Assessing management plans for the recovery of the european eel (Anguilla anguilla): a need for multi-objective analyses

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Assessing Management Plans for the Recovery of the European Eel: A Need for Multi-Objective Analyses

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Abstract.—The European eel *Anguilla anguilla* stock has been declining since the early 1970s and is currently considered to be outside safe biological limits. In June 2007, the Council of the European Union approved a regulation establishing measures for the recovery of the European eel stock. Each member state is required to develop eel management plans (EMPs) in order to achieve an escapement of at least 40% of the potential spawner biomass (with respect to undisturbed conditions) from each river basin. A reliable estimate of the potential spawner output of local stocks is crucial for the development of EMPs. Given the complexity of the eel life cycle, the use of mathematical models explicitly accounting for specific demographic traits and incorporating fundamental socioeconomic information is necessary to thoroughly assess the effectiveness of alternative management strategies. Here, using a case study approach, we show how mathematical modeling, based on sound field data, can contribute to the assessment of potential spawning stock and to the development of sound management plans. Then, we discuss how a multi-objective approach can be used to examine trade-offs between conservation and fishery goals and to help decision makers identify effective management policies.

Introduction

The European eel *Anguilla anguilla* is found and exploited in most European water bodies and a number of sites in northern Africa (Dekker 2000a). More than 25,000 people obtain a substantial income from eel fisheries (Moriarty and Dekker 1997). In recent decades, however, eel recruitment and eel catches have dramatically declined throughout the range of this species, which is presently considered outside safe biological limits (ICES 2005). The causes of its widespread decline are still poorly understood but most likely include changes in oceanic circulation (Castonguay et al. 1994; Knights 2003; Friedland et al. 2007), impact of new parasites (Lefebvre et al. 2002), habitat disruption, chemical contamination, and overfishing at different developmental stages (Dekker 2000b; Feunteun 2002; ICES 2005).

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Devising suitable strategies for the recovery of the stock is made particularly difficult by the unique and complex life cycle of the European eel. The European eel is a catadromous amphihaline fish whose biological cycle is fairly well known in the continental phase but whose oceanic phase remains surrounded by much mystery. Spawning areas are believed to occur in the Sargasso Sea. Larvae (leptocephali) reach the North African and European continental shelf where they develop into glass eels (small, unpigmented eels) and then metamorphose to elvers (small, pigmented eels). Although eel catadromy may be facultative (Tsukamoto et al. 1998; Daverat et al. 2006), a significant proportion of glass eels colonize brackish and freshwater environments. There they gradually become yellow eels (larger, still immature, pigmented eels) and grow for 2–20 years until they attain the critical size triggering sexual maturation and metamorphosis into the silver stage. Silver eels begin a 5,000-km journey that brings them back to the spawning grounds where they eventually mate and die.

Although decline of eel catches began in the late 1960s and recruitment collapse became evident in the 1980s (ICES 2005), the first comprehensive restoration plans are only now being developed (Dekker 2008). Dekker (2008) provides an exhaustive description of the political and scientific process that contributed to developing these conservation plans. Briefly summarized, in 2003, the European Commission issued a "Proposal for a Community Action Plan for the Management of European Eel" (Commission of the European Communities 2003), further developed in a proposal for a "Council Regulation Establishing Measures for the Recovery of the Stock of European Eel" (Commission of the European Communities 2005). A revised version of the text was unanimously approved by the European Parliament and finally endorsed by the Council of the European Union in June 2007. Its main target is to permit "the escapement to the sea of at least 40% of the biomass of adult eel relative to the best estimate of the potential escapement from the river basin in the absence of human activities affecting the fishing area or the stock" (Commission of the European Communities 2005). Member states are required to provide an eel management plan (EMP) for each river basin, with the aim of achieving this target via locally implemented measures. Those member states that do not submit an EMP to the commission for approval by December 31, 2008 "shall either reduce the fishing effort by at least 50% relative to the average effort deployed from 2004 to 2006 or reduce the fishing effort to ensure a reduction of eel catches by at least 50% relative to the average catch from 2004 to 2006" (Commission of the European Communities 2005).

The regulation's target escapement of at least 40% of the potential adult eel biomass is not clearly defined. The regulation refers to the "absence of human activities affecting the fishing area or the stock," a pristine state that may be unrealistically difficult to determine due to lack of historical data. ICES (2005) recommends, when possible, the use of existing and scientifically reviewed historical data on eel abundance and glass eel recruitment to derive a reference point. However, historical data are often missing, and when present, they usually come from sites where eel exploitation has a long history. The longest European data sets on eel catches have been collected in Lake IJsselmeer (the Netherlands), Lough Neagh (northern Ireland), Baltic Sea, and Comacchio lagoons (northern Italy) (Moriarty and Dekker 1997). These local eel populations have been strongly affected by fishing activities in the past century and even before (Moriarty and Dekker 1997). Therefore, estimating the potential spawning stock in the absence of human activities is a very hard task even for these sites, as human pressure began far before the collection of data. Long-term data from unexploited systems are often missing. In any case, inferring the productive potential of exploited areas from data collected in unexploited areas (though with similar characteristics) could cause serious underestimates, since fisheries activities are likely to have developed where stock densities were higher while historically unexploited areas were probably the less productive ones (Dekker 2003). Where the fishery targets only silver eels and almost all individuals are caught at the outlet of the lagoons (like, for instance, at Comacchio), the potential spawning output can be easily estimated from historical silver eel catches. For the fisheries where yellow eels are also caught (for instance, at Lake IJsselmeer and Lough Neagh), or where the fraction of silver eels caught is not reliably known (for instance, in the Baltic sea), the potential spawning stock cannot be easily assessed.

In cases where few data are available, the development of suitable mathematical models is often the only way to examine the consequences of different management strategies (De Leo et al. 2009).

Here, we illustrate the process for developing a conceptual framework to assess different management policies via mathematical modeling supporting the decision process. We start with a review of existing efforts to estimate the potential spawner production, which is the key reference point of an EMP. According to ICES (2005) guidelines, we only consider models based on field data from well-studied local eel populations. Then, we show how demographic models have been used to assess the consequences of different management policies on the viability of eel populations and how socio-economic information has been integrated into demographic models to evaluate the productivity and profitability of the fishery under different management scenarios. Finally, we discuss the potential contribution of multi-objective analysis supporting the identification of optimal management policies when decision makers are faced with contrasting objectives (typically, eel conservation and profitability of the fishery).

Bioeconomic Assessment of Eel Populations

A reliable estimate of the potential (pristine) spawner output of local stocks is the starting point for the development of EMPs in accordance to the regulation. However, conservation measures aimed at achieving the conservation target set by the regulation also affect, through possible limitations of fishing effort, the profitability of the fishery and, consequently, the social acceptability of a management plan. Therefore, the effectiveness of proposed EMPs must be evaluated not only from a conservation viewpoint, but also an economic one. To promote consensus among fishermen, decision makers should look for optimal fishing policies that achieve compromise between maximizing the viability of the stock and maximizing the profitability of the fishery. To this aim, it is crucial to have suitable tools to (1) estimate spawner output under undisturbed conditions, (2) predict the impact of different management policies on spawner output, and (3) estimate their influence on revenues.

Estimating Potential Spawner Outputs

Estimating potential spawner output (i.e., the biomass of mature silver eels that, in the absence of any fishing activity, would abandon a given site to begin their oceanic migration) provides a reference point to assess the impact of the fishery on the reproductive success of eel populations. Historically, most studies on eel population dynamics have been conducted in locations where commercial fisheries were present and fishing activities themselves provided the data used to develop models. These were usually aimed at assessing potential yields rather than spawner outputs. However, where the fishery targets only silver eels, estimating maximum yield also provides an assessment of potential spawner output. In contrast, where yellow eels are also exploited, estimating potential spawner output requires the development of demographic models, explicitly accounting for fishing mortality at all developmental stages. In the following, we briefly review the main studies that, in the past decades, provided reliable estimates of silver eel productions. Estimates are all expressed as a silver eel biomass per hectare in order to favor the comparison among results of different studies.

A first attempt to assess silver eel escapement through mathematical modeling was made by Rossi (1979) for the Comacchio lagoons and by Rossi and Cannas (1984) for the Porto Pino lagoons (southwestern Sardinia) through a simple life-table analysis. They provided an estimate of silver eel production before the recruitment drop of the 1980s, equal to 20 and 19 kg/ha at Comacchio and Porto Pino, respectively. Rossi (1979) reported also that silver eel production at Comacchio was much bigger in the period between the two world wars than in the 1900s, thanks to a water system configuration favoring juvenile recruitment.

Vøllestad and Jonsson (1988) used a long-term data series from the Imsa River (southwestern Norway) to develop an input–output model predicting total biomass and age distribution of silver eels from annual recruitment data. They estimated an overall yield of 3.51 kg/ha for the period 1975–1979. The mortality rate (assumed to be constant with age) was inversely correlated with the number of recruiting elvers, thus giving the first evidence for density dependence in eel mortality. Vøllestad and Jonsson's (1988) approach provides a powerful tool to predict yields at sites where elver recruitment and silver eel migration can be monitored and where the impact of commercial harvest is also reliably known. However, recruitment and silver eel migration cannot be readily measured in most eel fishing areas.

De Leo and Gatto (1995) developed the first model for the European eel, including a multiple classification of individuals by age and size. The model was based on data from the Valli di Comacchio lagoons (northern Italy) and accounted for inter-individual life history variability by means of a stochastic formulation. This represented a major improvement, as accounting for variability in the life cycle provides fundamental information about the uncertainty associated with harvest and the risk of stock decline. De Leo and Gatto (1995) estimated a silver yield of 6.15 kg/ha at Comacchio for the period 1989–1990. This figure is almost one-third of that estimated for the same lagoons by Rossi (1979) 15 years before, likely reflecting a recruitment drop in the 1980s. Later on, De Leo and Gatto (1996) applied their model to three data sets from the same sites, though from different periods (mid-1970s versus late 1980s) and revealed the dependence of prereproductive survival and mean body size at silvering upon eel density.

Dekker (2000), through a length-structured cohort analysis, estimated a potential silver eel production of about 4.4 kg/ha for Lake IJsselmeer. By using data from commercial catches, he calculated length-specific rates of total mortality, and under the assumption of constant natural mortality and silvering and escapement rates, he estimated fishing mortality. He argued that ceasing yellow eel exploitation in Lake IJsselmeer would lead to a many-fold increase in the adult eel population. He concluded that current, uncontrolled exploitation levels in the major eel fisheries might have negative consequences on the entire stock of European eel spawners.

Feunteun et al. (2000) used electrofishing and mark–recapture techniques in the Fremur catchment (northern France) to identify the relationship among silver eel dynamics, standing stock structure, and environmental factors such as flow, atmospheric pressure, rainfall, and lunar phase at a river basin scale. According to their study, silver eels represented almost 10% of the sedentary population in the catchment. However, only a small fraction of the silver eels (around 20%) effectively contributed to spawner output in the following migration period. In the Fremur catchment, where both natural and fishing mortality are low, the authors estimated an average spawner production of 1.3 kg/ha.

Rosell et al. (2005) examined data from tagging experiments and commercial sources at Lough Neagh (Northern Ireland) by means of cross-spectral analysis to investigate the relationship between explanatory variables (natural glass eel input, additional purchased glass eel input, mean water flow, and temperature) and response variables (yellow and silver eel yield). They found a significant dependence between yellow and silver eel yield on natural glass eel input 8 and 18 years before, probably reflecting the different life span of males and females. Their study revealed, despite the presence of commercial fisheries, a silver eel escapement of 2.5–3.5 kg/ha. This quite high estimate (considering Lough Neagh latitude and the fact that the local fishery exploits both yellow and silver eel) led the authors to consider the current management to be sustainable. Yet, the authors did not provide any assessment of the potential spawner production in undisturbed conditions.

Bevacqua et al. (2007) extended the approach proposed by De Leo and Gatto (1995) to account for interannual variability of glass eel recruitment and density-dependent juvenile survival while retaining the multiple classification of individuals by age and size and stochasticity in individual growth rates. They accounted for peculiarities of the eel life cycle such as delayed sex differentiation and sexual dimorphism in body growth through the model proposed by Melià et al. (2006) and described monthly variations in maturation rates with the model proposed by Bevacqua et al. (2006). By applying the model to a long-term data series from the Camargue lagoons (southern France), they estimated that current spawner escapement is far below the potential escapement (5.6 kg/ha) achievable in the absence of fishing at present recruitment levels.

Potential spawner escapement varies significantly among different sites, ranging between 1 and 20 kg/ha. Eel production is influenced by a number of environmental factors, such as temperature, salinity, and food availability, as well as by juvenile recruitment. Production is generally higher in brackish water bodies and at higher temperatures (up to 20 kg/ha before the recruitment drop of the past decades, around 6 kg/ha at present recruitment levels). In freshwater environments, lakes are usually more productive (about 4 kg/ha) than rivers (around 2–3 kg/ha). At sites where no historical data are available, gathering data on environmental parameters and present levels of juvenile recruitment is crucial to obtain preliminary estimates of potential production (through comparison with sites with similar conditions) and to provide the basis for the development of sound demographic models.

Assessing the Consequences of Different Management Scenarios on Spawner Output

Conservation of the European eel stock requires action in a number of fields, including structural measures to make rivers passable and to improve habitats, control of predators and parasites, improvement of water quality, and glass eel restocking. However, sustainable management of the fishery will certainly remain the central element of most EMPs due to their immediate consequences on spawner escapement. For this reason, we focus our analysis on management measures oriented to the regulation of the fishing effort. While it is easy to quantify the reduction in spawning output biomass due to silver eel fisheries, the consequences of yellow eel fishing on the spawning stock are not always easy to quantify. The impact of exploiting yellow eel was usually underestimated and often neglected, assuming strong compensatory density-dependent effects (ICES 2005). Recent works on different eel species, however, show that overfishing of yellow eels can dramatically impair spawner escapement.

Dekker (2000) established, through a length-structured cohort analysis, the historical impact of the well-documented fisheries of Lake IJsselmeer on both silver eel escapement and commercial catches. He concluded that yellow eel overexploitation in Lake IJsselmeer reduced female escapement to 0.14% and male escapement to 1.43% of pristine levels and that the fishing pressure on yellow eels precluded them from attaining a sufficient size to undergo sexual maturation and metamorphose into silver eels. Consequently, most of the catch was made up of yellow eels and spawner output was virtually absent.

Hoyle and Jellyman (2002) assessed the consequences of different management policies on yield and spawner biomass per recruit of two sympatric eel species in New Zealand, the New Zealand longfin eel *Anguilla dieffenbachii* and the shortfin eel *A. australis*. The local fishery targets both species, which are characterized by life cycles of different duration (the New Zealand longfin eel spends longer in freshwater and attains bigger sizes than the shortfin eel). They estimated that current exploitation rates have reduced the spawning per recruit of New Zealand longfin eel and shortfin eel females by about 95% and 40%, respectively. Then, they explored the effects of different decision variables, such as minimum legal weights and exploitation rates, on the spawning and fishing yield per recruit of both species, concluding that the two species require different management policies due to their different life cycles. Given the difficulty of developing different management policies for species that are hardly distinguished by fishermen, the authors suggested establishment of no-take reserves to protect New Zealand eels.

Doole (2005) applied a multiple-cohort bioeconomic model to the longfin eel fishery of the Waikato River (New Zealand) to investigate its optimal management and ascertain the appropriateness of current regulatory policies. He argued that using historical harvest data to calculate presently sustainable catches is inappropriate in light of the recent recruitment collapse. The author explored the consequences of management policies based on individual transferable quotas and the enforcement of protected areas on the status of the stock and the harvest. He argued that area closure and the spatial definition of harvest rights are attractive management options due to the territoriality of New Zealand longfin eels and that limiting the exploitation of older cohorts would increase yields. However, this last finding critically depends upon the specific spawner–recruitment relationship adopted. In fact, the author assumed that the number of juvenile eels entering the river in a given year and sustaining the local population depends on the abundance of local spawning stock 2 years before. Unfortunately, this assumption is not valid for local European eel populations, so that neither Doole's (2005) method nor his conclusions can be taken for granted in the management of European eel fisheries.

Bevacqua et al. (2007) evaluated the consequences of different management policies for the Camargue eel fishery. They estimated both silver eel escapement and harvest by local fishermen corresponding to different mesh sizes of the nets and different levels of fishing effort. By using realistic recruitment estimates, they could assess effective harvest and spawning output in absolute numbers and not only in terms of values per recruit.

All these studies clearly show that eels are particularly susceptible to overexploitation due to the singularity of their life cycle. In particular, downstream migration of silver eels facilitates their catch at particular places (e.g., bottlenecks). Also, their long lifespan is responsible for accumulation of high mortality rates as demonstrated by the major impact of fisheries on eel females and, in general, on long-living species (Dekker 2000; Jackson et al. 2001; Hoyle and Jellyman 2002). In addition, the absence of apparent stock–recruitment relationships at a local scale impairs the acceptance of sustainable management policies by fishermen communities.

Calculating Eel Fishery Profits

In addition to theoretical studies on the economics of fisheries (since the seminal works by Gordon 1954; Schaefer 1954), there are several studies regarding the exploitation of specific fish stocks in the literature (see, e.g., Myers et al. 1997; Orensanz et al. 1998; Kulmala et al. 2007). With regard to eels, however, examples of thorough bioeconomic analyses predicting the profitability of a fishery under different management scenarios are rare. While studies from other fisheries can provide useful information on the general guidelines to be followed to pursue sustainability in eel fisheries, the eel life cycle is so distinctive that general guidelines can be hardly applied to the development of specific policies for the management of eel stock. Here, we summarize the main results of the few bioeconomic analyses specifically focused on eel fisheries.

Gatto et al. (1982) assessed the profitability of different management strategies for the eel fishery of the Comacchio lagoons. The effort was traditionally exerted only on silver eels, which are fished by special devices called lavorieri, intercepting the entire flux of migrating fish. Gatto et al. (1982) concluded that extending the fishery to also target a fraction of yellow eels would allow fishermen to improve their gross economic return by about 10%. Almost 20 years later, De Leo and Gatto (2001) performed a stochastic bioeconomic analysis of eel fishing in the same lagoons aimed at optimizing the economic return from the Comacchio eel fishery. The authors explored the effect of extending the fishery to yellow eels and tested whether the decline of natural recruitment could be effectively supplemented by elver restocking. The authors analyzed different management policies in terms of fishing effort on yellow eels (defined as number of nets placed), net selectivity (mesh size), and restocking density. Net selectivity was expressed as a function of the fish size and the mesh size of the net. They explicitly considered harvesting costs, different selling prices for yellow and silver eels, and different discount rates to assess the optimal management policy for maximizing the average net economic benefit. They found that the highest profits could be obtained by fishing silver eels by lavorieri and fishing a fraction of yellow eels with 160 nets of 21-mm mesh. A stochastic approach allowed the authors to derive not only a point estimate of the economic benefit associated with the different management alternatives considered, but also the uncertainty of their estimates.

A Call for Multi-Objective Analyses

Fisheries managers must often cope with multiple, and possibly conflicting, objectives (Charles 1989; Hilborn 2007) such as maximizing catches, minimizing costs, minimizing bycatch, and maximizing spawning output per recruit. Considering several objectives at once provides a framework for the decision process, promotes a more appropriate role in the process for the analyst, and usually identifies a wider range of alternatives than those obtained by a single-objective analysis (Cohon 1978).

Multi-objective techniques represent an improvement with respect to traditional, single-objective approaches to planning problems (e.g., cost–benefit analysis) because they allow decision makers to address a number of objectives that cannot be reduced to a single dimension such as revenue (Meier and Munasinghe 1994). Multi-objective analysis can indeed help decision makers identify and highlight possible trade-offs among conflicting viewpoints. However, while it is widely agreed that the use of a multi-objective approach is highly desirable (Vaca-Rodriguez and Enríquez-Andrade 2006), substantial difficulties are encountered in identifying the ultimate goals of the different stakeholders and in providing a framework for the comparison between objectives. For these reasons, the use of multi-objective methods in fisheries research has been scarce over the past decades, although pioneering studies have been conducted since the early 1980s (e.g., Bishop et al. 1981; Charles 1989) and a few recent examples can also be found in the literature (e.g., Sylvia and Enríquez-Andrade 1994; Pan et al. 2001; Melià and Gatto 2005). Nevertheless, most efforts remain directed to the development of analytical tools to evaluate the impact of management strategies in a single-objective perspective.

The key concept of multiple-objective analysis is Pareto efficiency. An alternative (for instance, a fishing policy) is called Pareto-efficient when it is not possible to modify decision variables to improve a performance indicator (e.g., the viability of a fish stock) without worsening another performance indicator (e.g., the revenue of fishermen exploiting the stock). All other alternatives, for which there exists at least one feasible solution guaranteeing both higher viability and higher revenues, are called Pareto-dominated. The set of nondominated policies is called the Pareto boundary (or Pareto set) and represents the suite of alternatives among which the decision maker can reasonably choose. The Pareto optimal set and associated trade-offs supply a useful reference and important information to decision makers. Eventually, for any given problem, only one solution has to be selected by the decision makers. This solution is usually not the result of a formal maximization problem, but rather of a subjective evaluation of the relative importance of the objectives by the decision makers. Hence, it must be clear that the multi-objective approach concentrates on providing information to the decision makers regarding the range of effective choices and the consequences of different options rather than suggesting a single optimal solution (Gatto and De Leo 2000).

An example of applying this approach to eel management is provided in Bevacqua et al. (2007). They performed a Pareto analysis to identify the fishing policies providing the best compromise between two partially conflicting objectives in the management of the eel fishery of the Camargue lagoons: maximizing the escapement of silver eels towards the ocean and maximizing the harvest by commercial fishermen. Their results support the view that, at present, the Camargue eel fishery is inefficient with respect to the two objectives of maximizing spawner output and catch biomass. The main reason of such inefficiency is the use of highly selective fishing devices, which focus the fishing pressure on younger stages. In order to maximize the spawning output, the fishery would need to be closed, while yield maximization would require adopting a larger mesh size than currently used.

Yields or Profits?

Many local European eel fisheries are likely as inefficiently managed as the Camargue fishery. However, assuming the main goal of fishermen is the maximization of fishing yield is not always realistic. Indeed, informed fishermen are usually more interested in maximizing the revenues derived from selling their eel catches rather than maximizing yields (Hilborn 2007). Estimating the profitability of a fishery requires socioeconomic information on costs and revenues, which is often difficult to collect, especially for small-scale fisheries. Selling prices vary widely depending on a number of factors such as seasonal fluctuations in demand, provenance of the catch, and size of the fish. In most fish markets, bigger individuals are preferred to smaller ones (see, e.g., De Leo and Gatto 2001). In these cases, the fishing strategies adopted by fishermen cannot be correctly interpreted without explicitly incorporating the size price structure into the analysis. In the Camargue, for instance, the main cause of inefficiency of the fishery is the overexploitation of young yellow eels (Bevacqua et al. 2007), a practice that affects the size composition of the catch and, if the eel price per mass unit is related to the fish size or the maturation stage, can also affect profits. If we applied De Leo and Gatto's (2001) price structure to the analysis of the Camargue fishery, the inefficiency of current exploitation practices would become even more evident. In recent years, however, local market demand has shifted towards a marked preference for small-sized eels required by aquaculture. Therefore, the reduction of the overall harvestable catch caused by the use of a small mesh size might be compensated by the extra profit generated by selling the lucrative small eels to the aquaculture market. Despite the difficulty of gathering the necessary information, including fishing costs and revenues in the quantification of fishermen's objectives is of critical importance and can lead to very different management scenarios from those obtained by aiming to maximize yields. This approach is even more compelling when eels are exploited in a multispecies fishery where other species may also drive or influence the fishing strategy.

Final Considerations

The collapse of the European eel stock and glass eel recruitment requires immediate action to halt their decline. Although habitat considerations such as pollution and dams and hydropower stations certainly contribute to the decline, there is little doubt that, given the present level of recruitment, reducing fishing mortality is the most practical and effective short-term strategy to increase the spawning stock (ICES 2005). For some fisheries, this might simply require the reduction of the catch and consequently the profit—which, understandably, is strongly opposed by fishermen. Yet, recent analyses show that cases exist where the conservation target can be achieved without reductions in harvest (Bevacqua et al. 2007). Given the complexity of the eel life cycle and the duration of its continental life span, the only way to assess the efficacy of an EMP at the local level is to make use of demographic models of eel dynamics that allow the investigation of the effects of a large number of fishing alternatives (in terms of fishing effort, fishing gear, and length of the fishing season). The results can be surprising, as both spawning stock and catches can be substantially improved by using a suitable combination of fishing effort and mesh size, as demonstrated by Bevacqua et al. (2007).

As the European eel is a panmictic species, sustainable management strategies must have both a local and global scope. All bioeconomic analyses conducted on local eel populations have disregarded the existence of a global stock–recruitment relationship, considering spawner output as unrelated to recruitment. To date, the only attempts to assess the whole European eel stock and describe its dynamics have been conducted by Dekker (2000c) and Åström and Dekker (2007). Although these studies were chiefly focused on eel conservation rather than on the sustainability of the fishery from the fishermen's viewpoint, they represent a useful starting point for a comprehensive bioeconomic analysis of the European eel stock and its fishery.

Another often neglected aspect in the design of eel recovery plans is the inclusion of the economic component in fishery management. It is well known, in fact, that fishery dynamics are generally driven by economic forces occurring at the market level that try to match supply and demand (Pinnegar et al. 2006). A change in market price reflecting the consumer's willingness-to-pay to purchase eels at a given level of production can strongly affect fishermen's profits and consequently influence the set of optimal policies. For instance, in the late 1990s, the increasing Asian demand for glass eels on European and North American markets pushed selling prices to exceptionally high levels (up to €4,500/kg; Tesch 2003). In the following years, Japanese demand for glass eels was mostly satisfied on Asian markets, and glass eel prices in Europe began to decline. Market price fluctuations remain driven by the balance between Asian and local demand, which prizes small size eels for aquaculture (Allen et al. 2006). Given this global consideration, the European eel was included in Appendix II of the Convention on International Trade in Endangered Species in June 2007. This listing will likely have consequences on the international eel trade that will be important in shaping market scenarios and in producing cascading impacts on local fisheries. Moreover, after years of almost complete absence of regulation, European Union (EU) member states are now required by the end of 2008 to implement EMPs that will certainly affect thousands of small artisan fisheries scattered all around Europe. An effective enforcement of the EU regulation is difficult to achieve in such a fragmented situation, as free-riding incentives are always present.

Nevertheless, conflicts that are likely to arise between fishermen and policy makers as a result of the implementation of EMPs can be reduced and enforcement enhanced if the interests of fishermen are explicitly accounted for in the definition of the recovery plans. This implies that a detailed analysis of fishermen's preferences should be carried out. This task is far from trivial, as fishermen operating in small-scale fisheries affected by unpredictable environmental conditions do not always aim to maximize profits, but rather to minimize the variability of annual revenues (Chaboud 1995). Curiously enough, a similar attitude has been observed in small-scale African farmers who preferred to reject technological innovations when the potential increase in yield was associated with an increase in yield variance (Brossier 1989). In these cases, the use of stochastic models, explicitly accounting for the uncertainty in predictions, may allow decision makers to formulate risk-averse management policies that are more likely to be supported by fishermen.

Finally, when developing management plans, it should be remembered that small-scale fishing is not just a source of income but is often perceived also as a valuable "way of life" (Apostle et al. 1985). Factors such as sense of independence (i.e., being one's own boss), lack of options, socialization processes, cultural traditions, and so forth can indeed play a central role in defining fishermen's responses to regulations. Multi-objective methods can provide a way to explicitly account for several contrasting objectives that cannot be reduced to or evaluated in just monetary terms. Last but not least, multi-objective analysis also offers the further advantage of identifying a whole set of Pareto-efficient policies rather than just a single optimal policy simply expressed in economic terms. This approach provides decision makers with more opportunities to manage potential conflict among contrasting stakeholders while applying a rigorous and quantitative assessment of the conservation effectiveness of different fishing policies and conservation plans.

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