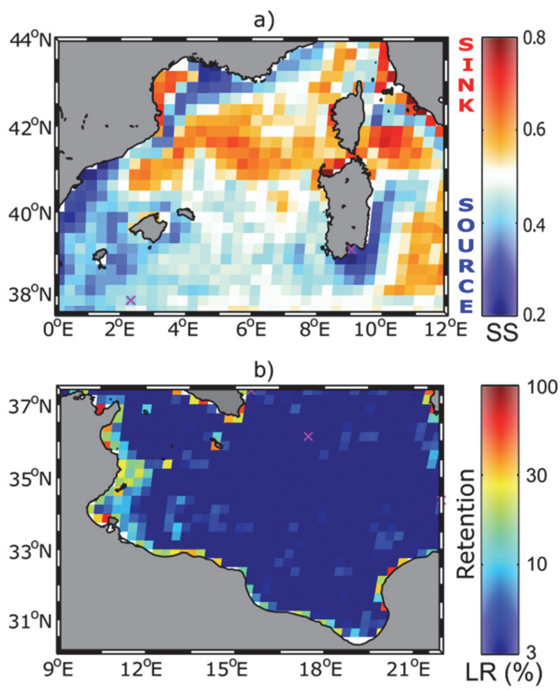

Figure 26.11. Connectivity studies conducted using a biophysical model simulating the dispersal of passive larvae in the upper water column for a pelagic dispersal during 30 days. a) Seasonal mean sink and source areas (relative importance of larval export versus import) in winter. b) Seasonal mean local retention (%) in summer. Adapted from Dubois et al. (2016).

Using biophysical modelling together with an integrated interpretation of retention and exchange connectivity indices give insight into how subpopulations are connected through larval transport; and, as such, helps to predict the effects of management measures or disturbances on both local and surrounding subpopulations. An accurate depiction of both local and broad-scale connectivity, as is allowed by connectivity proxies, is necessary to appropriately implement effective, spatially explicit management measures, such as marine reserves or fishery restrictions, by providing relevant information for managers and scientists to discuss implementation guidelines "case-by-case," in accord with sustainable objectives.

Marine protected areas for the conservation of coastal ecosystems

Marine protected areas (MPAs) are widely applied for the conservation of coastal ecosystems. Moreover, extensive research has made the case for promoting their application as fisheries management tool (Pérez-Ruzafa et al., 2008). Reducing fish mortality in the MPAs allows recovery of fish populations, which can result in spillover of larvae and adults to adjacent waters to the benefit of local fisheries (Goñi et al., 2008). In most cases, fisheries MPAs have been directed to enhance small-scale (artisanal) fisheries, operating in coastal waters and targeting highly resident species, which are the ones most benefitting from this conservation approach. MPAs are now a priority in the political environmental roadmap at a global scale, and member countries of the Convention on Biological Diversity agreed to reach a 10% of the marine real to be protected in 2020.

MPAs should meet specific conditions, such as incorporating the heterogeneity of the seascape and matching the biogeography of organisms, to ensure their functionality (Rees et al., 2017). Of particular relevance to the oceanography of regions where the protected areas are located, the MPAs should be connected to each other in order to build networks. The International Union for Conservation of Nature defines a MPA network as "a collection of individual MPAs operating cooperatively and synergistically at various spatial scales and with a range of protection levels that are designed to meet objectives that a single reserve cannot achieve." The Convention on Biological Diversity also specifies that currents, gyres, physical bottlenecks, and species dispersal processes, among other parameters, must be considered at specific MPA sites (see Annex II, https://www.cbd.int/decision/cop/?id=11663). The objective is to be able to design MPA networks were the size of each MPA and spacing between MPAs are based on scientific data informing by the patterns of adult movement and larval dispersal of protected species (see International Union for Conservation of Nature, https://www.iucn.org). For instance, Rossi et al. (2014) introduced the concepts of hydrodynamical provinces, which allow for a systematic characterization of the seascape connectivity. This information is useful when attempting to better define the relevant size and spacing guidelines of a given oceanic region in accord with management objectives.

The Mediterranean Sea is characterized by having a large number of small protected areas (Fig. 26.12). Most of them have been designed with the objective of increasing the abundance of living resources targeted by the fisheries or to act as areas that export biomass to neighboring areas.

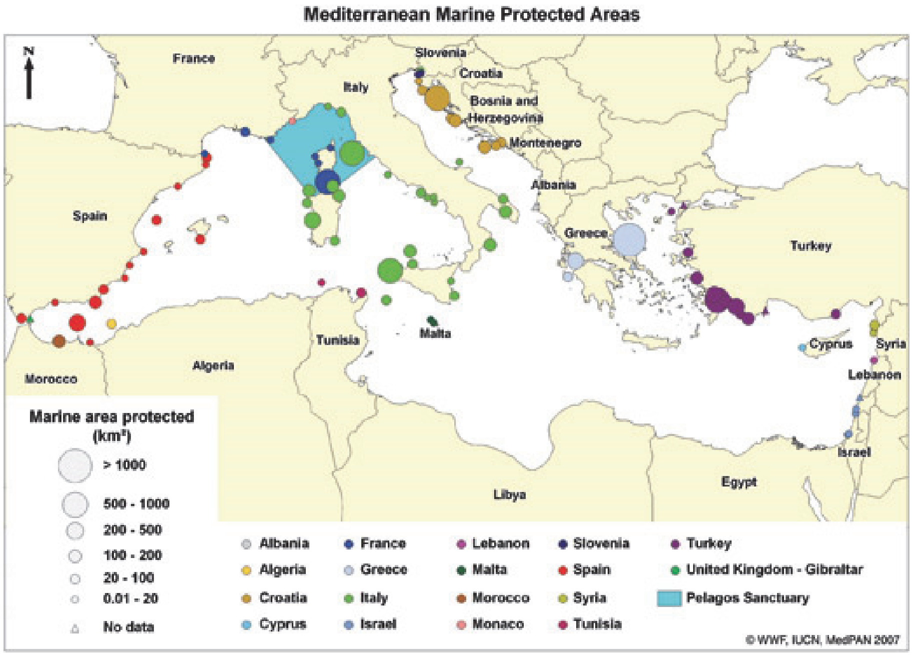

Figure 26.12. Marine protected areas in the Mediterranean Sea. Source: WWF, International Union for Conservation of Nature, Medpan (2007).

There are two main mechanisms through which marine protected areas act to improve fisheries: 1) larval exportation and 2) adult spillover from the protected to surrounding areas. Operational oceanography can expand our understanding of the distribution of species and life stages in order to address the biomass of targeted fish. One example is from Coll, et al. (2013) who looked at the biomass of fish as it was related to the coastal exposure, the benthic slope, rock rugosity, and depth. Continuous monitoring of these variables provides useful insight into the spatiotemporal dynamics of the species. On the other hand, life cycles develop in different habitats where the coastal and pelagic interphase plays a major role in connecting different life stages of the same species. Thus, there is a need for hydrodynamic and drifting models coupling the different spatiotemporal scales. Finally, operational oceanography can be used to develop tools for spatially dynamic marine protected areas since they enable the improvement of habitat prediction and management lines based on the spatial distribution of the species in relation to environmental variables.

The capability of the countries and international organizations to promote advances towards the implementation of effective MPA networks highly depends on our capability to assess the connectivity processes among specific locations in the sea (e.g., Rossi et al., 2014, Dubois et al., 2016). Toward this objective, we should consider which species are the object of protection and what the link is between their live cycles and the local oceanography. To accomplish this, the following biological characteristics must be considered: timing of the reproduction, early life biology, and developmental time to settlement. Operational oceanography should be encouraged to consider these issues in the development of hydrodynamic and dispersal models, considering that the life cycle occurs within different habitats (coastal/pelagic), and advocating for the development of complex hydrodynamic models coupling various spatiotemporal scales.

Challenges for the future of operational oceanography and marine living resources

There are only few examples of a systematic application of operational oceanography in the management of Mediterranean fisheries. Current assessments have not been able to ensure the sustainability of the fisheries, and nowadays 90% of the resources are overexploited (GFCM-FAO 2016). They do not integrate, or they include very poorly, environmental variability and its influence on the distribution and abundance of fish. The successful integration of operational oceanography into fisheries in the Mediterranean Sea has been recently discussed by experts in the framework of the Mediterranean Operational Network for the Global Ocean Observing System, identifying a number of gaps and challenges (Alvarez-Berastegui et al., 2017). These authors have proposed a roadmap based on the identification of specific oceanographic processes driving species ecology and the design of operational products specifically informing on those processes. The data accessibility and the data quality should be improved and new software should be created that enables data handling and end-to-end user communication. The usefulness of the operational oceanographic products can be proved by evaluating the impact of introducing environmental variability into a specific assessment model. This is one objective that can be tackled by the scientific community through European funding initiatives (e.g., EU Horizon 2020 funded project no. 773713, acronym PANDORA). Biochemical and physical oceanographic models are well developed, but extending them further up the food web to include plankton and fish has long been a major challenge for (de Young et al., 2004). As we have revealed in this chapter, most fish species pass through different developmental stages during their life cycle with changing habitats, thus varying their relationship with the environment. Such variability should be taken into account when linking biochemical models to stock assessment models.

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