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Stock–Recruitment Relationships and the Precautionary Approach to Management of Tropical Shrimp Fisheries

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Abstract. This paper examines the possibilities and implications of using precautionary management approaches to deal with the uncertainty regarding the stock–recruitment relationships in tropical shrimp fisheries. After a brief review of the stock–recruitment problem and related reference points in these fisheries, and in the precautionary approach in general, it proposes an empirical approach to the stock–recruitment relationship as a basis for the determination of safe and risky fishing mortality levels. It illustrates a management strategy based on the seasonal escapement of spawning biomass. Finally, it offers a discussion on the robustness of the empirical approach and on its validation using additional information.

Introduction

In a review of the evolution of world fisheries and fisheries management and of the role of FAO since its creation in 1945, Garcia (1992) highlighted the challenges facing fisheries at the onset of the 21st century. Among other issues, his paper stressed the need to examine the potential application to fisheries of the Precautionary Principle, which has become a central tenet of international and national environmental law and has been adopted by UNCED (Rio de Janeiro, June 1992) as a fundamental requirement for sustainable development. Since then, the Principle has gained attention in international fishery fora (Garcia 1994*b*) and it is likely that the concept will be progressively introduced in the national fishery contexts.

Acting with precaution implies acting in advance, taking into account current uncertainty and the potential consequences of possibly being wrong. Precautionary fisheries management will aim at reducing and eliminating negative impacts of the fishery (and other competing activities) on the resource and the fishing community itself, to ensure sustainability of the fishery. Recruitment failure is one of the negative impacts to be addressed in a precautionary fishery management context.

Principle 15 of the UNCED RIO Declaration states that: 'In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall be not used as a reason for postponing cost-effective measures to prevent environmental degradation.'

In general, the precautionary approach requires enterprises, states and organizations to take pre-emptive action in cases of risk of irreversible or severe damage to the resources and the environment, even when the cause–effect relationships involved have not been fully established. It specifically requires that, in case of doubt as to the impact of fishing, preventive or remedial action must be taken, giving the 'benefit of doubt' to the resource, with due consideration to the social and economic implications.

The UNCED requirement for caution in particularly risky conditions, which may require exceptional and drastic corrective measures, is being progressively replaced, through the ongoing process of the UN Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks (New York, March 1992), by a requirement to recognize the degree of uncertainty[1] that affects fisheries in general and to adopt precaution as a general characteristic of fishery management and development. This would help to avoid the necessity of resorting to exceptional but drastic rehabilitation measures.

A precautionary approach to fisheries management would explicitly recognize the finite nature of fisheries resources and make full use of the best scientific evidence available. It would adopt a broad range of reference points, pre-agreed decision-making rules and criteria and define action-triggering thresholds at which pre-agreed measures would be taken. It would also agree on acceptable levels of impact and risk, improve participation of non-fishery users and timeliness in the decision-making process. Precautionary management would, in addition, promote the use of responsible fishery technologies, adopting prior consent or consultation procedures before their introduction. It would finally improve monitoring, control and surveillance, adopt experimental approaches to management, institutionalize

[1]i.e. the probability of occurrence of unexpected outcomes.

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transparency and accountability and refrain from using subsidies (Garcia *1994a*, *1994b*)[2].

This paper examines the possibility and implications of using precautionary management approaches to deal with the uncertainty regarding the stock–recruitment relationships in tropical shrimp fisheries. A brief review of the stock–recruitment problem and related reference points in these fisheries is given. An empirical (non-parametric) approach to the stock–recruitment relationship is proposed which aims at reducing the risk of recruitment failure, based on an empirical determination of 'safe' fishing mortality and spawning biomass levels and on ensuring a sufficient seasonal level of spawner escapement. In conclusion, the reliability of the empirical method is discussed together with suggestions on how to assess the soundness of the conclusions it leads to, using additional information.

The Stock–Recruitment Problem in Shrimp Fisheries

Recruitment Reference Points

Fishery resources can withstand a certain level of fishing mortality while still conserving most of their resilience or capacity to return to their pristine state once the fishery-induced stress is removed[3]. A great part of this resilience is related to the capacity of the stock to reproduce itself even when the spawning stock has been reduced by fishing. The underlying biological mechanism is usually summarized by the stock–recruitment relationship (SRR). To ensure that everything possible is done to ensure stock persistence, management systems must use recruitment-related reference points expressed in terms of spawning biomass, recruitment, fishing effort and other measurable and controllable fishery variables. Recognizing the uncertainty in the exact value and position of any fishery management reference point, it has been proposed to differentiate between Target Reference Points (TRPs) to which fisheries development could safely aim, and Limit Reference Points (LRPs) or thresholds that precautionary fishery management should never exceed or perhaps even approach (FAO 1993; Garcia 1994*a*). In the traditional SRR models (Fig. 1), these reference points could refer to[4]:

R_{max}, the maximum recruitment and its corresponding S_{max} (Point A in Fig. 1). In the case of a dome-shaped SRR with little variance, R_{max} (and the corresponding stock level) would be fairly precisely determined and, assuming that current levels of S and R can be confidently estimated, it could be used as a TRP at which management could attempt to maintain the fishery on average. For stocks showing a SRR without a clear maximum, or with large variance, or when the current levels of S and/or R cannot be determined with sufficient precision, such a management strategy could be risky. However, R_{max} could probably be used as a LRP, corresponding to a level of stock (and effort) to be avoided.

R_{lim}, the upper limit in a 'flat' SRR (highly asymptotic or 'ramp' functions) and its corresponding stock size (S_{lim}) below which the otherwise-constant recruitment starts to decrease (quasi) proportionally to stock size (Point B in Fig. 1). For dome-shaped curves, R_{lim} will be very close to R_{max} and, in many cases, difficult to distinguish from it. The concept could be used for all instances in which a clear maximum recruitment is not discernable. When R falls below R_{lim}, the fishery productivity and resilience decreases, and this recruitment level (and corresponding stock size and effort levels) could probably be considered a LRP below which spawning biomass should not be allowed to fall. It could be used also as a 'threshold' level at which, depending on the stock behaviour, variability and related level of risk, pre-agreed courses of action could be triggered to ensure that the situation is corrected as soon as possible.

$R_{0.1}$, the point where the marginal recruitment[5] is 10% of the marginal recruitment at the origin of the SRR curve, and its corresponding stock size $S_{0.1}$ (Point C in Fig. 1). This reference point is proposed by analogy with the well known concept of 'marginal yield' ($Y_{0.1}$ and corresponding mortality $F_{0.1}$) developed by Gulland and Boerema (1973).

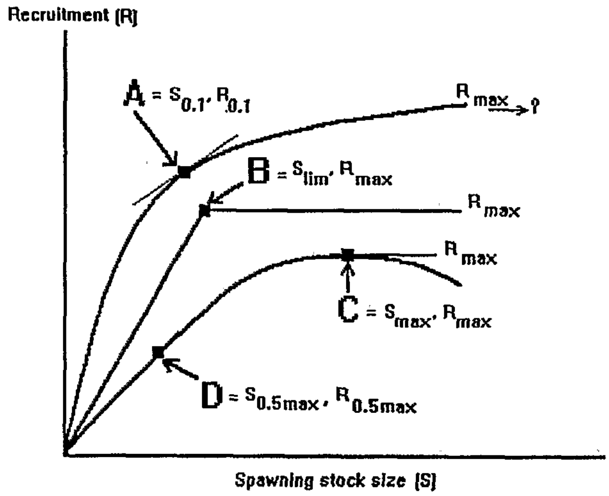

Fig. 1. Possible stock–recruitment management reference points for various shapes of the SRR.

[2]For more details about the precautionary approach to fisheries, see also the guidelines developed by the Technical Consultation on the Precautionary Approach to Fisheries organized by the Government of Sweden in cooperation with FAO in Lysekil, Sweden, 6-13 June 1995 (FAO, 1995).

[3]This, in environmental management terms, means that fishery resources have an 'assimilative capacity' in relation to fishing mortality.

[4]Each of the recruitment reference points has an equivalent reference point in terms of spawning biomass and effort or fishing mortality.

[5]The marginal recruitment is the difference in annual recruitment (of the main generation, when relevant) observed when spawning biomass increases by one unit.

In a strongly dome-shaped SRR, the corresponding level of stock biomass and fishing effort would be very close to those corresponding to R_{max}. In the case of a relatively 'flat' SRR, it would be very close to the level of effort corresponding to R_{lim}.

$\boldsymbol{R_{0.5max}}$ (and its corresponding $S_{0.5max}$) the point where recruitment is reduced to 50% of R_{max} (Myers *et al.* 1994), irrespective of whether the SRR is dome-shaped or relatively flat. Managing fisheries at that level would appear to be less precautionary than using R_{max} or $R_{0.1}$ because the assumption is that sufficient resilience persists, even at drastically reduced recruitment levels.

$\boldsymbol{R_{0.2Bv0}}$, the recruitment corresponding to $S_{0.2Bv0}$ where the level of the spawning stock per recruit is 20% of the value for the virgin stock (Myers *et al.* 1994). This value is often considered as a critical threshold below which sustainability of the stock is at too high a risk and at which (or close to which) corrective action should be taken.

One main impediment to the use of such recruitment-related reference points is that their determination, and the determination of the corresponding levels of spawning biomass and fishing mortality, requires a level of contrast in the data and statistical power in the analysis that are generally not available. Confronted with this problem, scientists have followed two main avenues. On the one hand, they have tried to increase the amount of variance explained by the SRR by including environmental variables (Garcia 1983; Penn and Caputi 1985; Gracia 1991). Based on a limited time series of data points, these multivariate SRRs have still to stand the test of time and, in the absence of a capacity to predict the causal climatic variable (rainfall, river outflow, cyclones or El Niño events), are of limited practical use for pre-emptive and real-time management. On the other hand, scientists have proposed to use a more empirical, pragmatic and non-parametric approach to the problem, arguing that 'it is not necessary to be able to fit a compensatory spawner–recruit model in order to detect a level of stock below which the recruitment might decrease precipitously' (Sissenwine and Shepherd 1987). A set of empirical reference points following that philosophy is described below.

Review of Evidence on Penaeid Shrimp SSRs

The relative roles of density-dependence and environmental control in shrimp recruitment have been the subject of increased attention during the past two decades. Garcia (1976) did not find a SRR in a penaeid shrimp stock of West Africa, but drew attention to the impact that combined artisanal and industrial fishing had on the relative fecundity-per-recruit which appeared to be reduced to about 30% of the virgin stock level. At the end of the 1970s, Garcia and Le Reste (1981) had found no documented evidence of the existence of any clear SRR in shrimps. At the beginning of the 1980s, Garcia (1983) examined all recent literature in support of the existence of stock–recruitment relationships in shrimp and prawns. Identifying artifacts and sources of misunderstanding, he concluded that there was still no convincing evidence of their existence and shape. He also drew attention to the dangers of applying, without caution, to tropical short-lived animals a concept developed for long-lived animals in colder waters. In particular, he showed how seasonal patterns and inter-annual trends in environmental conditions, as well as changes in the exploitation patterns of pre-recruits, were likely to produce spurious SRRs. He, therefore, proposed to make more systematic use of multivariate SRRs, combining stock, recruitment and environment information to produce an SRR surface response or 'family' of SRRs corresponding to the range of climatic conditions (Fig. 2). In a conventional SRR, the tangent to the origin of the SRR (or 'limit replacement line') is the Recruitment–Stock Relationship (RSR) for the level of fishing mortality at and beyond which stock replacement is statistically no more possible and there is a high risk of stock collapse. Garcia stressed that, in a multivariate SRR (linking stock, recruitment and environment), the limit replacement line should be conceptually replaced by a 'limit replacement area' delimited by the tangents at the origin to the lower and higher envelopes of the SRR response area (see Fig. 2). The paper also drew attention to the large amount of biological information available on factors affecting egg and larval survival in each life cycle stage that were being neglected when a correlation approach to the SRR was used. A similar comment has been made more recently by Ultang (1993) in relation to S–R studies and risk analysis.

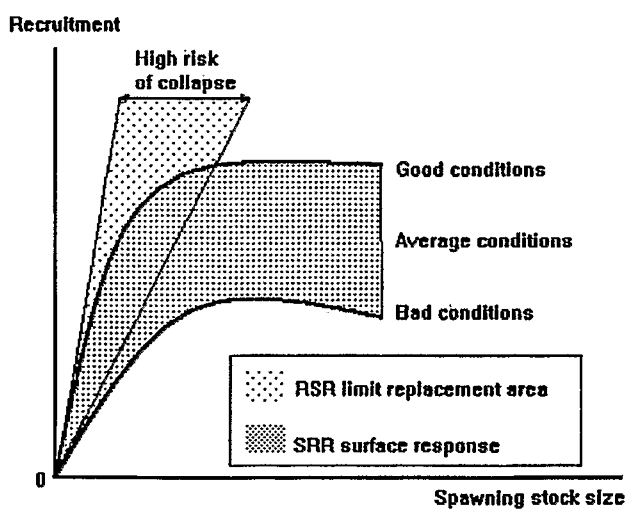

Fig. 2. Stock-recruitment model when natural variability is taken into account. Modified from Garcia (1983).The area of high risk is limited by the tangents to the two curves at the origin.

Garcia (1983) stressed that, despite the difficulty encountered in demonstrating SRRs, there was potential for recruitment overfishing in tropical shrimp and prawn fisheries due to the fact that these resources were recruited into the fisheries well before reaching their maximum fecundity. This warning was repeated later (Garcia 1985), emphasizing the fact that 'the effect of fishing on spawning capacity per recruit of the main annual generation and on the seasonal fecundity cycle was very drastic when fishing mortality approaches or passes the level of natural mortality, and it is obvious that beyond a critical level of mortality some serious and detrimental effect might happen'.

In the following years, the concept of a multivariate SRR was used by Penn and Caputi (1985), who produced some convincing evidence of the existence of a SRR (and of recruitment overfishing) in the *Penaeus esculentus* fishery in Exmouth Gulf (Western Australia), in the specific circumstances of a small and semi-enclosed fishery in an arid area affected by infrequent cyclonic rainfall events. A similar conclusion seems to have been reached for the same species in Shark Bay (Western Australia) where the conditions are largely similar to those encountered in Exmouth Gulf (Penn *et al.* 1989). In Mozambique, Silva (1989) has observed a significant decreasing trend in recruitment of the white prawn, *Penaeus indicus*, in the 1980s; this has been interpreted with a family of SRR curves corresponding to good, average and bad environmental conditions related to the Zambezi river outflow or local rainfall conditions. For a stock of white shrimp, *Penaeus setiferus*, in the Gulf of Mexico, Gracia (1991) identified a significant statistical relationship, following a Ricker model, between parental stock size and recruitment when including the river discharge before recruitment and during spawning. More recently, Mendo and Tam (1993) demonstrated that the relationship between catch and effort in the Peruvian penaeid shrimp fishery on *Penaeus vannamei* was best represented by a multivariate production model including river discharge or temperature, in relation with the El Niño phenomenon. Although these authors did not specifically refer to the stock–recruitment relationship, the impact of climatic factors on recruitment survival in shrimp is sufficiently documented to assume that their analysis illustrates indirectly an environmental effect on the SRR.

In summary, work undertaken on the relationship between stock and recruitment in shrimp populations has indicated the following. The current pattern of fishing on these short-lived and late-maturing animals has the potential effect of drastically reducing the fecundity-per-recruit and destabilizing the life cycle and reproduction strategy of the animals through an alteration of the seasonal spawning pattern and its timing in relation to the seasonal oscillation of favourable climatic conditions. Most attempts to identify density-dependent effects in recruitment in shrimp populations have been inconclusive or misleading, in particular because they neglected the short-lived nature of shrimp populations and the role of inter-annual variations in recruitment and in the apparent shape of the SRR. Finally, approaches to SRR that explicitly consider environmental impacts on SRR lead to the conclusion that the existence of significant density dependence at average- and high-level abundance of shrimp stocks cannot be ruled out.

Review of Management Advice

In the absence of evidence of a clear SRR for most shrimp fisheries, little practical guidance has been given to shrimp fishery managers on how to deal with the issue and the uncertainty surrounding it. Garcia and Le Reste (1981, p.137) recognized that, despite the fact that the possible existence of an SRR had not been demonstrated and that its eventual shape remained unknown, the high intensity of most shrimp fisheries and the fact that shrimps were often recruited before their full maturity called for caution. They recalled that, in such instances, the concept of fecundity-per-recruit would be useful to assess the reduction in spawning potential. Garcia (1983) concluded that: "for want of better information, it therefore seems advisable, both for economic and biological purposes, to manage shrimp fisheries by limiting the effort below some threshold level corresponding to an 'acceptable'[6] level of risk (of recruitment overfishing)" and that 'any management policy based on some sort of fishing effort regulation will lose efficiency in the absence of a clear freshwater and estuaries management policy'. Garcia (1989) referred to two main approaches to recruitment management: *(1)* stock enhancement and habitat conservation to improve estuarine carrying capacity and *(2)* improvement of spawning stock size through seasonal closures and overall effort-reduction policies. The issue of recruitment failure must be addressed whether it is due to overfishing or to natural factors or both, and precautionary management action might be needed when recruitment is affected, regardless of the cause.

In Australia, Bowen and Hancock (1985) were convinced of the existence of an SRR relationship and of 'the need to acknowledge it in research and data collection planning' and anticipated that 'management by controls of fishing effort and catch is not likely to provide a simple solution' but they did not provide any suggestion on how to take into account the risk of recruitment failure and subsequent economic losses in short-term management practice. On the basis of the evidence they had obtained on the existence of an SRR for *Penaeus esculentus*, but faced with the impact of infrequent and unpredictable cyclones, Penn and Caputi

[6]A discussion on 'acceptable' impacts and risk is given in the last section of this paper.

(1985) suggested that 'a practical management strategy for the stock can be based only on the average environmental situation[7] but with contingency plans to decrease efforts when low recruitment events occur'. The measures to rebuild the stock included reduction of fleet size and effort levels, restrictions on fishing of juveniles and a ban on fishing of spawners. A major difficulty was encountered in trying to segregate fishing on different penaeid species in mixed fisheries (Penn *et al.* 1989).

In the USA, Klima (1989) indicated that the management of shrimp fisheries in the Gulf of Mexico was based on the assumption that there was no SRR in shrimps and that recruitment overfishing was impossible. However, he recognized that recruitment overfishing was a distinct possibility in the Gulf and that care should be taken to ensure that it did not occur, offering no guidance, however, on how to do so.

Uncertainty, Risk and Precautionary Management

The impact of fisheries on recruitment should ideally be assessed and forecast with sufficient precision to reduce as far as possible the risk of significant recruitment decline, causing severe and costly damage to the resource and the fishery. A major problem is that the intrinsic nature of shrimp resources, deficiencies in fishery data, limitation of scientific models and the fluctuations of biological and economic variables all limit the capacity to forecast.

Uncertainty is generated by the natural variations of shrimp population parameters and, in particular, the year-to-year variations in the global and seasonal SRRs and in the seasonal recruitment patterns due to environmental effects on survival of recruits. Annual recruitment is sensitive to climatic conditions during critical stages of the life-cycle, environmental degradation (particularly in estuaries), and abundance of predators reduced through intensive fishing. In addition, the overall SRR in tropical shrimp stocks (using annual data on stock and recruitment levels) is, indeed, the result of the combination of a number of seasonal SRRs for the various seasonal cohorts resulting from continuous spawning, each reflecting a different level of spawning and survival to recruitment. Even with fairly well-behaved stocks, with low levels of noise in the SRR, there remains an uncertainty as to the exact value of the current levels of fishing and natural mortality. There are also uncertainties in the socio-economic parameters of the fishery related mainly to the world market, fleet dynamics and reaction of industry to changes in natural resources and to administrative decisions.

All these sources of variability lead to uncertainty in the information upon which the managers and industry leaders base decisions, as well as in the management implementation process. It must, therefore, be accepted that errors might be made and have been made in *(1)* measuring stock size, recruitment and environmental data (measurement error); *(2)* calculating population parameters based on such data (estimation error); *(3)* understanding relationships between effort, stock size, recruitment and environment (process errors); *(4)* representing mathematically these relationships (model error); *(5)* taking decisions based on inaccurate information (decision error); and *(6)* implementing the intended management measures (implementation error). The impact of measurement errors on the SRR has been stressed by Walters and Ludwig (1981). This impact and the effect of introducing environmental factors in the relationship have been specifically investigated for penaeid shrimps by Caputi (1988).

The combination of these categories of error might lead to two types of situation:

(i) Fishing is reduced or constrained in an attempt to reverse a declining trend in recruitment or to reduce as far as possible the risk of recruitment decline when, in fact, fishing at the current level has no impact on the annual recruitment (the potential impact on recruitment variability is not considered here). The cost of the error, e.g. in terms of foregone revenues, is borne by the fishery and, possibly, by the consumer. The protected stock would be conserved at a higher level with no benefit to industry and the unharvested surplus biomass will rapidly disappear through natural mortality.

(ii) Fishing is not constrained within biologically 'safe' levels and the spawning stock is depleted, leading to recruitment failure, possibly aggravated by unfavourable climatic conditions. This situation implies short-term costs for the resource and, possibly, long-term ones if its sustainability is threatened. It also results in decreased catches and revenues for fishermen. The economic losses to industry will depend on the extent and duration of the damage and on the extent to which reduced incomes are compensated by government subsidy and transferred to the tax payers. In tropical shrimp fisheries, fishery-induced recruitment failures should be overcome within a season or two if fishing effort is drastically curbed[8]. In general, this situation carries the greatest probability of economic damage.

Increasing research effort to substantially improve understanding of the stock–recruitment processes and relationship in order to significantly reduce the risk of error and related costs may imply that unrealistic financial and data requirements and management decisions will always

[7]i.e. based on the average SRR curve and corresponding acceptable levels of effort.

[8]The experience in Western Australia, however, indicates that it may not be that easy to curb effort as a response to a recruitment crisis or to manage effort on a depleted species when it is captured together with other more resilient ones (Penn and Caputi 1985; Penn *et al.* 1989).

have to be taken with less than complete and accurate information. A major problem is the identification of the risk involved in such decisions and of the measures required to reduce it.

In the present state of our knowledge, there is therefore always a risk that recruitment is affected at present levels of fishing and that this negative impact may be at least partly masked by errors in the data as well as by environmental fluctuations. As a shrimp stock consists of essentially one year-class, this risk, expressed as the probability that recruitment in year (t+1) is reduced significantly or fails, is more or less strongly related to the biomass that have survived to spawn the preceding year (t) which is itself a function of the cumulative fishing mortality applied to the stock between the time of recruitment and the spawning season. This risk is highest at the lowest spawning biomass and highest effort levels, regardless of the environmental conditions.

In most cases, shrimp resources are exploited in such a way as to lead to potential recruitment problems, possibly masked by inappropriate data and environmental 'noise'. What can be done? The traditional explicit or implicit management strategy has been that, in the absence of any definite evidence that recruitment is affected by fishing, there are no grounds to take measures when their biological outcome is dubious and their immediate costs to the fishing community may not be insignificant, at least in terms of forgone revenues.

The precautionary approach requires that, in the presence of a risk of recruitment overfishing, management authorities make full use of the best scientific evidence available (as requested by the 1982 Law of the Sea Convention) and, giving the resource the benefit of any doubt, take measures to reduce the impact of fishing effort (e.g. constraining fleet size, fishing areas and seasons) to reduce the risk of recruitment failure, and revise the measures as better data become available. If there is a probability that the damage to the resource could be irreversible, affecting the options of future generations, the duty of stewardship would require, in theory at least, that corrective action be taken even at high cost to present generations. If, as is more likely in the case of recruitment overfishing in short-lived species, the impact on recruitment is reversible through management, a cost–benefit analysis would indicate the measures to be taken, based on an analysis of the probability of recruitment failure, the related potential costs on the short and long term, as well as the cost of the potential measures.

It is often recommended to be cautious by taking preventive measures. This assumes that there is enough knowledge available to effectively anticipate future events and the exact effects of the measures. This will most often not be the case. Precautionary management systems should, therefore, have both a preventive capacity to avoid predictable problems as far as possible, and also a reactive capacity to correct problems which are bound to occur. A precautionary shrimp management 'toolbox' would therefore need to include long-term recruitment reference points as well as thresholds at which pre-agreed courses of action would be taken, recognizing the uncertainties in the data and in their exact value and position. For a more comprehensive discussion on the precautionary approach and the use of limit and target reference points see FAO (1995, 1996) and Garcia (1996).

Empirical Approach to SRR

There is enough evidence that the role of year-to-year environmentally driven fluctuations of recruitment must be taken into account in any approach to the problem of SRRs in shrimp fisheries. The classical SRR concept would therefore have to be modified as suggested by Garcia (1983) to take into account such fluctuations (Fig. 2). As both the SRR and the high-risk area are difficult to define statistically, one might have to use an empirical approximation. Csirke (1987), for instance, used a graphical approximation for the Patagonian-shelf squid fishery based on the broad borderlines of the stock–recruitment scatterplot to determine what could be a safe seasonal level of spawning stock abundance. A more elaborated approach has been used by Sissenwine and Shepherd (1987), Serebryakov (1991) and Mace and Sissenwine (1993) and has inspired the approach suggested below which includes the determination of the stock–recruitment scatterplot boundaries and the range of fishing mortalities at which the risk of recruitment overfishing is very high (F_{lim} range) or fairly low (F_{med} range). These ranges are defined below.

Defining Data-set Boundaries

The stock and recruitment data sets are usually represented by a scatter of points with no obvious relationship. A time series of spawning stock and recruitment data can usually be established using, for example, the average catch per unit effort (CPUE) during the spawning season as an index of spawning stock size, and the average CPUE during the main recruitment period as a recruitment index. The frequency distribution of the stock and recruitment data could be examined to determine the borders of the scatter diagram as well as the long-term average conditions (Fig. 3*A*). As suggested by Shelton and Morgan (1993), the cumulative distribution can be used to determine approximately the 10th, 50th and 90th percentiles of the observed stock and recruitment levels (Fig. 3*B*). The corresponding lines can be drawn on the stock and recruitment scatter diagram (Fig. 4). Alternatively, these lines could be drawn directly on the scatter plot, leaving respectively 10%, 50% and 90% of the data points above them (for recruitment) or on the left-hand side of them (for

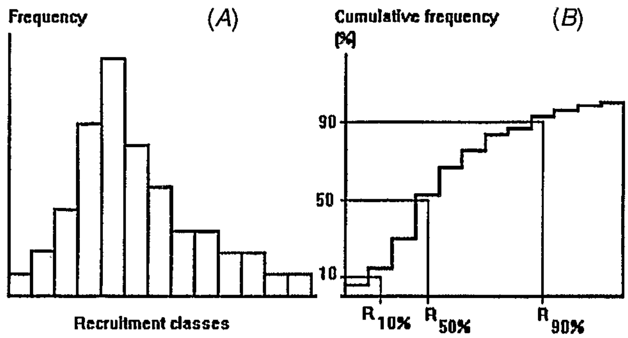

Fig. 3. *(A)* Frequency distribution and *(B)* relative cumulative frequency distribution of recruitment data. A similar approach could be used for data on spawning stock size.

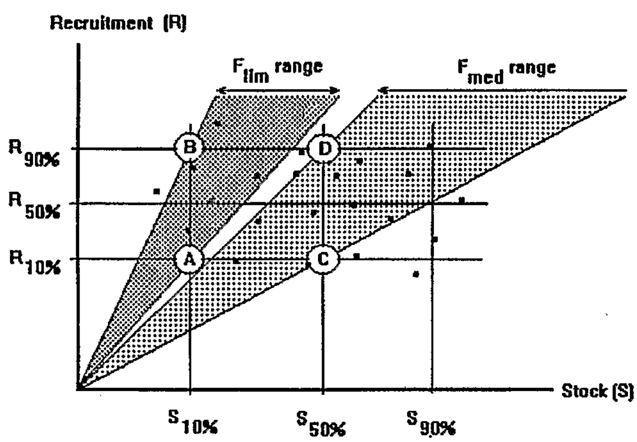

Fig. 4. Hypothetical stock-recruitment scatter diagram with lines corresponding to the 10%, 50% and 90% quantiles, showing the precautionary F_{lim} and the F_{med} ranges. Letters A to D identify particular intersections of the $R_{10\%}$ and $R_{90\%}$ borderlines (see text).

spawning stock size). These lines can be taken as conventional low, median and high levels of recruitment and spawning stock respectively.

An alternative would be to use the lowest observed values of stock and recruitment as the lowest boundaries (limits) of the data set but this would be less precautionary. Another option would be to calculate the lowest (and highest) stock and recruitment limits as the respective averages of the 10% highest and lowest values observed. This would have the advantage of producing boundaries with an estimate of their variance. The procedure suggested here establishes only the boundaries of the observed values (as opposed to the boundaries of possible values) and the probability of a 'surprise' would be lower if the whole range of possible values had been already observed and included in the data. This, obviously, will never be known, but precaution could be added to the procedure (e.g. in the case of small data sets) by choosing more precautionary lower boundaries. The choice of a 10th lower percentile as the lower (precautionary) boundary or threshold level in Fig. 4 is arbitrary. One could choose instead the 5th or 20th percentile, depending on the amount of safety that one wants to build into the system or amount of risk (probability of recruitment failure and related costs) that one is willing to accept, taking into account the level of exploitation of the stock.

The precautionary cushion needed will depend on the amplitude of the annual variability. Fig. 5 illustrates two stocks with the same average recruitment but different variability. The spawning biomass S_{lim} is a threshold below which, on average, the probability of entering the danger zone increases. If, for precautionary reasons, it is decided to avoid as far as possible entering the danger zone, and it is decided that replacement must be ensured even in the worst case, F_{med} could be used as the mortality target, leading, on average, to a stock S_{med} and a recruitment $R_{50\%}$. The difference between S_{lim} and $S_{50\%}$ is a precautionary 'cushion' (*c*). The comparison of the size of the cushion (*c*) in Fig. 5(*A*) and 5(*B*), differing only by the range of the natural variability in recruitment, shows that the larger the variability the smaller the resulting cushion. This shows that, in order to achieve the same level of precaution (same size of the cushion), the level of fishing authorized would have to be lower.

Defining the F_{lim} and F_{med} Ranges

The probability of recruitment failure is low when the spawning stock is large, but the low levels of fishing required to sustain such a situation may not produce high levels of catch. Higher levels of effort may be desired for

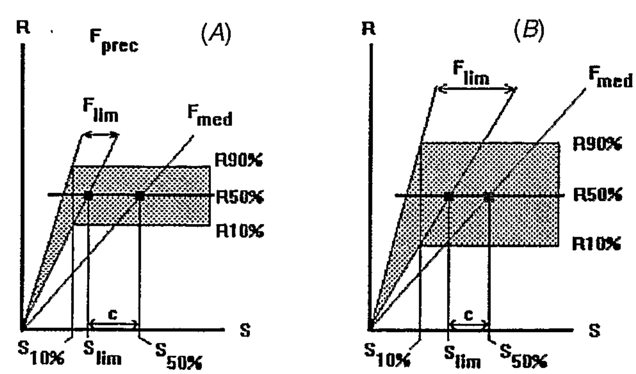

Fig. 5. Relation between the amplitude of the environmental variability and the size of the precautionary spawning biomass 'cushion' (*c*) or escapement needed to facilitate stock replacement under the worst conditions: (*A*) small variability; (*B*) large variability.

economic reasons, and the problem is to define how much effort is appropriate on the basis of an appreciation of the risk of recruitment failure involved. The stock and recruitment levels (and fishing mortality) corresponding to the 50th percentile of the observed stock and recruitment distributions (equivalent to their median) have empirically demonstrated their sustainability for many years and can be considered safe because the stock has shown to be able to maintain itself at these levels, at least under the climatic conditions that prevailed during the period of observation.

The high-risk fishing rates (F_{lim} range) could be approximated by joining the origin of the scatter plot to the intersections between the $S_{10\%}$ and $R_{10\%}$ lines (*A* in Fig. 4) and $S_{10\%}$ and $R_{90\%}$ lines (*B* in Fig. 4). These two lines could be taken as an approximation of the two replacement lines (RSRs), tangent at the origin of the stock–recruitment surface response shown in Fig. 2. Similarly, the F_{med} values, corresponding to median values of spawning stock size, could be estimated from the intersections between the $S_{50\%}$ and $R_{10\%}$ lines and the $S_{50\%}$ and $R_{90\%}$ lines on the stock and recruitment scatterplot (intersections *C* and *D* in Fig. 4).

The F_{lim} and F_{med} lines drawn by joining the origin of the scatter plot to *A*, *B*, *C*, and *D* are replacement lines (RSRs) corresponding to a certain level of fishing mortality, and their slope (*R*/*S*) is the inverse of the spawning stock-per-recruit (*S*/*R*) for that level of fishing mortality in a yield-per-recruit model, provided similar units are used for spawning biomass and recruitment respectively in the S–R scatter plot and the yield-per-recruit model (Sissenwine and Shepherd 1987)[9].

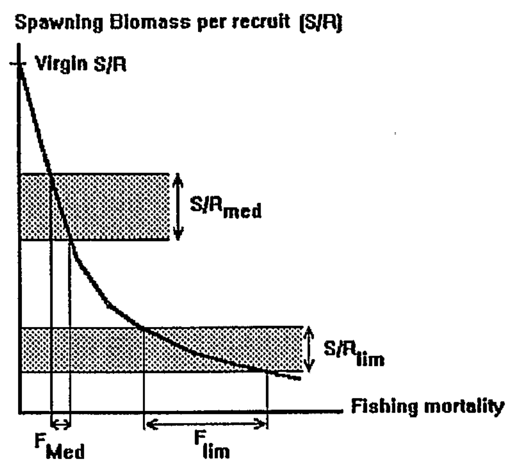

Fig. 6. Approximate determination of the fishing mortality rates corresponding to the high risk area (F_{lim} range) and average safe conditions (F_{med} range)

The procedure to estimate the F_{lim} and F_{med} ranges could be summarized as follows: obtain a time series of *S* and *R* values; plot the S–R scatter diagram (as in Fig. 4); establish cumulative distributions of the *S* and *R* frequencies; determine the 10th and 50th percentiles for *S* and *R* (Fig. 3); draw the corresponding boundaries on the S–R scatter plot (Fig. 4); draw lines from $S_{10\%}$ intersections to the origin (F_{lim}); draw lines from $S_{50\%}$ intersections to the origin (F_{med}); calculate their slope $(R/S)_{lim}$ and $(R/S)_{med}$ (attention to scale!); invert these values to obtain $(S/R)_{lim}$ and $(S/R)_{med}$; plot stock-per-recruit as a function of *F* using a *Y*/*R* model (Fig. 6); find the F_{lim} and F_{med} values corresponding to $(S/R)_{lim}$ and $(S/R)_{med}$; and determine corresponding f_{lim} and f_{med} fleet sizes.

A Dynamic Approach to Recruitment Management

Most penaeid shrimp fisheries are strongly seasonal, and the spawning stock size depends not only on the fleet size and annual level of effort but also on the seasonal (and spatial) distribution of this effort which, together with the trawl mesh size, determine the *F*-at-age pattern (or fishing regime). At high levels of effort, this seasonality becomes a key factor in management, which requires sometimes a real-time, dynamic approach to management.

Such an approach might be appropriate when the stock consists of one main seasonal generation exploited by the fishery between recruitment and the first massive spawning, as is the case for many of the intensively exploited shrimp fisheries of the world. In this case the spawning stock biomass at the beginning of the spawning season is a function of the annual recruitment, the level of fishing mortality (and fleet capacity), the opening date of fishing (which determines the age at first capture) and the date of the closure of fishing (which together with the fleet capacity and the opening date determines the cumulative mortality applied to the stock during a fishing season). Fig. 7(*A*) illustrates that for a given recruitment the spawning biomass threshold will be reached at a time which will depend on the date of opening of the fishery, and the cumulative fishing mortality applied (a function of the fleet capacity), leading to the need to have variable closing dates to ensure a certain escapement. Fig. 7(*B*) illustrates the fact that, for a given date of opening of the fishery, the spawning biomass threshold will be reached at different times in the year, depending on the annual number of recruits entering the fishery and on cumulative fishing mortality, leading to the need for variable closure dates to ensure that the spawning biomass does not fall below the selected threshold.

[9]This, in most cases, implies that stock and recruitment data used in the scatterplot shown in Fig. 4 should be absolute values (e.g. from a virtual population analysis, or converting CPUE data into biomass or numbers using a catchability coefficient (*q*) obtained through tagging or De Lury models) and not relative indexes (such catch-per-unit-effort).

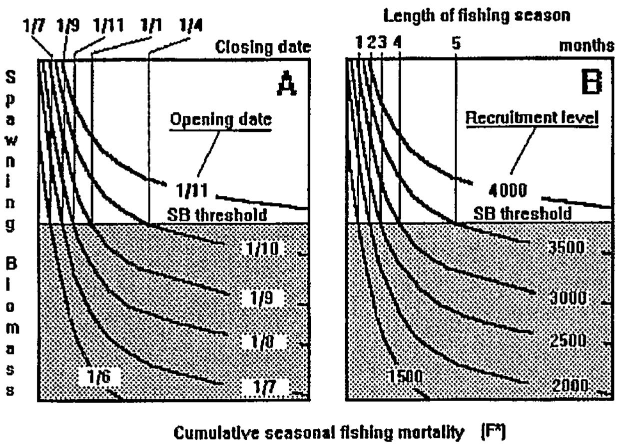

Fig. 7. Determination of the fishing seasons closing dates and duration, based on the evolution of spawning biomass (S) as a function of seasonal cumulative mortality (F^*), for various opening dates (left) and recruitment levels (right). Shading: area of unacceptable risk.

The Concept of Escapement

Whether or not a relationship between spawning stock size and annual recruitment has been demonstrated, the problem for precautionary management is to control fishing so that enough spawning biomass is left at the beginning of the spawning season to ensure an acceptable probability of avoiding recruitment failure. This residual biomass is often called 'escapement', and its magnitude depends on shrimp growth, mortality, maturity and fishing regime (age at first capture, fishing mortality). Used originally for salmon fisheries, the concept of escapement has been progressively applied to many other fisheries, particularly for fisheries on short-lived animals such as squids (Beddington *et al.* 1990; Rosenberg *et al.* 1990; Hilborn and Walters 1992), and is appropriate for intensive shrimp fisheries. As described below, escapement can be expressed in absolute or relative terms. It can be kept constant, based on average conditions, or be variable and tailored to each year class (real-time management). Management aimed at ensuring a level of escapement may control the age at first capture (or date of opening of the fishing season) and effort levels (or length of the fishing season).

Absolute escapement can be defined as a quantity of biomass that must be left at the time of spawning to ensure an acceptable probability to avoid recruitment failure. Its determination requires that an absolute value of the long-term or yearly recruitment is known. The level of escapement implemented (relative to spawning biomass in the absence of fishing) should reflect the level of precaution considered adequate for the stock. The escapement (which is a target reference level of spawning biomass) should not be established too close to the S_{lim} range because of the uncertainty of its exact position and the risk involved in inadvertently passing it. It could, however, be established at the S_{med} level (corresponding to F_{med} range) for which there is enough evidence of sustainability. Management based on constant absolute escapement would aim at maintaining, at each spawning season, a constant spawning biomass, despite annual variations in recruitment. It would make the best possible use of each year-class, accepting as a consequence wide variations in annual catches, effort levels and fishing seasons (see Fig. 7). Aiming at a zero risk (i.e. ensuring enough escapement even for the worst case) might be very costly in terms of forgone catches and is perhaps technically impossible. An alternative would be to determine some probabilities of recruitment failure and adopt a constant absolute escapement corresponding to an acceptable risk from the economic point of view if, because of assumed reversibility, the long-term biological risk is considered practically nil. This approach seems to have been adopted for the collapsed Exmouth Gulf tiger prawn fishery in Australia, and has resulted in a recovery (Penn *et al.* 1989).

Relative escapement (or proportional escapement) is often defined as the proportion of the virgin biomass that must be left in the water to ensure an acceptable probability to avoid recruitment failure. In an equilibrium approach, it could be expressed in terms of percentage of the long-term average spawning biomass or biomass-per-recruit in the absence of fishing (virgin biomass or biomass-per-recruit). In a more dynamic approach, it could be defined as a proportion of the spawning biomass that a particular year-class would produce in the absence of fishing. When the stock is exploited, the biomass available at the beginning of the spawning season (S) is given by

$$S = R \cdot e^{-(F+M)(t_r - t_s)} \cdot w_{ts},$$

where t_r is the time or age at recruitment, t_s the time or age at the beginning of the spawning season, and w_{ts} the individual weight at time or age (t_s). For a virgin stock, the biomass (S_V) would be given by

$$S_V = R \cdot e^{-(M)(t_r - t_s)} \cdot w_{ts}.$$

As a consequence, for a given stock, the relative escapement (S/S_V) depends only on the level of fishing mortality. A constant relative escapement strategy could be implemented simply by ensuring a constant fishing mortality, controlling overall fleet size, the total fishing effort and, possibly, its seasonal distribution. It would leave a variable spawning biomass from year to year, depending on recruitment. It might be easier and less costly to implement than a strategy based on a constant absolute escapement (or constant spawning stock size), but it would not make the best use of the large age-classes and would also risk leaving insufficient absolute spawning biomass in case of a weak year-class.

A variable escapement strategy could aim to *(a)* tailor fishing from year to year to make better use of good year-classes, within the limits imposed by the fleet size (in case of a limited entry system, for instance), *(b)* limit the fluctuations of fishing effort and landings to levels compatible with industries' constraints and market capacity, particularly in open access systems, and *(c)* compensate for natural fluctuations, e.g. leaving higher-than-average absolute escapements when the recruitment has been particularly poor and vice versa. An analysis of the constant and relative strategies should be undertaken to determine their respective performance, taking into account the stock characteristics, levels of variability and uncertainty. Such a comparison has been undertaken for the management of anchovies in South Africa; this showed that constant relative escapement strategies were superior in terms of total catch, catch variability and risk to the resource (Anon. 1992). In the case of the Exmouth Gulf tiger prawn fishery, however, Caputi (1992) showed that a constant-spawning-stock policy (constant absolute escapement) was preferable to a constant-effort strategy (or constant-relative-escapement strategy).

Real-time Management and Seasonal Fine-tuning

Management measures such as limited entry, fleet size controls, upper limits on monthly efforts, fishing seasons and closed areas could be established as long-term measures aiming at ensuring some average escapement. This strategy could work with long-lived animals with low recruitment variability even though it would require revision, from time to time, to adjust to drifts in population and fishery parameters. In the case of short-lived animals with highly variable recruitment, long-term average controls may need to be 'fine-tuned' to optimize the fishery, taking into account the year-to-year variability (real-time management).

The opening and closing date of the fishing season, for instance, may be fixed on average yield and value-per-recruit calculations. The opening date may have to be adjusted when migration timing (and age at migration) is changed by unusual climatic events such as heavy rainfall, droughts, floods or cyclones. The closing date which, on average, depends on fleet size and monthly fishing mortality rates, may be adjusted from year to year to account for variations in recruitment or catchability.

The average fishing-season parameters could be re-calculated each year. The opening date, for instance, could be fixed on the basis of pre-recruit surveys undertaken by scientists or by a small fleet sample. Recruitment index could also be calculated on the basis of the fishery data collected during the first few days or weeks[10] of the season, depending on the overall level of effort and forecast duration of the season, without having to wait for post-mortem virtual population analyses. For this purpose, a relationship could be established between annual recruitment and CPUE during the recruitment period, based on historical data. If the fishing mortality were high during recruitment and had changed during the period of observation or if the recruitment period were protracted, the recruitment index would be affected by fishing mortality and this would have to be taken into account. A theoretical example is given in Fig. 8, where two average relations are shown corresponding to two different levels of effort during the recruitment period.

The closing date (at which the threshold escapement would be reached) may also be adjusted, towards the middle or the end of the fishing season. If catch and effort data were collected on a quasi real-time basis and showed a significant discrepancy with the expected seasonal trajectory (Fig. 9), the fishing season could be interrupted when the escapement threshold level of spawning biomass was reached. The corrected date could also be projected some time in advance to give some lead time to the industry. It is evident, however, that the higher the relative fleet capacity, the shorter the fishing season, the less the possibility to fine-tune the management system and the higher the risk to overfish the spawning biomass and miss the escapement objective.

In order to facilitate decision-making in such variable fishing systems, it would be useful, and indeed precautionary, to develop beforehand an overall strategy regarding the relation between the seasonal patterns of fishing and the likely state of the resource. It could be agreed, for instance, that the season will not be closed at all as long as the recruitment is above $R_{90\%}$, that its duration will be proportional to recruitment when recruitment is between $R_{90\%}$ and $R_{10\%}$, and that fishing will be banned if recruitment falls below the $R_{10\%}$ level (Fig. 10*A*). A more liberal strategy would be with no closure above $R_{90\%}$, fixed-duration closure between $R_{90\%}$ and $R_{10\%}$ (possibly fine-tuned), variable closure between $R_{10\%}$ and R_{low} and total ban if a recruitment lower than any of those already experienced occurs (Fig. 10*B*). This control law could be modified in many ways based on an appreciation of the risk involved in each part of the stock and recruitment data range and its potential cost to industry and to the community.

Discussion and Conclusions

The approach to the SRR and to shrimp recruitment management described in this paper is precautionary because:

[10]This implies that accurate CPUE data are available as well as an estimate of the seasonal catchability for the recruitment period (to estimate absolute recruitment). Alternatively, the CPUE can be used as a recruitment index.

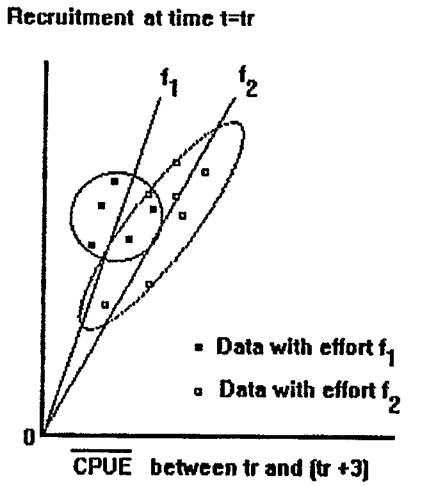

Fig. 8. Illustration of a relationship between the CPUE obtained during the recruitment period and the recruitment at two different levels of effort, f_1 and f_2.

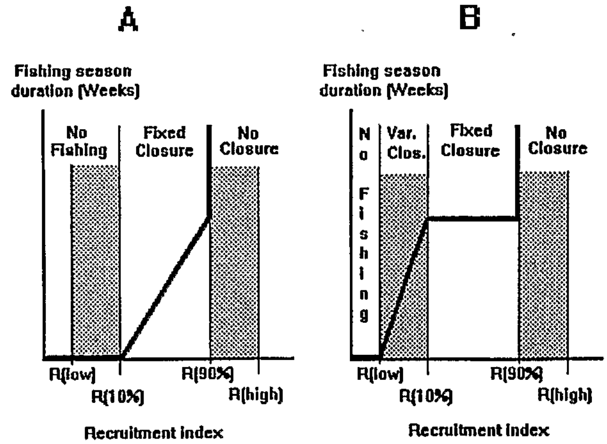

Fig. 10. Theoretical examples of control laws which could be used for the determination of fishing seasons strategies, based on observed levels of recruitment. R_{low} and R_{high} are the lowest and highest recruitment observed. $R_{10\%}$ and $R_{90\%}$ are the levels below which 10% and 90% of the recruitment data points are located (cf. Fig. 5)

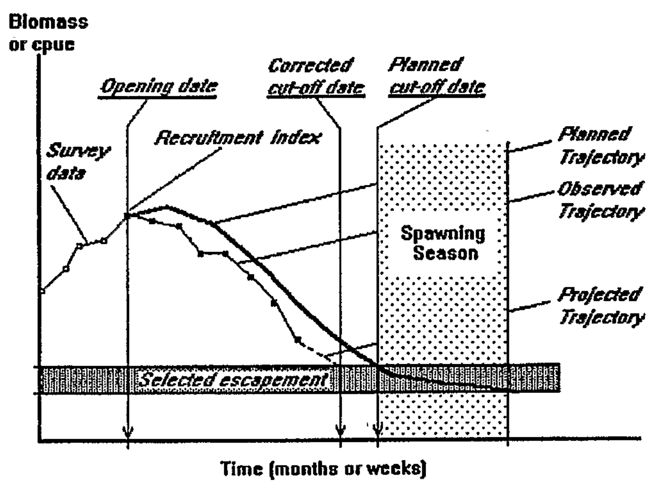

Fig. 9. Expected and observed seasonal evolution of biomass and spawning biomass indices and definition of the fishing calendar on the basis of the required spawning stock escapement at the beginning of the spawning season.

(a) It recognizes formally that a risk of recruitment failure exists even though the shape of the SRR may not be clarified and recruitment failure may not have yet occurred;

(b) It makes full use of the scientific information available;

(c) It does not wait for a high level of scientific significance about the causal relationships before providing advice on pre-emptive action;

(d) It defines specific recruitment-related reference points corresponding to 'risky' and 'safe' levels of spawning biomass and mortality and uses precautionary thresholds at which corrective action is taken (on season length). It also provides a method to determine the confidence limits of the reference points and thresholds (see below).

The assessment method needs to be thoroughly tested on real data, for instance in areas where a satisfactory parametric SRR has been obtained. In addition, the cost of a dynamic approach for real-time management needs to be carefully weighted against the costs of recruitment failure through risk analysis.

The impact and relevance of fine-tuning fishing seasons have been the subject of much research, particularly in shrimp fisheries. A review is available in Garcia (1989) and a recent analysis has been conducted by Watson *et al.* (1994). The benefits of fine-tuning depend on the accuracy and precision of the parameters used for forecasting the resource and the fishery trajectory and on the year-to-year variability. Fine-tuning may be more justified when stock fluctuations are high (frequent oscillations of large amplitude) than when stocks are rather stable with rare perturbations of large amplitude. Real-time effort controls are also more justified when the fishing effort and, therefore, the risk of recruitment failure, is very high although, in this case, more direct measures to reduce fleet size might be more effective.

The following sections provide some preliminary insight into the problems of reliability of the proposed approach and on ways to assess the soundness of the conclusions it leads to.

Reliability of the Approach

Generally, for stocks of long-lived species consisting of many year-classes, a given year-class (i), with a certain number of recruits, will develop its spawning biomass and spawn during its entire mature lifespan, producing successive annual batches of offspring. In such a case, population persistence requires that the cumulative spawning biomass (S^*_i) produces enough cumulative recruitment (R^*_i) to replace the year class. In practice, however, the stock–recruitment relationship is usually established between spawning biomass (S_y) for a given year (y), summed over age-classes, and the total recruitment for the following year (R_{y+1}) without any indication of the year-classes from which it comes. The procedure assumes that the spawning biomass and the recruitment produced by a given year-class during its entire life span can be approximated by the spawning biomass and recruitment produced by all year classes on any given year. This assumption of equivalence, which requires strict conditions of equilibrium, may not always be fulfilled, particularly when population parameters (growth, natural mortality and maturation) and fishing patterns (F-at-Age) change with time and fishing intensity. The impact of such drifts in population and fishing parameters on the SRR have been investigated by Shelton and Morgan (1993). Jacobsen (1992), working on Arctic cod and haddock, found that the values obtained through the non-parametric method were fairly robust to the values of M.

In short-lived animals like shrimps (and squids) this assumption of equivalence is not required, because stocks consist of essentially a single year-class. In this case, and provided the data are pooled properly on the basis of the recruitment seasonal cycle, the spawning biomass and recruitment data used in the SRR arise from the same year-class, with the same underlying biological parameters and fishing patterns.

It is clear that the reliability and, therefore, the degree of precaution really exerted when the empirical approach is used, depends heavily on the amount and quality of the available data, the length of the stock and recruitment time series, and the contrast in the conditions observed in terms of effort, environment, spawning stock and recruitment. Losses may occur in years when recruitment success is exceptionally low (through erosion of the spawning stock beyond the reference point), or when it is exceptionally high (through forgone economic resources that could have been captured). The probability and extent of the losses could be reduced by combining the empirical approach with seasonal fine-tuning.

Maintenance of F below the F_{lim} range is no guarantee that recruitment will not fail sometimes because of environmental or multispecies effects (changes in predation) or because, despite its precautionary nature, the range has still been too high. It will, however, show to those in the industry who are accountable that everything possible has been done to avoid mismanagement. Fishing at levels equal to or higher than F_{lim} may also not automatically lead to recruitment failure. It is important to realize that, when environment fluctuates, the risk of recruitment failure is never nil but increases with high levels of F and low levels of spawning biomass. One should, therefore, see the F_{lim} range not as a deterministic limit below which fishing levels are completely safe but as an area close to which the risk increases rapidly. One could use a pseudo-jackknife procedure to obtain some minimum estimate of the variance of the estimated ranges. If a number of data points (n) are available, one could repeat (n+1) times the empirical procedure described above, eliminating one data point of the time series, each time, in sequence. This would produce (n+1) estimates of the F_{lim} and F_{med} ranges, the mean and variance of which could be estimated and used in risk analysis.

Validation of the Empirical Method

The method produces results that must be carefully considered before being accepted as a basis for management. The empirical determination of the F_{lim} range is such that it will most probably include some observed data points, pointing to the fact that F levels in that range only indicate a higher risk of recruitment failure, particularly when high fishing mortalities coincide with low recruitment success. If the average recruitment level observed within the F_{lim} range is lower than the average recruitment at lower fishing mortality levels (e.g. in the F_{med} range), the validity of that range as a precautionary reference point will be confirmed. However, in most case, this range should clearly be seen as a precautionary one because the related levels of F would have been observed in the past without leading to collapse. The range can be proved to be too 'liberal' if, despite limiting efforts below it, recruitment happens to fail. It would be difficult to prove that the empirically determined range is over-conservative unless 'excessive' effort levels are systematically applied to test it.

In the absence of evidence of recruitment failure in the data, it will be particularly important to substantiate the results of the method with other sources of information, as described below, to facilitate acceptance and compliance by industry. As a matter of fact, such a cross-validation should be also required for other, less empirical, and more statistical approaches to the SRR.

The shape of the yield curve relating catch to effort is related to the shape of the SRR. In shrimp fisheries, the yield curve is often well defined, provided there is enough contrast in the catch and effort data. Not surprisingly, however, those variable stocks for which the production modelling raises most problems are those for which the SRR is more poorly defined. The two concepts could nevertheless be combined for cross-validation.

It is usually agreed that fishing beyond the maximum sustainable yield (MSY) increases recruitment variability (and risk of recruitment failure). A common rule of thumb is that MSY corresponds to fishing mortalities close to the level of natural mortality. The Schaefer model is one of the most conservative because it assumes that the stock decreases linearly with effort and collapses when fishing mortality reaches a value close to twice the fishing mortality at MSY ($F_{lim} = 2F_{msy}$). A usual approximation is that MSY is reached when $F_{msy} = M$ and therefore a limit fishing mortality rate could be set at $F_{lim} = 2M$. In the absence of specific data, one could use as a first approximation the average values calculated by Garcia (1983) for a number of penaeid shrimp stocks (F_{msy}=1.3 to 1.9 per year and M= 2.1 to 2.7 per year). Another and more conservative approximation would be to use $2F_{0.1}$ (from a *Y/R* model) instead of $2F_{msy}$.

It would therefore be advisable to draw also on the S–R scatter plot (Fig. 11) the replacement line corresponding to $F=2F_{msy}$ and $F=2M$ respectively, calculated by the inverse procedure (i.e. find the S/R corresponding to $F=2M$ in the spawning biomass-per-recruit model (Fig. 6), inverting it to find the related *R/S* and using this value as the slope of the replacement line). Their position relative to the F_{lim} range would indicate whether the results obtained with the empirical approach are reasonable or not. One could also position $F=3M$ on the graph as an extreme limit. It is suggested that if those independent and conventional limits for fishing mortality fell within the F_{lim} range, the analysis might be considered reasonable. If they fell well on the left of the F_{lim} range, the analysis might be over-conservative. If, on the contrary, they fell on the right of the F_{lim} range, the analysis might be over-optimistic.

Another limit replacement line that could be drawn to obtain a feeling about the soundness of the conclusions is the one corresponding to a fishing mortality at which the spawning biomass is only 20% of the virgin spawning biomass-per-recruit which, in the fisheries literature, is often considered a limit below which it would not be precautionary to fall. This would be done by finding the S/R corresponding to this relative level (and the related level of F) and inverting it to obtain the slope of the replacement line.

As part of an internal validation procedure, it is critical to examine the trends reflected in the S–R data points which should be serially linked on the scatterplot. Fig. 12 shows some of the situations that may occur, showing the potential data range, the available data range and the time trend in such data. In Fig. 12(*A*), the observed data cover a large part of the range with no trend in R. This would indicate fairly random variations of R and an increasing level of F. These conditions are ideal for the application of the empirical approach and should lead to concern only if current F levels are close to $F=2M$. In Fig. 12(*B*), the narrow data range and upper trend could indicate that F has increased as conditions for recruitment success improved. This could be dangerous in the future, because a rapid crash in recruitment can be expected as the climatic conditions worsen, assuming that their improvement is part of a temporary oscillation. Fig. 12(*C*) would, on the contrary, indicate that F is close to the limit values and that recruitment is worsening for climatic or fishery-related reasons or both. This is dangerous, because any worsening of climatic conditions or increase in effort is likely to lead to further recruitment failure. Fig. 12(*D*) would indicate that F has been quasi-constant but that environment has been worsening. Reduction of effort might be needed to help the stock recover, even though fishing might not be responsible. The analysis should try to identify environmental parameters with similar trends and assess their likely reversibility (progressive degradation of nursery

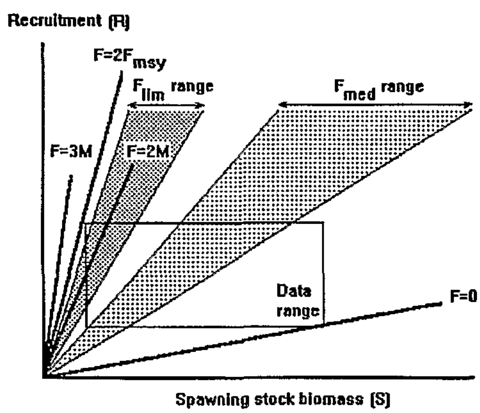

Fig. 11. Example of a possible position of the F=0, $F=2M$, $F=2F_{msy}$ and $F=3M$ replacement lines on a *RS* scatter plot in the case of a reasonable interpretation.

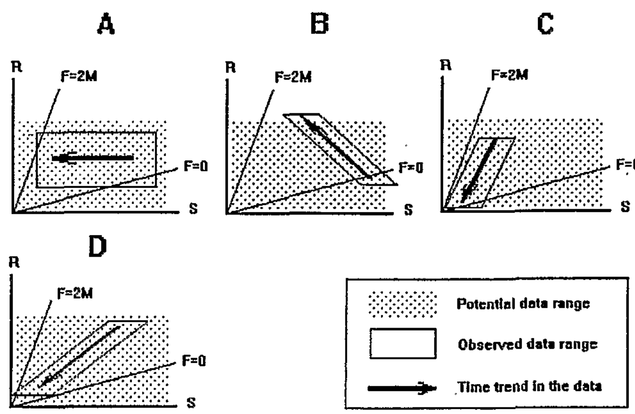

Fig. 12. Possible relationship between observed and potential data ranges and trends.

areas by urban development is unlikely to be reversible!).

In all of the above examples, the explanation given is not assumed to be the only or most correct one. The point is to look at other data available (other than S and R) to see whether the situation apparently reflected in the SRR can be explained by the levels and trends of F in the fishery or by the trends in relevant climatic conditions. The higher the level of coherence with other information, the more confidence one could have in the results.

Further guidance on this matter has been provided by the ICES Working Group on Stock Assessment Methods (1993). Myers *et al.* (1994) suggested consideration of the slope of the relationships between the stock and recruitment data located on each side of the S value selected as a safe management threshold (or target) for management to determine whether the situation appears risky, reasonable, overly cautious or aberrant (Fig. 13). Situations as in Fig. 13(*A,B*) would appear as risky because there is a large potential for increase in R at levels of stock higher than the selected management thresholds. Situations as in Fig. 13(*C,D*) would seem reasonable because the thresholds correspond to optimal level of recruitment. Situations as in Fig. 13(*E,F*) would correspond to overly cautious situations because higher levels of recruitment would apparently be possible even at lower stock thresholds. Finally, Fig. 13(*G*) would give an example of an aberrant situation because there is no rational explanation for such a situation.

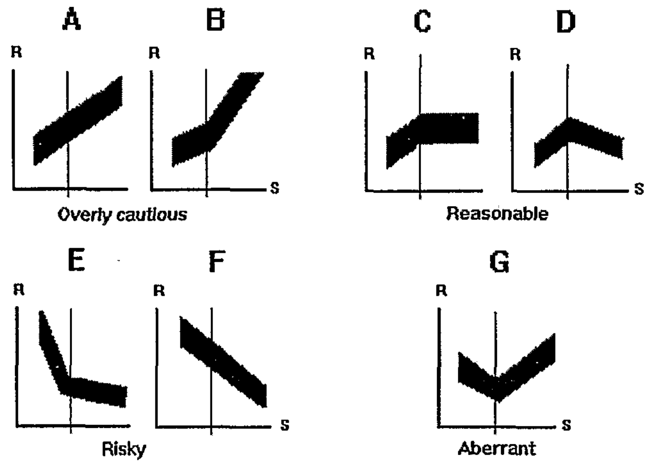

Fig. 13. *Examples of possible shapes of the S-R scatterplot in relation to* the stock threshold used for management (S) reference point. The data range is indicated by the shaded area. The threshold is shown by the vertical line splitting the scatterplot into two parts. (Inspired by Myers *et al.* 1994).

Risk and Acceptable Impacts

In tropical shrimp fisheries, it is likely that the adverse impacts of fisheries on recruitment are easily reversible through effort controls and are unlikely to seriously affect future generations of fishermen and consumers. As a consequence, a fair amount of risk of recruitment failure might be acceptable to industry and to the national community. However, when many species of shrimp are exploited at the same time, the less resilient could be depleted and could continue to be caught accidentally at a rate that would impede their recovery. In addition, impacts that might be considered reversible, and therefore acceptable from a resource conservation standpoint, may not be acceptable from an economic standpoint because of the immediate social and economic costs. Although this argument is opposite to that usually favoured by conservation lobbies, it may be particularly appropriate for shrimp fisheries. It should be noted that, contrary to fishery impacts, environmental impacts on nursery areas, through coastal development, alterations of river flows, domestication of lagoons and estuaries, pollution, etc. are likely to have longer lasting effects on recruitment, possibly leading to species replacement. They should, therefore, be subject to a precautionary approach. Fishermen, particularly in areas where they have acquired access rights, could invoke the precautionary principle to stop or mitigate the negative effects of other industries on the shrimp resources.

Managers need to be presented with the probability of the negative outcomes for the state of the resource and the fishery (such as a potential decrease in catch, revenues or recruitment) for the different management options available to them. This requires what is generally referred to as risk analysis. A general approach to risk analysis in fisheries has been presented by Hilborn and Walters (1992). In risk analysis, the various sources of error are taken into account, including the variance of the parameters used in the model (sensitivity analysis), the various possible models and the information not yet included in the models. In addition, probabilities must be assigned to the expected values of each outcome of the various management options. Hilborn and Walters suggested also that the management options could sometimes be experimentally tested, forcing the system in order to obtain responses and reduce uncertainty (e.g. improving knowledge on SRR at low stock levels by allowing high effort levels for a few years).

Risk analysis in shrimp fisheries as a basis for a precautionary approach to recruitment management would require that population and fishery parameters, and in particular the recruitment thresholds and the current mortality, spawning biomass and recruitment levels, be expressed in probabilistic terms. The observed data points give an estimate of the probability of occurrence of stock and recruitment levels. A suggestion has been made above for a simple way of calculating a confidence interval for the threshold range (F_{lim}). Shelton and Morgan (1993) have shown how recruitment probabilities estimated from a non-parametric analysis could be used to assess the probability of failing to achieve replacement recruitment at different spawner biomass levels. Rosenberg and Restrepo (1993) explored by simulations the various methods available to express uncertainty in stock assessments, projected stock status and scientific advice and the interaction between such uncertainty and management strategies. In analysing the risk of recruitment overfishing, they, as well as Myers *et al.* (1994), noted that the non-parametric approach used by Serebryakov (1991) to determine recruitment thresholds performed poorly, was very unstable as biomass changed and may not be robust across data sets. This points to the need to be particularly cautious when using methods with low statistical power and to validate the conclusions with as much external information as possible. Finally, it should be stressed that, to be useful in decision making, a risk analysis should be expressed not only in biological terms (e.g. probability of a recruitment collapse) but also in economic terms, using appropriate discount rates.

Considering (or agreeing) that a certain level of impact on stock size (corresponding to a certain risk of recruitment failure) is 'acceptable' does not mean that this level of impact is definitely approved). It means that it will be tolerated but kept under review and modified, if required, as knowledge progresses. It could be agreed, for instance, that reduction of spawning biomass to 25% of the virgin level is 'acceptable', based on some past evidence, subject to revision of that agreement in the light of new experience obtained in that fishery or in similar ones elsewhere. The degree of acceptability of a given impact on recruitment will be determined, *inter alia,* by the degree of reversibility of this impact (e.g. if the fishing stress is reduced or suppressed) and its potential cost to the various stakeholders (including consumers and the society at large) as well as the cost of the measures aimed at reducing it with appropriate weighting given to short- and long-term conservation needs.

The identification of impacts and the determination of the causal factors requires research capacity to discriminate between the effects of year-to-year 'natural' fluctuations, the impacts of fishing, and anthropogenic degradation, including global climate change. It requires the development of an effective enforcement capacity to ensure that such acceptable levels will be respected. It may finally require the establishment of 'safety net' arrangements (e.g. in terms of insurance, compensation, etc.) to protect the users and the resource in case of recruitment failure.

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