

FISHERIES IN LAGOON-ESTUARINE ECOSYSTEMS

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In this chapter, we review the “four factors”—recruitment, growth, natural mortality, and fishing mortality—viewed in classical fish dynamics as needed for predicting future from present stock sizes—in the context of lagoon-estuarine fisheries, and discuss the connection between fish catches, community dynamics, and ecosystem functioning. We compare worldwide catches from lagoon-estuarine systems and briefly discuss their management with emphasis on the *bordigue*, a form of tidal trap used in the western Mediterranean area to harvest fish previously recruited to a lagoon and/or to retain undersized fish for another growth cycle. This form of harvest/management, which requires complex social arrangements, may, short of aquaculture, represent the optimum way of using lagoon-estuarine ecosystems to produce fish.

18.1 INTRODUCTION

We briefly review the factors that determine fisheries yield in coastal lagoons, which have been defined by Ardizzone et al. (1988) as “bodies of water (from low brackish to hyper saline) partially separated from an adjacent sea by barriers of sand or other sediment, with openings through which seawater can flow”.

See Kjerfve (1994) for other definitions, and Day and Yáñez-Arancibia (1982) for an ecosystem-based definition of coastal lagoons and estuaries. “Fisheries” refers to the catching of fish and aquatic invertebrates and, hence, excludes aquaculture. When we refer to coastal lagoons, we generally mean coastal and estuarine systems in general. The literature on lagoon-estuarine ecosystems is immense; that on lagoon fisheries is also too large for a balanced review to fit into the space available for this chapter, even after aquaculture is excluded. We, therefore, concentrate on a few themes that we think are of special relevance to lagoon fisheries, yield prediction and management, and to fishes only. Our examples focus on one lagoon-estuarine ecosystem of the Gulf of Mexico and on West African and Mediterranean lagoons. We chose the first two locations because we worked there; and the Mediterranean case because this is where the management scheme emerged that we would like to point out to the readers. Except for a few references, we do not cover the important lagoon fisheries of the Indo-Pacific area. These lagoons are included, however, in the compilation of lagoon fisheries catches discussed in the following section. This chapter builds on the fisheries chapter in the first edition of *Estuarine Ecology*, and readers are encouraged to refer to that chapter also.

18.2 FISHERIES CATCHES FROM COASTAL LAGOONS

Kapetsky (1984) is still the reference that presents the largest data set on catches from coastal lagoons and compares these with catches from other exploited marine and fresh water ecosystems. As can be seen from Table 18.1, coastal lagoons are, overall, more productive than other ecosystems in terms of fisheries yield, whether one uses the mean or the median as a measure of central tendency. This can ultimately be accounted for by the generally high primary production in coastal lagoons (Nixon, 1982, 1988), for which three reasons may be suggested: (i) Availability of organic matter inputs via rivers (Kapetsky, 1984; Caddy and Sharp, 1986; Deegan et al., 1986; Yáñez-Arancibia et al., 1985a, 1985b; Yáñez-Arancibia and Aguirre-León, 1988; Day et al., 1997; Laffaille et al., 1998; Bianchi et al., 1999; Sánchez-Gil et al., 2008); (ii) Shallowness, conducive to rapid remobilization of nutrients (Qasim, 1973a; 1973b; Jones, 1982; Nixon, 1982; Quignard, 1984; Deegan et al., 1994, 2000; Deegan, 2002); and (iii) Velocity and volume of water exchanges between the sea and the estuarine system, which also directly affects fish production via recruitment (e.g., Bourquard and Quignard, 1984; Caddy and Sharp, 1986; Deegan et al., 1986; Yáñez-Arancibia, 2005; Yáñez-Arancibia et al., 2007).

However, coastal lagoons do not have uniformly high yields and, indeed, the frequency distribution of Kapetsky's yield data is strongly skewed (Fig. 18.1). Some factors leading to this nearly log-normal distribution are, with regard to the numerous occurrences of unproductive lagoons:

1. Extreme salinity and temperature fluctuations, turbidity, anoxic conditions, or toxic discharges (Gunter, 1967).

TABLE 18.1 Fisheries yields of coastal lagoons (all groups included) as compared with the yields of other aquatic ecosystems

Systems	Yields (t/km ² /year)		
	Median	Mean	<i>n</i>
Coastal lagoons	5.1	11.3	107
Continental shelves	4.8	5.9	20
African/Asian reservoirs	4.2	7.5	41
Coral reefs	4.1	4.9	15
River floodplains	3.2	4.0	33
Reservoirs (United States)	1.3	2.4	148
Natural lakes	0.5	2.8	43

Source: From Kapetsky (1984).

2. Very shallow sills, preventing sufficient recruitment.
3. Excessive illumination or turbidity, both of which can lead to reduced primary productivity (Qasim, 1973a, 1973b).
4. Lack of sufficient fishing effort (Quignard, 1984; Bailey, 1988), a condition that is increasingly rare.

The few extremely productive lagoons in Figure 18.1 may benefit, on the other hand, from a number of positive factors:

5. A coastal habitat supplying a large recruitment (Pauly, 1986b).
6. Fertilization from rivers and via agricultural runoff, or human sewage and through water exchanges with the sea.
7. A management regime that makes the best of the incoming recruitment.

18.3 FISH POPULATION DYNAMICS AND ITS FOUR FACTORS

18.3.1 Russel's Axiom

The definition of "fisheries" in the introduction implies the need for management, because common-property, open-access natural resources systems, given competing users, cannot produce high, sustained yields if left to themselves (Hardin, 1968).

Fishery science and especially its "operational" subdiscipline, fish population dynamics, are often articulated by means of Russel's axiom, that is:

$$B_2 = B_1(R' + G') - (M' + F') \quad (18.1)$$

which states that a well-defined stock (= population) of fish biomass (B_1) will have after an arbitrary period Δt , the biomass B_2 as a result of positive processes (R' = recruitment; G' = growth) having added to the stock, while negative processes (M' = natural mortality; F' = fishery catches) have reduced it (Russel, 1931; Ricker, 1975).

Equation 18.1 does not have a form allowing its direct use for assessment, and hence, this equation is generally used only for defining a problem, as done here. On the other hand, the four processes included in the equation, plus some peripheral processes also considered by fishery biologists (Fig. 18.2), have been put in a mathematically tractable form (Schaefer, 1957; Beverton and Holt, 1957; Ricker, 1954, 1975; Gulland, 1983; Pauly, 1984, 1998; Hilborn and Walters, 1992). In this chapter, we present a few of the models that

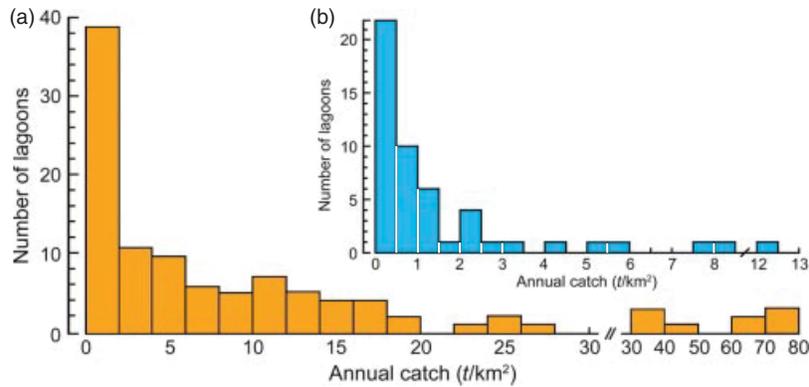


FIGURE 18.1 Frequency distribution of fishery catches from coastal lagoons. *Source:* From Kapetsky (1984). (a) Finfish, $n = 106$. (b) Penaeid shrimp, $n = 51$.

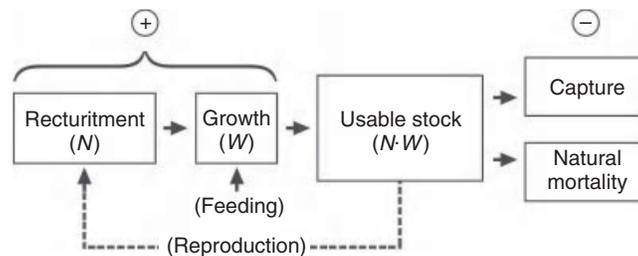


FIGURE 18.2 Schematic representation of four key factors determining the future biomass of and catches from a stock: Recruitment where $N =$ number of fish added to the stock, individual growth in weight (W) of the fish recruited into the usable stock, natural mortality, and capture via fishing mortality. Feeding and reproduction, although necessary for stock build up and maintenance, are usually not part of classical fish population dynamics. *Source:* Adapted from Russel (1931) and Ricker (1975).

have resulted from these efforts, specifically those that have been used in dealing with lagoon-estuarine systems. The four factors shall be examined in the sequence: growth, natural mortality, fishing mortality, and related factors (mainly catch/effort), with recruitment being last, because it is the most complex factor to investigate, model, and predict.

18.3.2 Growth of Fishes in Lagoon-Estuarine Systems

Lagoon environments are highly seasonal, more so than the open marine environment to which they are connected. Thus, the food types (Aguirre-Leon and Yañez-Arancibia, 1986; Chavance et al., 1984; Fig. 18.3) and food consumption, and hence, the growth of lagoon fishes are bound to oscillate seasonally, whether the fish in question undertake seasonal migrations in and out of coastal lagoons or not. Another, perhaps the dominant, source of seasonal oscillations is water temperature, which exerts a profound influence on the metabolic processes of poikilotherms and hence on their growth (Pauly, 2010).

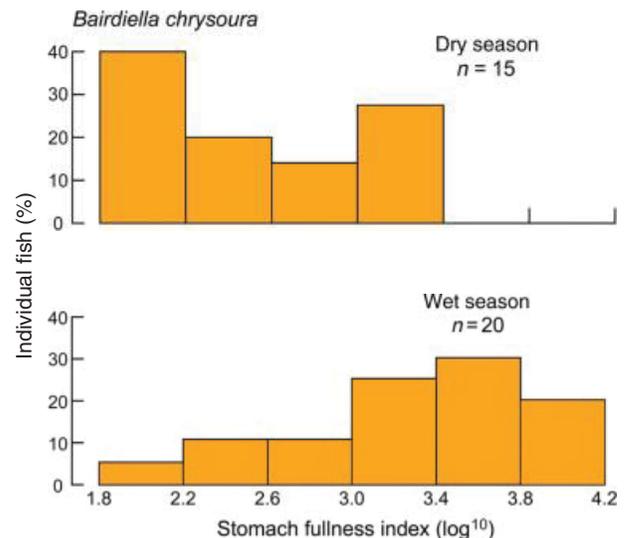


FIGURE 18.3 An example of seasonal changes in the stomach contents and hence, presumably the food consumption of a lagoon fish, the silver perch *Bairdiella chrysoura*, Terminos Lagoon, Mexico. *Source:* Adapted from data in Chavance et al. (1984).

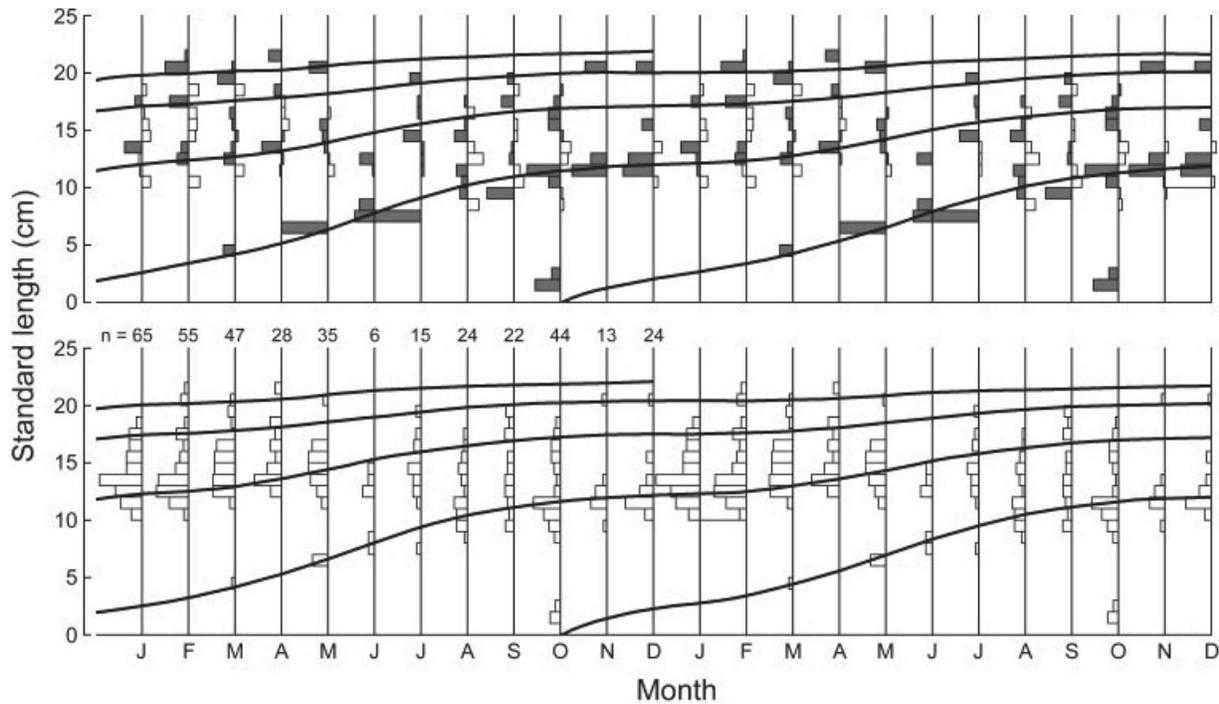


FIGURE 18.4 Seasonal growth of the checkered puffer *Sphoeroides testudineus* (Tetraodontidae) from Biscayne Bay, Florida, based on length frequency data from Targett (1979; lower panel). Note “doubling up” of the data set, and sample sizes ($n = 65, 55, \text{etc.}$). The upper panel shows the “restructured” length frequency data, as used internally by the ELEFAN program of Pauly and David (1981). *Source:* Adapted from Pauly and Ingles (1981).

Various authors have modified the von Bertalanffy equation (Bertalanffy, 1938), commonly used to express growth of fish, to accommodate seasonal growth oscillations (see e.g., Longhurst and Pauly, 1987; Hoenig and Chaudhury Hanumara, 1982; Soriano and Jarre, 1988; Pauly, 2010).

Figure 18.4 presents an application example pertaining to a puffer fish displaying weak seasonal growth oscillations, as is often the case in tropical and subtropical waters (Pauly and Ingles, 1981; Longhurst and Pauly, 1987). The growth models presented by the authors above can accommodate stronger growth oscillations, all the way up to a very short period of zero growth, for example, when temperatures are lowest (Pauly, 2010). However, these models cannot accommodate longer periods of zero growth. Therefore, we used a model that can accommodate a (“winter”) period of growth stagnation called *no-growth time* (NGT; Pauly et al., 1992). To fit such a curve, the time axis is divided into one growth and one NGT over each period of one year. Then, during growth time, we have

$$L_t = L_\infty [1 - \exp(-w)], \quad (18.2)$$

in which L_t is the length at age t , and where

$$\omega = K(t' - t_0) + \frac{\frac{K}{2\pi}}{(1 - \text{NGT})} \left[\sin \frac{2\pi}{1 - \text{NGT}}(t' - t_s) - \sin \frac{2\pi}{1 - \text{NGT}}(t_0 - t_s) \right], \quad (18.3)$$

where t' is obtained by subtracting the total amount of NGT that the fish experienced from the age t , since $t = 0$.

The other parameters are L_∞ the asymptotic length, that is, the average length the fish would attain if they lived indefinitely; K , twice is the parameter expressing how fast L_∞ is approached, t_0 is the theoretical “age” at length zero if the fish always grew according to the equation, and t_s is the parameter adjusting a seasonal cycle to start at $t = 0$. Note that the seasonal growth itself (outside of NGT) is described by a sine wave curve with period $1 - \text{NGT}$, and that the unit of K' is $(\text{year} - \text{NGT})^{-1}$ instead of year^{-1} .

An application example for this model is given in Figure 18.5. As might be seen, the model predicts a no-growth time of about three months (January to March) for the European seabass (*Dicentrarchus*

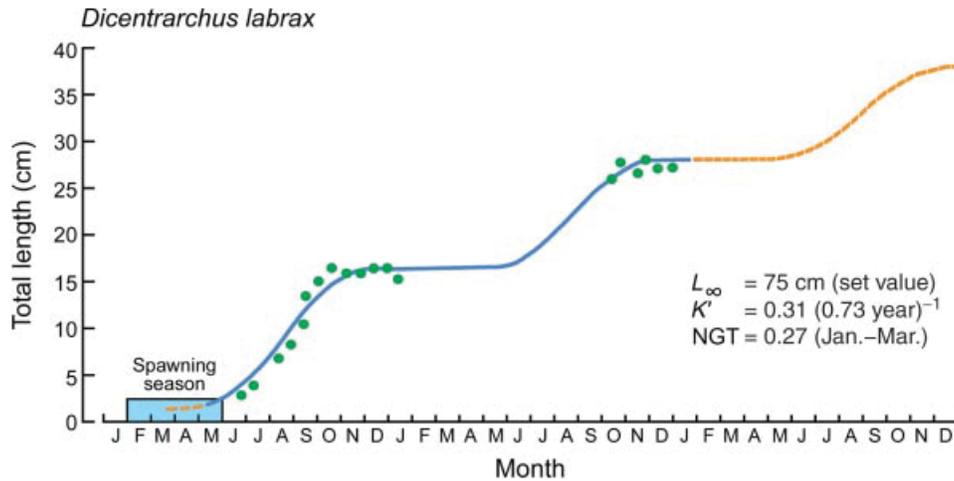


FIGURE 18.5 Seasonally oscillating growth of a European sea bass, important in Mediterranean lagoon catches. *Source:* Monthly size data from Quignard (1984); maximum size ($\approx L_{\infty}$) and spawning season from Beauchot (1987).

labrax) in l'Etang d'Or, France, a feature that other seasonal growth models could not have picked up.

When growth is not seasonal, that is, when one deals with data points that are one year apart or when working with otolith microstructures of fish not belonging to a given cohort, the standard (non-seasonal) von Bertalanffy curve can be used. It has the form:

$$L_t = L_{\infty}(1 - e^{K(t-t_0)}), \quad (18.4)$$

where L_{∞} and t_0 have the same definitions as in Equations 18.2 and 18.3, where K has the dimension of time⁻¹ (e.g., year⁻¹). An application example is presented in Figure 18.6.

The growth of fishes within coastal lagoons relative to that of conspecifics growing in other habitats appears to be a function of (i) the type of lagoon and/or of habitats being compared, (ii) the species of fish, and (iii) the life stage of the fish species.

Thus, Chauvet (1988) suggests that shallow, eutrophic lagoons lead to improved growth compared with that in deep lagoons, strongly influenced by the marine regime. He also noted, with regard to Mediterranean species such as gilthead sea bream (*Sparus aurata*) and European sea bass, that the lagoon habitat appears to lead to higher growth rates among the juveniles and young adults (Fig. 18.7), while among the larger, older specimens of these two species, growth within lagoons is at best equivalent to, and generally less than, that in the marine environment (Chauvet, 1988).

The West African coast offers further and clearer indications of at least small coastal lagoons being habitats, leading, independently of fishing effects, to

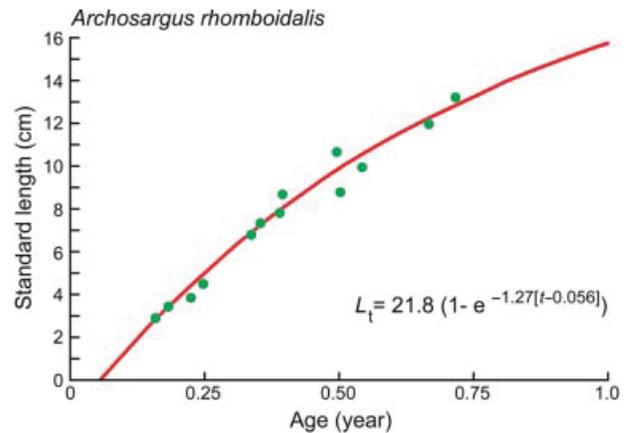


FIGURE 18.6 Growth of Western Atlantic sea bream *Archosargus rhomboidalis* (Sparidae) in Terminos Lagoon, Mexico, as inferred from counts of otolith microstructures (recomputed from Chavance et al., 1986). The new parameter estimates derived here differ from those originally presented because a nonlinear routine was used to fit the data: the new estimation of $L_{\infty} = 22 \text{ cm}$ is closer to the maximum length in Terminos Lagoon (23 cm) than the original estimated $L_{\infty} = 20 \text{ cm}$. *Source:* Adapted from Chavance et al. (1986).

reduced final (maximum) sizes among resident fishes: (i) the maximum observed size of the blackchin tilapia *Sarotherodon melanotheron* (Cichlidae) in the small poikilohaline Sakumo Lagoon was 19.5 cm (Pauly, 1976) versus 25 cm in the much larger estuarine Lagos lagoon (Fagade, 1974), and (ii) the two forms of the "bonga" *Ethmalosa fimbriata* (Clupeidae) appear to occur in West Africa, one occurring along the coast, and in estuaries and large "open" coastal lagoons, and reaching sizes of up to 30 cm, and the other

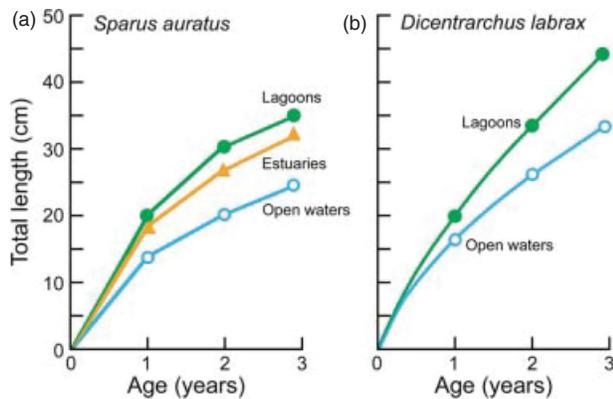


FIGURE 18.7 Growth differences among juveniles of two species of fishes important to Mediterranean lagoon fisheries. (a) Gilthead sea bream. (b) European sea bass. Note improved growth in the lagoon habitat. *Source:* Adapted from Chauvet (1984, 1988).

limited to a length of about 15 cm and occurring and reproducing only within closed lagoons (Longhurst and Pauly, 1987). Note that these effects are independent of, and added to, the size-based artificial selection that is imposed by a long-term fishery, and which ultimately results in small adults (Conover and Munch, 2002; see also Pauly (2002) for the case of *S. melanotheron*).

Improved growth of juveniles and limited maximum sizes of adults are not necessarily incompatible. Indeed, rapid juvenile growth due to availability of abundant food and high habitat temperatures generally implies a reduction of maximum adult sizes. Longhurst and Pauly (1987) give reasons, amplified in Pauly (2010), why this should be so.

18.3.3 Natural Mortality of Fishes in Coastal Lagoons

The natural mortality of a fish population is straightforward and can be modeled using:

$$N_2 = N_1 e^{-M\Delta t}, \quad (18.5)$$

where N_1 and N_2 are the numbers of fish at the beginning and end respectively and M is the instantaneous rate of natural mortality during a period Δt . Instantaneous rates such as in Equation 18.5, for example, natural (M) and fishing (F) mortality, can be added to yield the total mortality (Z) and the latter used in equations analogous to Equation 18.5.

Beverton and Holt (1959) were the first to demonstrate rigorously that the growth performance of fishes is strongly correlated with their natural mortality, that is, that the growth parameter K of fishes with similar L_∞ values (Eq. 18.4) generally remains

close to a constant proportion of M . Their findings were generalized by Pauly (1980) based on data from 175 fish stocks to yield the empirical equation:

$$M \approx (K^{0.65}) \frac{T^{0.46}}{L_\infty^{0.28}}, \quad (18.6)$$

where L_∞ is the asymptotic length (total length, in centimeters), K is per year, and T the environmental temperature in degree Celsius.

Hence, lagoon fishes, which tend to have higher K and lower L_∞ values than their conspecifics in open waters, can be expected to have generally higher natural mortalities than their open-water counterparts. This explains the observation of Chauvet (1988), who noted that “strangely, it is in the lagoon habitats that are most favorable for growth that the mortality rates are highest . . .”

It is important, however, to distinguish between the relatively low natural mortality rates affecting late juveniles and adults, which are fairly constant and largely predictable, from those affecting larval and early juveniles, which are high and essentially unpredictable.

Moreover, an important distinction with regard to lagoons is that between natural mortality rates as discussed above and catastrophic mortalities, as caused, for example, by dystrophic crises (Chauvet, 1988). The former may be seen, at least as far as populations rather than individuals are concerned, as a gradual process. Thus, natural mortality, as influenced or determined by predation, will be more or less continuous over a certain period and can be compensated for by population growth, leading to the observed narrow range of M/K values. Otherwise, populations could not maintain themselves over evolutionary timescales.

Catastrophic mortalities, on the other hand, which are quite frequent in lagoon-estuarine systems, are episodic events, usually connected with sudden changes of water characteristics such as dissolved O_2 , H_2S content, and temperature, which can induce large-scale death among resident stocks and sometimes their total annihilation.

Many natural or anthropogenic factors may cause catastrophic mortalities in coastal lagoons, including the following:

1. Eutrophication, leading to nighttime depletion of oxygen and/or benthic production of H_2S , which can be released into the water column by storms.
2. Cold or hot spells, particularly effective in shallow lagoons (Gunter, 1952, 1957, 1967).
3. Terrigenous pollution, for example, from agricultural pesticides.

Catastrophic mortalities are difficult to incorporate into standard population dynamics models and have indeed not generally been considered explicitly in fisheries management. Their probability of occurrence and their prevention are, however, important aspects of management schemes involving *bordigues* and aquaculture in coastal lagoons.

18.3.4 Fishing Mortality and Related Statistics

Fishing mortality defined above as $F = Z - M$ can also be defined as follows:

$$F = \frac{C}{B}, \quad (18.7)$$

where C is the fisheries catch (in weight) during a given period and B is the mean biomass during that same period. Equation 18.6 provides the rationale for attempts to estimate the biomass of fishes in coastal lagoons using, for example, tagging (Lam and Lasserre, 1984). Given Equation 18.7, we also have

$$C = q \cdot f \cdot B, \quad (18.8)$$

where f represents the fishing effort and q is the catchability coefficient of the gear used to generate the level of effort f . These definitions imply that C/f (the catch per unit of effort or CPUE) is, given a constant q , proportional to the biomass and hence can be used to monitor the status of a stock whose absolute biomass may be unknown (Fig. 18.8a).

Lam and Lasserre (1984) reviewed the applicability of these and related models, notably yield-per-recruit (Y/R) and cohort analysis, to lagoon fisheries, and the methods, for example, surveys or tagging studies, used to estimate their parameters. Their conclusions were as follows:

1. The assumption of equilibrium implicit in most standard models for analyzing the population dynamics of fish (notably Y/R analysis) render these models questionable when applied to data from lagoon fisheries.
2. The scattered and often small-scale nature of fisheries operation in coastal lagoons generally makes the routine collection of C/f data too costly. Hence, such data are lacking for most lagoons (Kapetsky, 1984) or are largely unreliable (Bailey, 1988).
3. The methods that may be most appropriate for lagoon fisheries, that is, virtual population analysis or cohort analysis (Gulland, 1965; Pope, 1972), which have the advantage of not requiring estimates of fishing effort, do require catch-at-age data, which can be obtained in a cost-effective

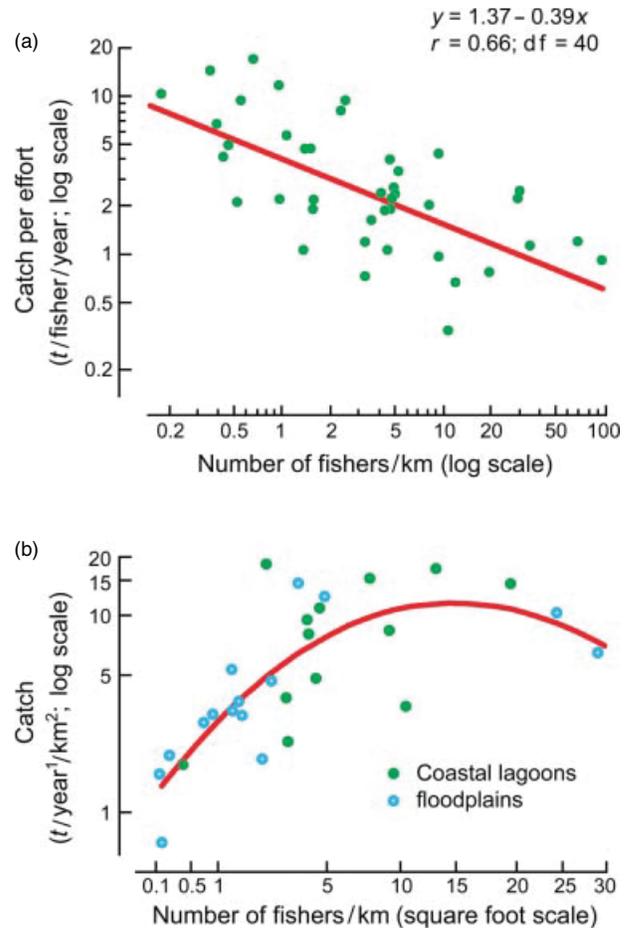


FIGURE 18.8 Examples of the relationship between fishing effort per area, that is, fishing intensity, and dependent variables. (a) Relationship between C/f and fishing intensity in 42 coastal lagoons (Kapetsky, 1984). (b) Relationship between yield, C , and fishing intensity in 13 coastal lagoons and 15 river floodplains, which appear to have similar yield. Source: After Bailey (1988).

manner only for the most important species in major lagoon fisheries.

4. It may be most appropriate to manage lagoon fisheries as a black-box system, using a form of adaptive management in which the catches resulting from initial interventions are monitored and used to refine the next set of interventions.

Bailey (1988), working on various tropical small-scale fisheries data sets, including coastal lagoons, noted that the inclusion of fishing effort added considerably to the precision of empirical (i.e., black-box) models in predicting yields in such systems. He derived, for lagoons ($n = 13$) and floodplains ($n = 15$),

the joint model (Fig. 18.8b):

$$\log_e(\text{yield} + 1) = -0.19 + 1.44f^{0.5} - 0.19f \quad (18.9)$$

for an annual yield expressed in tons per square kilometer, and where f is the fishing effort per area (here, fishers per square kilometer of lagoon or floodplain area). This model has an intercept unequal to zero and, hence, predicts a nonzero yield where $f = 0$. It should not be used with small values of f (Bailey, 1988).

While pleased with the predictive power of his model, given the heterogeneity of the available data set (Kapetsky, 1984), Bailey (1988) also noted that external approaches such as his may have reached a dead-end, not because of their empirical nature, but because of the lack of acceptable data “in terms of number of systems and quantity of variables measured consistently” and that this type of approach may thus “have reached an impasse with respect to prediction of future size of stocks or yield.”

While based on different premises, this conclusion echoes that of Lam and Lasserre (1984). The application of classical methods of fish population dynamics and fishing management to coastal lagoon fisheries appears inappropriate, even if isolated elements of lagoon resource systems can be described by these classical methods.

18.3.5 Recruitment of Fish Stocks in Lagoon-Estuarine Systems

18.3.5.1 The Fishery Approach toward Recruitment

Providing reliable predictions of the recruitment of a fish stock for use in fishery management is something that has largely eluded fishery biologists, despite massive efforts being put in since the very beginning of fishery science as a discipline of its own near the end of the last century (Pauly, 1986a). Classical population dynamics, as formulated in the text of Beverton and Holt (1957) or Ricker (1958), resolved this problem by combining the basic processes presented above into models for predicting yield per recruit as a function of the control variable such as F and age at first capture (t_c). An example of such model is as follows:

$$\frac{Y}{R} = F \cdot e^{Mr_2} W_\infty \left[\frac{1}{Z} - \frac{3e^{-Kr_1}}{Z+K} + \frac{3e^{-2Kr_1}}{Z+2K} + \frac{e^{-3Kr_1}}{Z+3K} \right], \quad (18.10)$$

where $r_1 = t_c - t_0$ and $r_2 = t_c - t_r$, Z and K are as defined above, W_∞ is the weight corresponding to L_∞ , and recruits of age t_r are defined as fully metamorphosed young fish whose growth is described

adequately by an equation also describing the growth of the adults, whose instantaneous rate of natural mortality is similar to that of the adults, and who occur in or swim into some fishing ground (Pauly, 1984, 1994).

Following Ricker (1954), numerous fishery biologists have attempted to develop models linking the parent stock and the subsequent recruitment. The various curves resulting from these efforts have not been reviewed here (but see Sharp and Csirke, 1983).

18.3.5.2 The Ecosystem Approach toward Recruitment

Ecological implications of recruitment in functional structures of estuarine and coastal fish communities, and implications to fisheries in coastal lagoons and estuaries are key concerns toward ecosystem-based management of coastal fisheries in the Gulf of Mexico and elsewhere.

Three groups of fishes occur in coastal lagoons: (i) sedentary species: those which spend their entire life cycles within coastal lagoons; (ii) seasonal migrants: those which enter the lagoon during a more or less well-defined season from either the marine or the fresh water side and leave it during another season (Fig. 18.9); and (iii) occasional visitors: those which enter and leave a lagoon without a clear pattern within and among years. Group (i) is usually very limited, especially when species with planktonic stages are considered. Most lagoon fishes spawn outside lagoons. The above-mentioned black chin tilapia, a male mouth brooder, is an exception and its special ability to withstand large variations of temperature and salinity has enabled it to dominate the fauna of small closed lagoons completely along the West African coast (Pauly, 1976).

Generally, however, it is the members of group (ii) that dominate the fauna of coastal lagoons, for example, by contributing near 100% of the ichthyofauna of many Mediterranean lagoons (Quignard, 1984). Group (iii) is represented in the Mediterranean by species such as the garfish *Belone belone* or the Atlantic mackerel *Scomber scombrus* (J.P. Quignard, personal communication), by species such as snapper *Lutjanus* spp. or crevalle jack *Caranx hippo* in West African lagoons (Pauly, 1975), or species such as gafftopsail sea catfish *Bagre marinus*, Atlantic anchoveta *Cetengraulis edentulus*, Western Atlantic sea bream *Archosargus rhomboidalis* or tomtate grunt *Haemulon aurolineatum* in lagoons of the southern Gulf of Mexico (Fig. 18.9).

To these three basic groups, two other groups may be added (iv) marine, estuarine-related species, which spend their entire life cycle in the upper shelf under

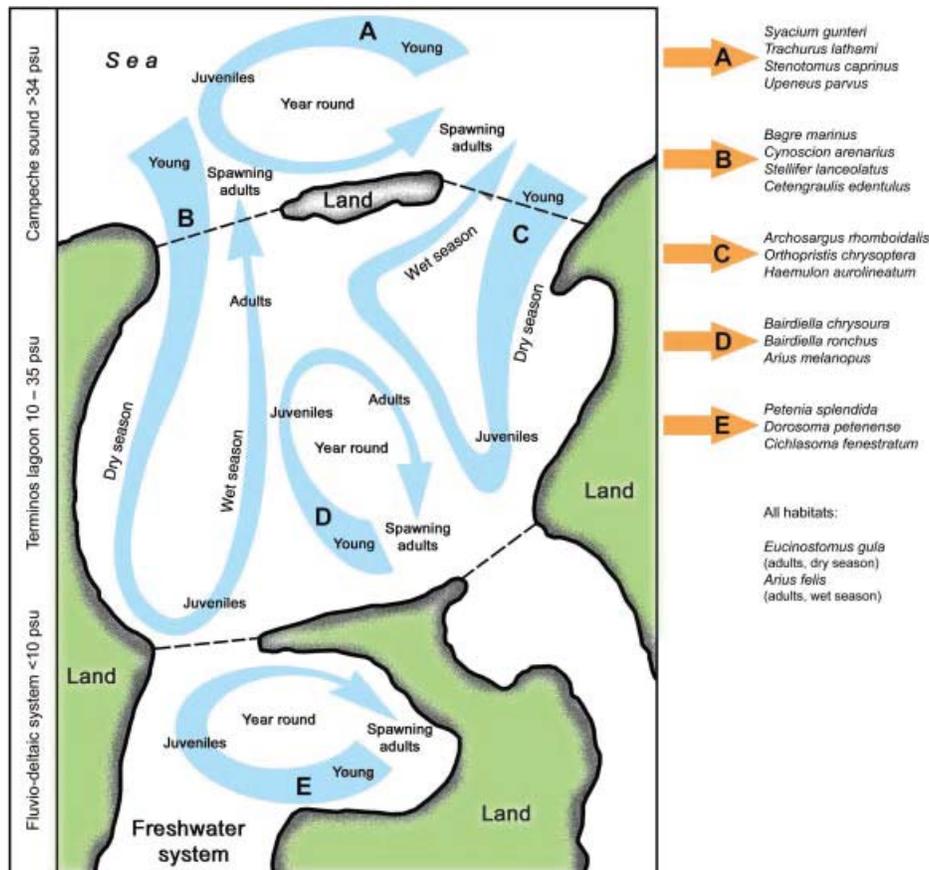


FIGURE 18.9 Examples of fishes with characteristic migration pattern within, outside of, and into and out of Terminos Lagoon, Southern Gulf of Mexico. *Source:* Redrawn from Yañez-Arancibia et al. (1988); Yañez-Arancibia and Sanchez-Gil (1988); Sanchez-Gil and Yañez-Arancibia (1997).

the influence of an estuarine plume, for example, fringed flounder *Etropus crossotus*, shoal flounder *Syacium gunteri*, and rough scad *Trachurus lathami* (Sanchez-Gil and Yañez-Arancibia, 1997; Sanchez-Gil et al., 2008); and (v) fresh water, estuarine-related species, which spend their entire life cycle in the fluvial-deltaic zone in the upper reaches of estuarine systems, for example, *Petenia* spp. and *Cichlasoma* spp (Yañez-Arancibia et al., 1993, 1994).

Different opinions exist with regard to the mechanisms of recruitment into lagoons of group (ii) fishes. Quignard (1984) and Chauvet (1988), representing the “Eastern Atlantic school,” stress that the recruitment of group (ii) fishes into coastal lagoons is not necessarily due to migrations (Harden-Jones, 1968). Rather, fishes of this group are either flushed into lagoons while still in the planktonic stage, or swim as early juveniles into lagoons against the outgoing current, either due to their effort to stay close inshore or due to coastal wanderings (*errances* in French texts) in search of food.

The other school, which may be called “Western Atlantic,” stresses on the important role that lagoons play in the life cycles of many coastal fishes. Here, lagoons are viewed as major elements of small-scale migrations, which, by involving lagoon/estuarine habitats, allow a high standing stock to be maintained (Fig. 18.10).

In either case, the relative level of recruitment into coastal lagoons will be determined between lagoons by the ease with which fish can penetrate into these and between years by the overall number of potential recruits along the coast. The former point implies, as also emphasized by Chauvet (1988), that recruitment to coastal lagoons can be artificially increased by keeping the mouth of lagoons open during periods when juveniles of preferred species occur along the coast, or by deepening the sill of lagoons with very shallow mouths.

Coping with between-year variability of recruitment to lagoons is more difficult, and one of the

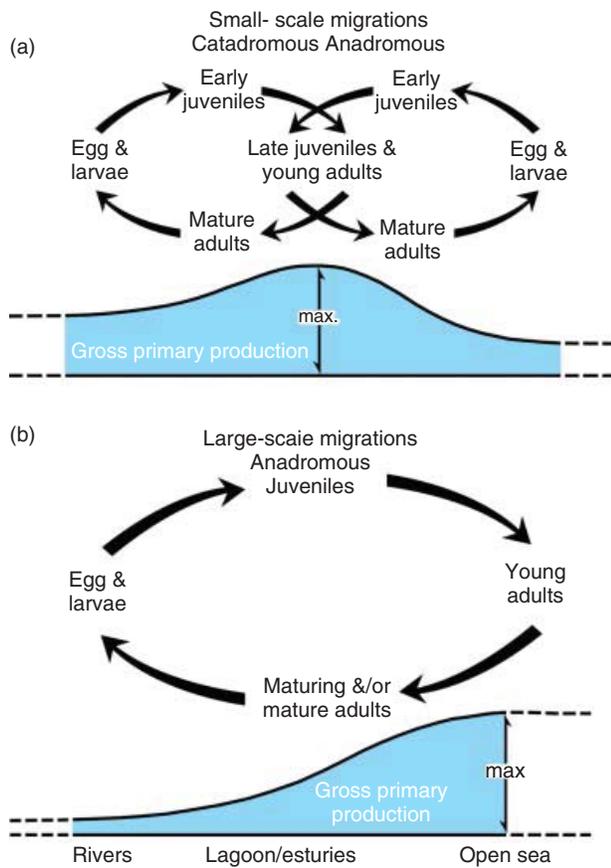


FIGURE 18.10 Schematic representation of (a) small-scale migrations involving shelf, lagoon/estuary, and fresh water habitats and allowing certain fish stocks to maintain higher abundance than if they utilized only one type of habitat, and (b) large-scale migration. Note the marked difference of the scheme in (a) to the cold/temperate situation, characterized by large-scale anadromous migration. *Source:* After Yañez-Arancibia and Sanchez-Gil (1988).

few practical approaches for dealing with this problem is management through bordigues, the gear and management tool to which the Food and Agriculture Organization of the United Nations (FAO) has devoted its first manual on lagoon management (Chauvet, 1984).

18.4 MANAGEMENT OF LAGOON-ESTUARINE FISHERIES

18.4.1 Conventional Fisheries Management

As alluded to in the introduction to this chapter, fisheries, at least in modern times, tend to quickly

become overfished unless they are well managed, the result of an overwhelming harvesting capability applied to finite resources that belong to no one before they are caught (common property) and which everyone has the right to exploit (open access). Fisheries management, therefore, generally involves putting restrictions on (i) access to the resources, (ii) number of gears, (iii) type of gear deployed, (iv) timing of effort deployment, or (v) some combination of these (Pauly et al., 2002). The models used to derive the numbers needed for such management are commonly analytical models (Beverton and Holt, 1957), or surplus-production models (Schaefer, 1957), with either of these possibly containing some economic component, that is, consideration of fishing costs and gross returns.

One commonly used analytic model, structured around the four factors discussed above, is the yield-per-recruit model (Eq. 18.9), which can be used to assess the optimum size/age at first capture. The optimum mesh size in a given fishery with known fishing mortality identifies the optimum fishing mortality, given a certain unique range of size/age at which the fish of a given stock should be caught. Such computations can be made more realistic by adding a size-value relation into the model, which leads to optimum monetary or nonmonetary return per recruit being evaluated (Die et al., 1988).

Surplus-production models, on the other hand, can either be time- or space structured. In the former, a time series of catch data from a given fishery is related to the corresponding time series of effort data such that the optimum level of effort, yielding the largest (hopefully) sustained catch (maximum sustained yield or MSY) is identified (Schaefer, 1957; Ricker, 1975). The other class of surplus-production model is based on the assumption that a number of units compared, such as lakes, lagoons, and coastal stretches, had similar potential production before onset of a fishery and that catch differences between them are due to different levels of effort (Munro, 1979). This leads to models such as Equation 18.8, which allow rough estimation of potential or optimum yields for given levels of effort. This allows the assessment of whether a lagoon is under- or overfished. Unfortunately, long time series of catch and effort data, needed for fitting time-structured surplus models, are generally lacking for lagoon-estuarine systems.

Yield-per-recruit models, on the other hand, when thoughtlessly used to assess fishes or shrimp stocks within lagoons, tend to lead to the same results: wherever they are applied, they suggest that it is better to let the generally small fish and shrimp that occur inside lagoons escape, and be caught later

by some offshore fishery. This reflects the fact that, until recently, fishery research viewed lagoons as one side of an antagonistic relationship, in which often poor, small-scale fishers catch large numbers of undersized fish and shrimp, which if they had escaped from the lagoons, would have contributed yields to the (usually industrial) fisheries outside the lagoons (Garcia and Le Reste, 1981). There exists, however, an approach by which the conflict between lagoon and coastal fisheries can be resolved, and this involves turning coastal lagoons from marginal sites for harvesting of undersized fish into production units making the most of the natural recruitment they receive, just as any well-managed coastal fishery is supposed to do.

18.4.2 Using “Bordigues” As a Tool for Lagoon-Estuarine Fisheries Management

The French word “bordigue” (from the Provençal *bourdigo*) refers to a fishing gear widespread around the Mediterranean and representing the culmination of an evolution spanning over two millennia (Chauvet, 1988; McCann, 1988). It is essentially a trap, and its basic principle is simple: all young fish attempting to get into the lagoon through a bordigue can, but those who try to leave the lagoon cannot (Fig. 18.11). Bordigues, which are usually placed along the channel connecting a lagoon and the sea, thus differ in principle from gears such as traps, fish corrals, and gill nets that are often deployed in great numbers within the lagoon, but without totally blocking the outlet, and which hence let a fraction of the fish leave the lagoon to the sea.

Here, the question might arise how can a gear that retains all the fish attempting to leave a lagoon be useful to management? The point is that the bordigues are constructed so that the fish they retain are not killed, but rather graded according to size, and diverted into holding pens through adjustable panels of different mesh sizes. Only fish that have reached market size are harvested. The others are returned to the lagoon to grow until the next harvest season along with fresh recruits that have just entered the lagoon. Figure 18.12 contrasts the operation of a bordigue over a period of several years after being set up with the traditional exploitation scheme of a lagoon, as repeated every year.

As might be seen in Figure 18.12a, the harvest of a conventionally managed lagoon will be based only on the single recruitment event preceding it, there being no fish left in the lagoon from previous recruitment. Thus, catches will vary between years as a function

of recruitment levels, given consistent effort, and the fish caught will be of low sizes.

Bordigues, on the other hand, lead to a harvest level that is a function of the average level of recruitment over several years, besides harvesting fishes that are always of optimum size. Thus, bordigues allow the kind of resource exploitation that is optimal in terms of yield-per-recruit analysis, where fish that have not grown to sufficient size escape through the mesh of the gear, grow some more, and then may be caught, or again escape through the mesh of gear, depending on whether they have grown to some size deemed as optimal in terms of weight or price.

As in a well-managed fishery, the optimum size at harvest in a bordigue will thus depend on the ratio between growth and natural mortality. Therefore, it would make little sense for the small fish retained by a bordigue to be returned to a lagoon in which natural mortalities are such that they offset any gain in individual weight of the released fish. Thus, managing a lagoon by means of a bordigue also implies removing as many sources of natural mortality as possible, for example, by filling in deep pools in which large predators can accumulate, as well as reducing the likelihood of catastrophic mortalities by preventing inflows of pollutants. *Acadja*-type structures within lagoons, which enhance the survival and the growth of young fish, may be considered in this context.

The technical aspects of the construction of bordigues have been discussed in Chauvet (1988). It is worth mentioning that their *construction* requires sophisticated engineering and large investments. However, daunting the technical and financial aspects of the construction of bordigues are, it is social factors that usually prevent their widespread implementation. Notably, the use of bordigues as a fishing gear and management tool requires from those with access to or fishing rights in a lagoon an extremely high degree of cooperation and well-honed management skills. Bordigues must be staffed permanently to prevent them from becoming clogged with drifting sea grass and to change the retaining panels of different mesh sizes depending on which species are in the process of swimming to different retention chambers. Also, fishing within the lagoon must be restrained, as it could otherwise offset the gains obtained by returning undersized fish retained by the *bordigue* to the lagoon. Fishing in lagoons equipped with bordigues (Table 18.2) is not suitable for individualistic fishers. Bourquard and Quignard (1984) document the case of a bordigue that failed because of their noncooperation.

We have not presented the bordigue as a management tool for lagoon fisheries because we

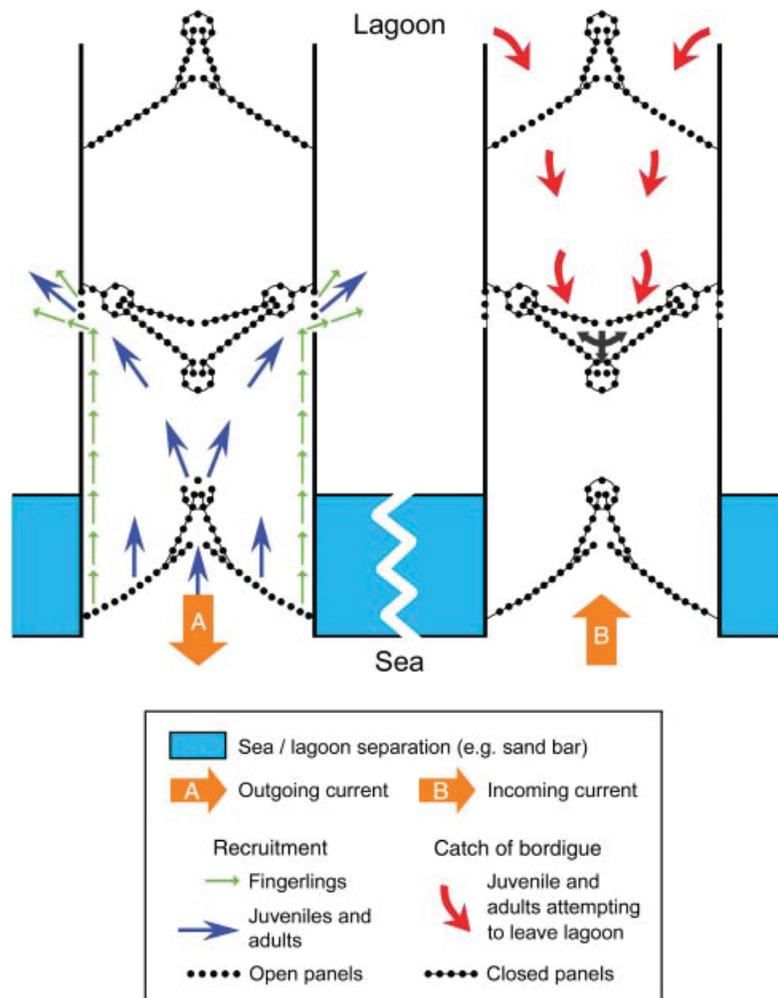


FIGURE 18.11 Schematic representation of a (Tunisian) bordigue, showing (a) how recruits are let through to the lagoon when the water flows out of the lagoon, and (b) how fish attempting to leave when the water flows into the lagoon are caught to be either marketed or returned to the lagoon for another growth cycle. *Source:* After Chauvet (1988).

believe that this method of harvesting and managing is likely to become widely adopted outside its area of origin. We realize that, although it is technically applicable in principle in virtually any place in the world, the potential for its adoption outside the Western Mediterranean is rather low, mainly because of the high degree of cooperation and management skill that is required.

Rather, we have presented the bordigue as an important element in the continuum of lagoon fisheries, which range from totally unmanaged to partially and well-managed fisheries and beyond, to extensive, semi-intensive, and intensive aquaculture operations. Indeed, the bordigue is one of the most sophisticated capture fisheries regime one can imagine. It requires a level of cooperation and of management skill probably higher than that involved in

extensive aquaculture, whose yield the bordigue can approximate (Table 18.2). Other worthwhile management regimes for lagoon-estuarine fisheries do exist and have been discussed by Kapetsky and Lasserre (1984) and Mann (2000); see also the fisheries chapter in Day et al. (1989).

18.5 DISCUSSION

18.5.1 Uncertainty to Understand Fish Resource Dynamics

Fish production in lagoon-estuarine systems is generally high (Day et al., 1989; Yañez-Arancibia et al., 1994, 1993, 1988; Mann, 2000), and this generally leads to high fishery catches. From our experience, one reason

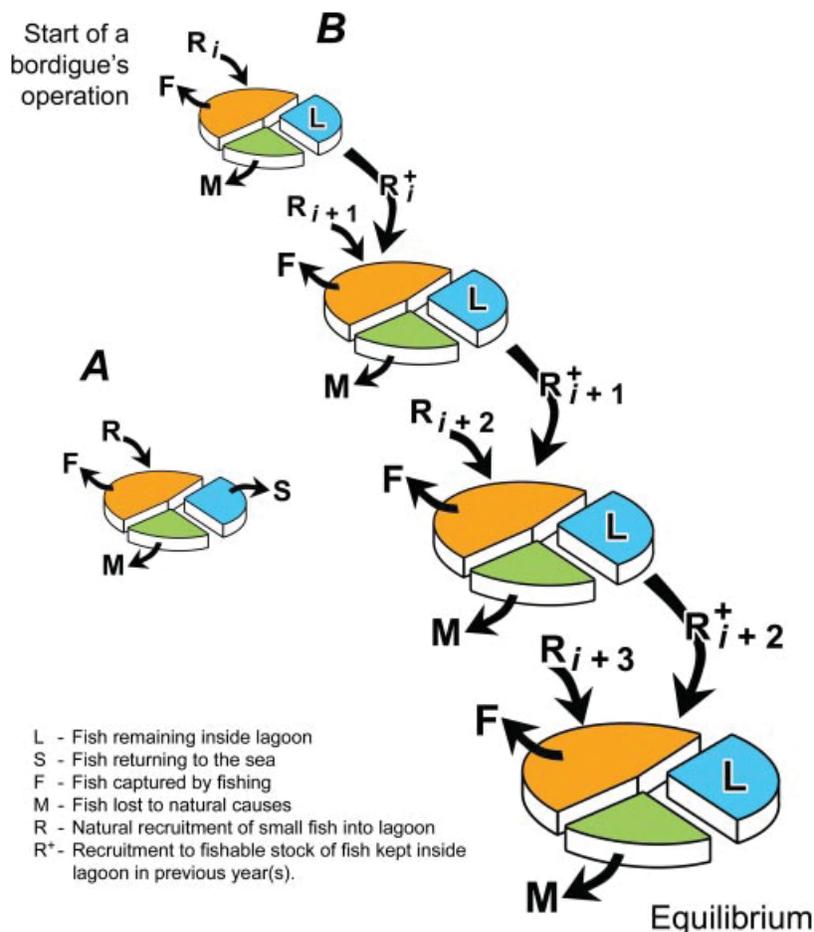


FIGURE 18.12 Schematic representation of differences between (a) a lagoon exploited by gears deployed within the lagoon and (b) a lagoon exploited/managed via a bordigue. Note the buildup of fish biomass within the lagoon in case (b), due to retention of undersized fishes, which would have left the lagoon in case (a). *Source:* After Chauvet (1988).

for this high production is that many of the fish species of importance in lagoon-estuarine environment are either (i) *r*-selected *sensu* (Pianka, 1978), that is, relatively small, fast growing, high production/biomass (P/B) ratio or (ii) the juveniles of *K*-selected species, that is, the fast growing, high production stage fishes whose large adult form, however, typically occurs outside the lagoon. The high P/B ratios of the constituent species are not the only explanation for the generally high production of lagoon-estuarine fish communities. The high biomasses themselves, that is, the high carrying capacities of these ecosystems in terms of seasonal food availability to fishes, also play a crucial role.

In areas where lagoon systems have maintained themselves over long periods (i.e., the Gulf of Mexico), evolutionary mechanisms have emerged that have stabilized and refined such seasonal programming, making the fish population in question gradually

more dependent on the estuarine system for the maintenance of high biomass. In other areas where the lagoon system does not persist or is not regularly open to juvenile migration (i.e., along the coast of Northwestern Africa, the Pacific coast of Mexico, and the eastern coast of East Australia), the use of lagoons seems to be more a matter of random movements along the coast and of inshore movements, that is, *errances*. This implies (i) a lower conversion of primary and secondary production into fish flesh and hence (ii) lower biomasses of coastal fishes. However, the practical difficulties in separating random along-shore/inshore movements, that is, *errances*, from evolutionary fine-tuned, *aimed* movements toward and within estuaries, and the difficulties involved in precise field estimation of biomass and conversion efficiencies, make rigorous testing of the hypothesis difficult. Indeed, this may be the main reason for the continuing debate on the degree of dependence

TABLE 18.2 Comparative fishery yields of lagoons with and without systems to improve survival and/or growth of recruits (Chauvet, 1988)

Location System	Annual Mean ² Yield, t/km ²	Standard ² Error, t/km ²	n
Africa	—	—	—
Fishing only	0.10	0.52	10
Acadja ^a and fishing	7.75	2.57	3
Mediterranean	—	—	—
Without bordigues ^b	0.83	—	52
Nonpermanent bordigues	0.82	0.64	10
Permanent bordigues	1.85	0.18	2
Permanent bordigues plus artificial stocking ^c	3.77	2.96	4

^aSee Kapetsky (1981) for a description of *acadja*-based fisheries.

^bComputed by subtracting bordigues yields from grand mean for Mediterranean.

^cThis is a form of aquaculture (Ardizzone et al., 1988).

of tropical coastal fishes on coastal lagoons and estuaries.

18.5.2 An Unfinished Agenda

Longhurst and Pauly (1987) have pointed out that relatively few finfish and shellfish species are fully adapted to a life cycle within a lagoon-estuarine system *sensu stricto*. Nevertheless, it is clear that in the tropical and subtropical regions of the Gulf of Mexico, and especially in monsoon-type areas where *estuarinization* of the continental shelf occurs (i.e., in front of Tampa Bay, Apalachicola Bay, and along the coasts of Mississippi, Louisiana, Texas, Veracruz, Tabasco, and Campeche), the difference between lagoon-estuarine areas and the inner shelf is smaller than in areas where the monsoon-type winds are unimportant. There are also sufficient descriptions of specialized estuarine fish faunas for it to be clear that they exist in the Gulf of Mexico, where the size of the estuaries and their tidal regime permit a relatively long flushing period (Gunter, 1957, 1967). If the Guntherian hypothesis of estuarine dependence of continental shelf, fish stocks cannot be applied for the tropical regions as a whole (Longhurst and Pauly, 1987), at least it can be applied in a straightforward manner to the tropical and subtropical regions of the Gulf of Mexico, especially the soft-bottom communities of the inner shelf associated with extensive deltaic systems, significant river discharge, and broad areas of coastal vegetation

(Deegan et al., 1986; Pauly, 1986b, 1998; Pauly and Yáñez-Arancibia, 1994; Baltz et al., 1993, 1998; Chesney et al., 2000, Chesney and Baltz, 2001; Sánchez-Gil and Yáñez-Arancibia, 1997; Sánchez-Gil et al., 2008; Yáñez-Arancibia et al., 1993, 1988, 1998, 2007).

A significant fraction of the harvested secondary production in the western Gulf's "fertile crescent" (Mississippi River mouth to the northern tip of the Yucatan Peninsula, and including some areas the Atlantic coast of Central America) is derived from estuarine ecosystems, including areas on the shallow shelf influenced by estuarine plumes (Darnell, 1990; Chesney and Baltz, 2001; Yáñez-Arancibia, 2005; Sanchez-Gil and Yáñez-Arancibia, 1997; Sanchez-Gil et al., 2008). Characteristics of these estuaries are high riverine discharge rates, large fresh water surpluses, and low water residence times. Much of the production and subsequent trophic transfer may therefore occur outside the physical boundaries of the estuaries, that is, in association with plumes of fresh water over the inner continental shelves. These contrasting sources—estuary and shelf—of trophic delivery to the fishery forage base, and ultimately to larger consumers, is one cause of uncertainty on how we view the functions of estuaries and the shelf ecosystem they influence.

Thus, high fisheries production may be attributable in part to the lagoon- and estuary-like conditions prevailing in large parts of the inner continental shelf during high river discharge periods, as relatively a few fish species are wholly adapted to life cycles within lagoon-estuarine systems. Moreover, in the subtropical and tropical parts of the Gulf, and especially in areas where high river discharges lead to the shelf exhibiting estuary-like conditions, the distinction between estuaries and the shallow shelf is clearly smaller than in other areas (Longhurst and Pauly, 1987; Pauly and Yáñez-Arancibia, 1994; Yáñez-Arancibia et al., 1994; Yáñez-Arancibia, 2005).

As a consequence, if the "recruits" (= young fish) utilize estuaries and coastal lagoons, the population in question will be "estuarine dependent." If the recruits to that population regularly utilize the estuarine plume on the inner continental shelf, then they will be "estuarine-related," or simply opportunistic. For estuarine-dependent species, seasonal and inter-annual variation in environmental conditions (e.g., temperature and salinity) may serve as ecological filters that define the quantity of suitable habitat for early life history stages. Utilization of coastal habitat types, particularly with regard to estuarine dependence, the occurrence of a life history stage in more than one habitat type is insufficient to refute the hypothesis of nursery function of a given habitat

type. A species may be estuarine dependent at one end of its range and less so at the other end. It is the controlling variables that are important, not the biologist's definition and characterization of a habitat type.

Nevertheless, Yáñez-Arancibia (2005); Cowan et al. (2008); Baltz and Yáñez-Arancibia (2010) preferred to take a fish's eye view of the habitat and used the distribution and abundance of a species or life history stage, rather than environmental gradients, to define its habitat. Using this approach, a species may be characterized as estuarine dependent if one of its life history stages requires some combination of environmental conditions typically found in estuaries. Environmental conditions that control recruitment success for a species may vary across its range, such that a species may be dependent on estuaries at locations throughout most of its range, but rely heavily on sea-grasses-covered coastal sand flats at another location. The identification of nursery habitat types should require at least a comparison of the densities of early life history stages in other nearby habitat types, but a better characterization would derive from identifying where enhanced survival, growth, and recruitment occur.

18.5.3 Habitat Protection As a Management Tool

A number of investigations have demonstrated the existence of complex, seasonally changing relationships between fisheries yields and high nutrient loads, fresh water inputs, shallow depths, large areas of tidal mixing, coastal vegetated area, surface area of lagoon-estuarine systems, and the resulting high productivities that are typical of estuaries and estuarine plume ecosystems (Deegan et al., 1986; Nixon, 1988; Iversen, 1990; Sanchez-Gil and Yáñez-Arancibia, 1997; Yáñez-Arancibia et al., 2007; see figures in Day et al., 1989). As a result of these relationships, and despite the small aggregate spatial extent of estuaries (< 1% of the global marine area), a fraction exceeding 50% of US and Mexico fishery yields have historically been derived from estuarine or estuary-dependent species (Gunter, 1967; McHugh, 1967; Houde and Rutherford, 1993; Vidal-Hernandez and Pauly, 2004).

Thus, management decisions must account for this seasonal pulsing habitat, and the protection of its different components, including the aquatic vegetation, in the context of comprehensive environmental planning. Coastal fisheries resources are an expression of ecosystem functioning and to assure the persistence of such resources, the protection, and conservation of essential habitats is the key.

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