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Potential reference points, precautionary management frameworks and harvest control rules for UK shellfish species

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Executive summary

Biological reference points have been used in fisheries science and management for many years, but the last decade has seen has seen a significant increase in their usage, with the implementation of a precautionary approach to fisheries management, increasing importance of certification and more formalised management approaches. Fisheries science surrounding reference points has received new interest with the aim of defining limit, threshold and target reference points. Limit reference points take account of the stock and fishery characteristics to define (stock and fishery) situations that should be avoided, threshold (buffer or precautionary) reference points take account of uncertainty to provide a high probability that the limits are not reached, by triggering remedial management actions, while target reference points use stock and fishery characteristics to define situations that maintain the stock in desirable or in some way optimal situations. Any given fishery situation, and therefore reference point, can be expressed in a variety of metrics quantifying the particular aspects of the stock (e.g. biomass, spawning stock biomass, recruitment) and the fishery (e.g. yield, fishing mortality, fishing effort). Precautionary management frameworks are defined by reference points and formalised pre-determined management actions to be taken under different stock and fishery situations, harvest control rules (HCRs). The development of pre-agreed HCRs that explicitly state the nature and extent of management actions to be taken is fundamental to the precautionary management, because without pre-agreement, negotiations between managers, fishermen and scientists can become entrenched and protracted, resulting in stock deterioration before agreement on remedial management measures can be reached. In addition, predefined management actions can be implemented in computer programs and this permits extensive evaluation of alternative management strategies through computer simulation. HCRs are not restricted to a particular form of control, but most tend to operate through direct input (fishing effort) or output (TACs and quotas) controls. Indirect input/output control may be achieved though spatial and seasonal closures and although changes in technical measures, such as size limits and net mesh size controls, may also form part of management plans, they tend to be less flexible than direct input/output controls.

Traffic light systems have developed, primarily in data poor situations, to allow the synthesis of signals from a range of sometimes-empirical indices and indicators. They use scoring systems to combine metrics of different scales or units providing an overall indication of stock or fishery health. Scoring systems can include fuzzy logic and ramp functions, but the selection and weighting of indices to be used in the synthesis is crucial to the overall score. Traffic light (TL) systems can, and preferably should, be extended to include HCRs, thereby acting as a precautionary management framework, rather than simply producing a combined index. Traffic light systems have been criticised for a lack of scientific rigour. Nonetheless, they have been quite widely used in Canada, particularly for crustacean stocks, but they have not been applied to any significant extent in Europe.

In Europe, precautionary management systems for finfish have been relatively well developed through the ICES forum. Reference points for finfish stocks have focussed around the provision of limit reference points based on determining the spawning stock biomass at which recruitment is impaired and the fishing mortality likely to cause stock collapse, and the thresholds to ensure a high probability that these are avoided. These reference points have typically been based on age structured analytical assessments and stock recruitment relationships. Explicit rebuilding plans were initially implemented for severely depleted stocks, but following the realisation that, in the absence of explicit targets, stocks tended to be managed close to the threshold level, management plans with target reference points, are now being developed for a wider range of stocks. Management strategy evaluation through computer simulation is used to develop and test harvest control rules.

Shellfish stocks have tended to receive less attention than finfish, have poorer quality data sets and also have particular biological characteristics that complicate stock assessment. As a result reference points and precautionary management frameworks for many shellfish stocks are less well developed.

Crustacean species pose particular problems because they cannot be routinely aged and time series of stock and recruitment data are rarely available. The use of static gear, which may be targeted at particular species, but may take a by-catch also makes estimation of effective fishing effort problematic. These factors remove the potential for calculating many of the limit reference points used for finfish stocks and may also cause problems with methods that utilise catch and effort data. Alternative assessment methods and reference points therefore tend to be used. Harvest ratios based on TV surveys of burrow densities have been applied for *Nephrops*, while length cohort analysis with per recruit analyses and examination of CPUE trends may form a basis for lobster and crab assessments and reference points. Data poor crustacean species such as spider and velvet crabs tend not to be routinely assessed and the development of simple or empirical approaches possibly using TL systems may provide a way forward for these species.

Offshore bivalve fisheries pose different problems, frequently due to differences between the scale of biological populations and fisheries data. The species are mainly sedentary and the stocks and fisheries are spatially structured with population parameters that may differ at local scales. Age and length data may be available, but; often not at useful spatial scales. Reference points and management approaches based on the spatial distributions of stocks and fisheries, in conjunction with information on stock densities (or catch rates), may provide a means for reference and control.

By contrast, many inshore molluscan stocks, particularly cockles and mussels, have well developed management plans incorporating monitoring programmes, reference points and management controls. These typically use annual surveys to obtain absolute estimates of biomass and use a variety of control measures (spatial and temporal closures, TAC, access limitation, daily quotas) to achieve the management objectives that are framed using reference points such as medium term biomass being above some limit, short term biomass being above a limit, a target harvest ratio and a balanced age structure.

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1 Introduction

The concept of reference points has been in place for many years, while harvest control rules have tended to be implicit (rather than explicit) in management of fish stocks. However, new momentum and direction to the development and application of fisheries management theory has evolved over the last two decades in response to a number of drivers. World summits (e.g. UNCED, 1992; WSSD, 2002) have set targets for sustainable management of natural resources and management agencies have embraced the development of the Precautionary Approach (PA) to fisheries management. The increasing importance of certification and adherence to codes of conduct, particularly within fish marketing, has also placed the spotlight on the science of fish stock assessment. Underpinning principles for the precautionary approach were provided by the FAO Code of Conduct for Responsible Fisheries (FAO, 1995) and the UN Agreement on Straddling Stocks and Highly Migratory

Stocks (Doulman, 1995). This has resulted in more explicit consideration of reference points, as the basis to measure stock and fishery status, within precautionary management frameworks, that define limits, thresholds and/or targets (again in terms of reference points) and utilise harvest control rules, that specify pre-defined management actions aimed to ensure the fishery is moved towards and maintained in a sustainable target area.

Traditionally, reference points were derived to encapsulate some particular feature or aspect of the stock or fishery and in this context they have often been referred to as biological reference points. Reference points may be based on or expressed in terms of a number of the properties of the stock and fishery, but typically might quantify; output from the fishery (yield), the level of exploitation exerted on the stock by the fishery (fishing mortality, F), the size of the adult stock, or its reproductive potential (biomass or spawning stock biomass, SSB). Given assumptions about an underlying population dynamics model it is usually possible to calculate the family of metrics that correspond to a particular reference point. Thus a typical example of a traditional biological reference point would be maximum sustainable yield (MSY), the maximum yield that could be sustained by a stock in the long term, and a reference point that can potentially be derived from either age-structured analytical assessments or from surplus production models. Associated with this point are F_{MSY}, the fishing mortality that would produce MSY in the long term, and B_{MSY}, the equilibrium biomass that would result from harvesting at this level. There are also other metrics associated with the reference point with important ones including fishing effort and recruitment, although these may not always be available. In this particular example, the family of (MSY) reference points provide us with quantitative information in terms of a range of aspects about the stock and fishery that would result from (or result in) management of the resource at this level. Comparing estimates of the current position, using any of these metrics, will enable us to make a conclusion as to the current status of the stock relative to the situation of MSY and might inform on the direction required to move the stock/fishery towards (or away from) the reference point. This particular example is of a reference point that represents a relatively healthy stock position, but others may be indicative of exploitation levels, or stock positions, that are very unfavourable and would want to be avoided. Thus any particular reference point could be classified either as a target reference point or a limit reference point, although in some cases it is not always clear in which category a reference point belongs.

Historically, fisheries management has tended to try to manage towards target reference points, but as Caddy (1998a) notes management approaches based on target reference points (TRP) alone have proved vulnerable to over fishing. This was partly because of high levels of uncertainty in locating the fishery position relative to the TRP, but frequently exacerbated by continued over exploitation during delays in implementing recovery measures, due to the absence of pre-negotiated management plans and a lack of mechanisms for obtaining rapid consensual decisions on suitable action by managers, fishermen and scientists. The development of the precautionary approach to fisheries management resulted, at least initially, in a much greater emphasis on limit reference points that could be used to define stock and fishery positions that should be avoided. A consideration of uncertainty is inherent in the precautionary approach, with a greater level of precaution required with increasing lack of understanding regarding the resource and its dynamics, or inability to control its exploitation. Precautionary management frameworks have therefore been developed to provide a basis for management by formally defining healthy and unhealthy stock and fishery positions and thresholds (trigger points) at which management measures must be introduced. Typically, they may be defined in terms of limit reference points, that must be avoided with high probability, threshold (pa) reference points, that take account of uncertainty in the estimation of current and reference stock/fishery levels to trigger action before the limit is approached and target reference points designed to move the stock or fishery to, or maintain it in, some favourable position. The precautionary management framework provides the structure to trigger management actions designed to achieve certain aims, while the detail of how this will be achieved is contained within the harvest control rule (HCR).

Harvest control rules are a key component of precautionary management frameworks. They aim to replace *ad hoc* provision of advice with a more rigorous management structure in which objectives, such as the avoidance of limits and the achievement of thresholds and targets, along with the corresponding courses of action to be taken under particular circumstances, are explicitly stated. FAO defined HCRs as pre-agreed specifications for the management actions that will be taken to respond to estimated or perceived states of nature (FAO 1995; 1996). Similarly, the ICES Study Group on Management Strategies defined an HCR as an algorithm for pre-agreed management actions that is a function of variables related to the status of the fish population (ICES 2006b). The key aspects of HCRs are then that they are pre-agreed, and that they explicitly state the nature and extent of management actions that will result in response to a particular stock diagnosis. HCRs are not restricted to a particular form of control, but most HCRs are designed to control either catch or effort directly through TAC control, control of days at sea, or seasonal closures. Spatial closures do not control the level of input of out put, but rather aim to control the interaction between exploitation and the resource and are also widely applied in shellfisheries. Many fisheries for shellfish species are managed primarily through technical measures and the absence of direct input or output control complicates the development of effective and flexible harvest control rules.

In this review we consider some aspects of the history and development of reference points, precautionary management frameworks and harvest control rules and comment on the potential for application to some UK shellfish stocks.

2 Biological reference points

As noted in section 1, reference points can be markers, against which to assess the status of stocks or fisheries or, used as triggers or targets for management actions. They need to reflect a range of different aspects of stock and/or fishery performance and may therefore be couched in terms of a number of metrics. The common fisheries metrics (yield, F, SSB, recruitment and effort) were mentioned above, but reference points can also be extended to include social, economic or wider environmental considerations if these were deemed appropriate

Morrissey (1993) confirms the three categories; status indicators, targets and limits and also highlights that they may also be measured in either relative or absolute terms. It should also be noted that in addition to reference points that identify optima or limits, others might only be directional.

Reference points are most useful if they:

- are based on well-estimated parameters,
- have stable characteristics and are durable,
- are tractable and have manageable data requirements,
- are transparent, such that the processes defining them are clear and managers are aware of what features are being measured.

However, their application has also been criticised, especially with regards to problems of model based reference points that might not account for particular life history aspects of the species concerned, or where population parameters cannot be accurately estimated (Hilborn, 2002; Mangel *et al.*, 2002; Koeller, 2003; Orensanz *et al.*, 2004).

The quality of data being used for stock assessment is another issue that needs to be considered and may be influenced by the management system in place. In eastern Canada, where F based strategies were implemented through quota control a gradual decline in the quality of catch data was observed (Rivard & Maguire, 1993). Similar, data problems have been noted in ICES. For several UK crustacean species, quantification of fishing effort is a problem, and changes to reporting systems, even when they improve data quality, may compromise the integrity of the time series. Further, stock recruit data and age structured data are often lacking for many shellfish species (e.g. Crustacea) and the dynamics of bivalves and cephalopods are often heavily influenced by environmental factors. These complicate stock assessment with the result that proxy metrics may be required. The most important of these is catch rate, (catch, or landings, per unit effort, CPUE or LPUE), which is frequently used as a proxy for stock abundance.

In cases where time series of quantitative data are lacking the use of proxy variables and 'indicators' becomes important. Caddy (2004) regards reference points as critical values of indicators that may be derived from analysis, from observation, by expert judgment, or by comparison with data from earlier periods in the fishery when productivity was higher and sustained and also, but not exclusively, from population models. In these cases it may be appropriate to use multiple indicators of different units and scales and pragmatic methodological approaches such as traffic light systems have developed as a means of combining and synthesising these data.

In this section we are primarily concerned with the theory of biological reference points, their data needs and relevance in terms of gauging stock or fishery status and informing management.

Table 1 presents some common reference points, many of which were considered by ICES (1997; 2001) during the development of their precautionary management framework. These and others are discussed in more detail and to some extent in order of increasing complexity and data needs in the following text. Each section provides some background on the theory and data needs along with some examples of their application where available.

Table 1. Some commonly used reference points

Reference point	Definition	Data needs	References
$F_{0.1}$	F at which the slope of the YPR curve is 10% of its value at the origin	Catch weight at age, natural mortality exploitation pattern	1,
[2]F_{max}	F giving the maximum yield of a YPR curve	Catch weight at age, natural mortality exploitation pattern	1,
[2]$F_{35\%SPR}$	F corresponding to a level of SPR which is 35% of Virgin SPR, i.e the SPR when F=0	Stock weight at age, natural mortality, exploitation pattern, maturity at age	1,
F_{low}	F corresponding to a SPR equal to the inverse of the 10^{th} percentile of observed R/SSB	Stock weight at age, natural mortality, exploitation pattern, maturity at age, SSB and recruitment series	1,
[2]F_{med}	F corresponding to a SPR equal to the inverse of the 50^{th} percentile of observed R/SSB	Stock weight at age, natural mortality, exploitation pattern, maturity at age, SSB and recruitment series	1,
[2]F_{high}	F corresponding to a SPR equal to the inverse of the 90^{th} percentile of observed R/SSB	Stock weight at age, natural mortality, exploitation pattern, maturity at age, SSB and recruitment series	1,
[2]F_{MSY}	F corresponding to maximum sustainable yield from an age structured assessment	Stock weight at age, catch weight at age, natural mortality, exploitation pattern, maturity at age, stock recruitment relationship	1,
[2]F_{MSY}	F corresponding to maximum sustainable yield from a production model	Total catch and CPUE (or effort series)	1,
2/3 F_{MSY}	2/3rds of F_{MSY}	As F_{MSY}	1,
[2]F_{crash}	F corresponding to a SPR equal to the inverse of the R/SSB at the origin of a stock recruitment relationship from an age (or length) structured assessment	Stock weight at age, natural mortality, exploitation pattern, maturity at age, stock recruitment relationship	1,
[2]F_{crash}	F corresponding to the higher intersection of the equilibrium yield with the x-axis of a production model	Total catch and CPUE (or effort series)	1,
[2]F_{loss}	F corresponding to a SPR equal to the inverse of the R/SSB at the lowest observed spawning stock (loss)	Stock weight at age, natural mortality, exploitation pattern, maturity at age, SSB and recruitment series	1,
[2]F_{comfie}	F corresponding to the minimum of F_{med}, F_{MSY} and F_{max}	As F_{med}, F_{MSY} and F_{max}	1,
F*			
F>=M	Empirical (for top predators)	Natural mortality and sustainable fishing mortalities for similar resources	1,
F<M	Empirical (for small pelagics)	Natural mortality and sustainable fishing mortalities for similar resources	1, Patterson, 1992; Thompson, 1993
Z_{mbp}	Level of total mortality at which maximum biological production is obtained from the stock	Annual data series of standard catch rate and total mortality	1,
[2]B_{MSY}	Biomass (SSB) corresponding to maximum sustainable yield from an age structured assessment	Stock weight at age, catch weight at age, natural mortality, exploitation pattern, maturity at age, stock recruitment relationship	1,
[2]B_{MSY}	Biomass (SSB) corresponding to maximum sustainable yield from a production model	Total catch and CPUE (or effort series)	1,

Table 1 continued. Some commonly used reference points

Reference point	Definition	Data needs	References
[2]MBAL	A value of SSB below which the probability of reduced recruitment increases	SSB and recruitment series	1,
[2]$B_{50\%R}$	The level of spawning stock at which recruitment is half the maximum of the underlying stock recruitment relationship	Stock recruitment relationship	1,

[2]$B_{90\%R90\%Surv}$	Level of SSB corresponding to the intersection of the 90th percentile of observed survival rate and the 90th percentile of recruitment observations	SSB and recruitment series	[1],
[2]$B_{20\%B\text{-}virg}$	SSB corresponding to a fraction of the unexploited biomass. Estimated as the point where the replacement line F=0intersects the stock recruitment relationship, or as the biomass from an SPR curve when F=0 and average recruitment is assuemed	Stock recruitment relationship or stock weight at age, natural mortality, exploitation pattern, maturity at age, recruitment series	[1],
[2]B_{loss}	Lowest observed spawning stock biomass	SSB series	[1],
R_{med}	50th percentile of recruitment	Recruitment series	
Virgin SPR	The level of SPR at F=0	Stock weight at age, natural mortality, exploitation pattern, maturity at age	
G_{loss} or SPR_{loss}	The inverse of the R/SSB at the lowest observed SSB when a (loess or lowess) smoother has been fitted to the SSB and recruit data i.e. G_{loss}	SSB and recruitment series	Cook, 1998a.
S*	The SSB at which recruitment starts to decline as estimated using a two line stock recruitment model	SSB and recruitment series	O'Brien & Maxwell, 2002; ICES, 2002.
Z*	Total mortality permitting a 50% chance of spawning at least once in the life history	Total mortality, von Bertalanffy growth parameters, maturity at size	Die & Caddy, 1997; Caddy, 1998a

[1]as described in ICES, 1997; 2001

[2]ICES (1997) listed the precautionary approach usage of these reference points as 'limit', but noted that not all reference points are intrinsically equal, and their interpretation is case specific. For example, F_{max} can be considered as a target, when it is well defined and corresponds to a sustainable fishing mortality, but it would be a limit if it is ill defined and/or corresponds to unsustainable fishing mortality. Similarly F_{MSY} is suggested as the minimal international standard for limit reference points in the UN agreement on straddling fish stocks and highly migratory fish stocks, but could in some particular cases be considered a target. In contrast, F_{crash} represents a level of fishing mortality at which the probability of stock collapse is high. The probability of F exceeding F_{crash} should therefore always be very low.

2.1 Reference points based on yields

Data on landings are the most readily available source of information for most fisheries and although more likely to reflect exploitation levels that inform on stock dynamics, under certain circumstances, past yields can provide an indication of future potential and there are examples of yield based reference points currently in use in fisheries management. These tend to be in developing fisheries or where there is a long history of exploitation, considered to represent close to maximal yields, that continues to the present time (i.e. there is no evidence of decline). Annala (1993) proposed 3 yield based reference points that could be established by simulation.

- Maximum Constant Yield (MCY), the maximum constant catch estimated to be sustainable and considered relatively conservative,
- Current Annual Yield (CAY), the catch corresponding to a constant F regime with an acceptable risk level and
- Maximum Average Yield (MAY), the average of historical CAYs, which is considered close to maximum sustainable yield (MSY) (Caddy, 1999b).

ICES has on occasion used recent average yields to advise on TACs for *Nephrops*, for example for the Porcupine Bank stock, where in the absence of exploitation boundaries for the stock and in view of the relative stability of landings it was advised that landings for fisheries units 16 to 19 should not exceed the average landings of 2000-2002 (ICES, 2006). Implicitly this yield was considered sustainable.

2.2 Direct estimates, distributional measures and trajectories of historic data

2.2.1 Direct estimates

Some molluscan species such as cockles occur in well-defined beds that can be directly surveyed to provide absolute estimates of biomass. Cockles can be aged by interpretation of external shell rings. Relatively precise age structured statistics relating to both stock size and landings permit the use of limit reference points based on minimum absolute levels of biomass (both current and medium tem), as well as proportions of adults with additional reference levels for the proportion of cockles damaged by dredging (EJSFC, 2008). Cockle fisheries are often managed on the basis of harvesting a constant proportion. Bell *et al*. (2001) modelled predation of cockles by birds and found that fishing did not appear to increase overall cockle mortality provided no more than 30%-40% of the overall abundance was removed. A 33.3% harvest ratio has been used as a target reference point for a number of cockle fisheries and was empirically decided upon on the basis of F_{max} for a range of fish stocks (*pers. comm.* C. Bannister).

Mussels have similar beds and are also frequently surveyed to provide direct estimates of biomass. Similar limit reference points have been derived including: minimum stock levels current year and 6 year average, minimum proportion of adults on the bed, minimum absolute stock density after which dredging must cease. Target reference points are frequently expressed as harvest ratios, typically in the region of 20% of the targeted stock biomass (i.e. adults or juveniles for relaying).

2.2.2 Distributional measures

Averages of historical data are frequently used, both formally and informally, to provide a longer term benchmark against which current performance can be assessed. For example, ICES (2001a) concluded that the northeast Arctic shrimp stock was “probably within safe biological limits” because “surveys indicate that the biomass is close to the 1985–2000 average”. The 1985–2000 average biomass index is implicitly used as a target reference point.

Prager (1994) noted the advantages of normalising time series or expressing current values relative to some reference level and therefore in a dimensionless form. Although frequently used for this purpose, caution should be used when standardising data against extreme values as they are often poorly estimated (Caddy, 2004). It may also be necessary to take some account of the type of distribution of the variable, for example, the geometric mean is frequently used as a measure of average recruitment, reflecting the tendency for recruitment data to be log normally distributed. The median may be used where a non-parametric central estimate is required, and percentiles can be used to provide more peripheral estimates of historic distributions. One peripheral reference point is B_{loss}, the lowest observed spawning stock biomass, which has been widely used by ICES as a limit reference point in the absence of evidence for any decline in stock in the historic trajectory of SSB.

A problem with using these measures based on historic series is that they reflect the exploitation history rather than informing on some aspect of the stock and fishery dynamics. The time series of data must be reasonably long and accompanying caveats such as no evidence for stock decline are very important. Even so there is a risk that historic measure may be biased if exploitation continues over a long time at some sub-optimal level. There is the risk that there may be a gradual decline in the variable through time, but this may be masked to some degree by noise, and the reference point will creep down as the stock declines.

2.2.3 Trajectories

Taking the trajectory of historic data into account can add value to the perception of stock status, one application of which is the use of phase plots of SSB against F, commonly produced as part of ICES advice. Azevedo *et al*. (2003) carried out a visual inspection of plots of R-SSB and F-SSB data for 66 ICES stocks (excluding *Nephrops*) and categorised 4 types of trajectory for F on SSB;

- 1-declining SSB with increasing F,
- 2a- narrow F range and wide SSB range,
- 2b- wide F range and narrow SSB range,
- 3-undefined or random.

They suggested that 42% were in category 3 and concluded that for both SSB-R and F-SSB plots, historical evidence per se is not enough to arrive at PA reference points because other important factors such as changes in exploitation pattern or stock productivity need to be taken into account. However, simulation work carried out for the ICES Comprehensive Fishery Evaluation Working Group (Kell *et al*. 1997; ICES, 1997) showed that stock trajectories managed within a biomass and fishing mortality limit based framework often followed a cyclic or spiral course due to assessment errors. This was even the case when given perfect data because of the time lag between assessment and management implementation. Cyclic plots are often observed in historic stock and fishing mortality trajectories and may obscure a simple relationship between SSB and F. There must always be some doubt regarding any lag in time scales that might be used to synchronise the two time series, since SSB is an aggregate metric consisting of components, which have been subjected to variable times of exploitation and are not the result of any one year's exploitation. Generally, no shift in time indices is applied to these data, but implicit in consideration of the trajectory, the relative position of subsequent SSB is considered in response to a given F level.

Under the assumption that there may be some tendency for the trajectory to cycle clockwise and that stocks rebuild at low Fs and decline during periods of high F, such phase plots can inform on the levels of F likely to crash the stock (F_{crash}). A proxy for F_{crash} is likely to be found on the right of the plot, where the stocks tend to be declining, whilst fishing mortalities leading to rebuilding are on the left of the plot. Smith *et al*. (2003) compared this approach with other methods of reference points for *Nephrops* stocks with contrasting exploitation histories (Figure 1). These plots do provide evidence for declining mature male biomass at Fs of 0.7-0.8 (Farn Deeps and Biscay) and 0.7-1.0 (N. Galicia) and similar declining female SSB at Fs of 0.6

(Biscay) and 0.25 (N. Galicia) with the Farn Deeps females less convincing, but possible around 0.15. Female *Nephrops* tend to have lower levels of exploitation, especially in winter fisheries, as they tend to be ovigerous at this time of year and spend more time in their burrows. This probably explains the generally lower Fs for females, least noticeable in Biscay, a predominantly summer fishery and most marked in the Farn Deeps, a winter fishery. These visual estimates of F_{lim} were generally similar to, and relatively central amongst, a variety of alternative analytical reference points for the same stock and sex categories (Table 2).

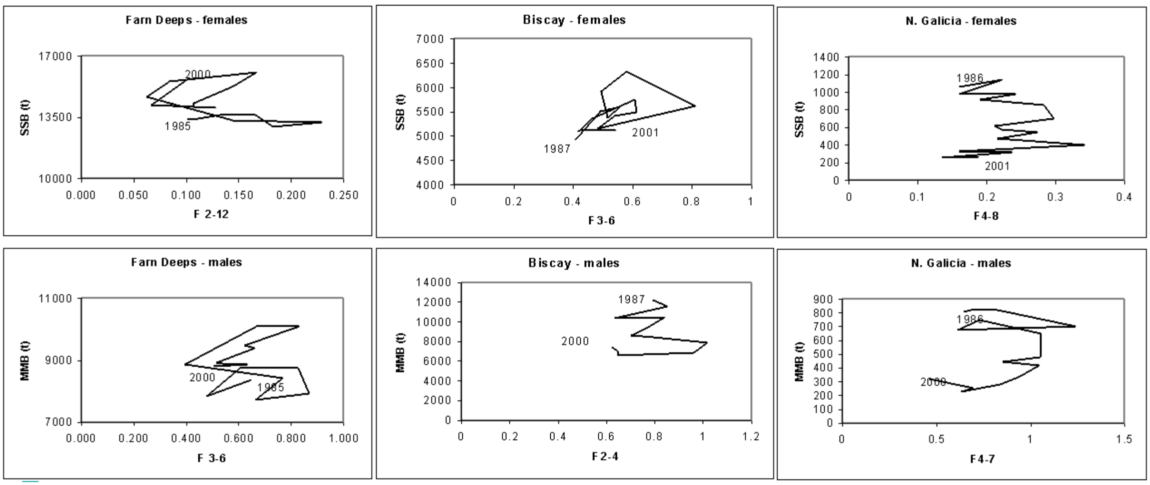


Figure 1. Phase plots of SSB against F for a selection of Nephrops stocks

Table 2. Comparison of visually estimated F limits from SSB on F phase plots with analytical F reference points

Reference point	**Farn Deeps females**	**Farn Deeps males**	**Biscay females**	**Biscay males**	**N. Galicia females**	**N. Galicia males**
$F_{\text{Decline phaseplot}}$	0.15	0.7	0.6	0.7	0.16	0.7
F_{loss}	0.2	0.79	0.74	0.75	0	0.48
$F_{\text{crash twoline}}$	0.16	0.77	0.62	0.63	0.04	0.44
F_{high}	0.21	0.87	0.74	0.78	0.11	0.87
F_{med}	0.14	0.67	0.53	0.6	0.04	0.42

For many shellfish stocks, time series of analytical estimates of SSB and fishing mortality may not available, but there may be potential in using CPUE and fishing effort series, as proxies, in a similar manner (see section 2.3).

2.3 Proxies and empirical reference points

2.3.1 Proxies

Caddy (1999b) highlights the problem faced by NAFO in 1998, that neither age structured data or stock and recruitment data were available for many of their important fisheries, in particular those targeting cepalopods or crustaceans. In these cases it may be necessary to seek less rigorous analytical approaches to setting reference points. Although this may seem less satisfactory there may ultimately be benefits as if the reference points and management system are simple and transparent, buy-in from Industry and management may be achieved more readily. Reference points in this instance could reflect some particular feature in the time series of data such as high (as target) or low (as limit) points in some time series. The reference point B_{loss} mentioned earlier is an example of a limit reference point based on the historic distribution of data. In some instances it may be preferable to consider stock status relative to a particular year, rather than express it in absolute terms. This is particularly the case where trends can be ascertained, but the absolute level cannot be estimated consistently and may vary between annual assessment updates.

Tully *et al*. (2006) listed the following stock indicators and reference points and their relevance in their lobster stock assessments:

- Annual landings - reflecting the overall level of fishing activity relative to the past,
- Standardised catch rates of legal lobsters - as an index of the abundance of legal sized lobsters in the stock,
- Standardised catch rates of pre-recruit lobsters – as an indication of recent recruitment to the stock and the likely strength of the fishery in the near future,
- Mean size of lobsters in the landings – as an indication of stock size structure, dependent upon other information. For example, reduced mean size may indicate fewer large lobsters or more smaller lobsters in the fishery dependent on the two indices above. However, as a central statistic, mean size may not necessarily be very responsive,
- Proportion of lobsters > 120 mm CL - reflects previous recruitment and fishing mortality rates and is a useful indicator of egg production because these lobsters are proportionally of higher reproductive value,
- The proportion of the female stock that is v-notched - indicates the proportion of the population receiving protection and can provide information on the level of exploitation over the season
- Annual estimates of fishing mortality - provide an indication of the level of exploitation and can be used to estimate per recruit reference points.

An assessment of lobsters in the Bay of Fundy used the following indices: landings, Autumn catch rates based on sampling at sea, exploitation level based on Length Cohort Analysis (LCA), production indicators (pre-recruit and ovigerous female proportions from sampling at sea, ovigerous female proportion and settlement index from dive surveys). However, the relationship between increased effective effort and landings trends was highlighted as a source of uncertainty. Recommendations for future indicators included: comparing fishery dependent abundance indicators with changes in effort, developing fishery independent indicators for legal sizes (by moult class), ovigerous females and pre-recruits, developing fishing pressure indicators such as trap-hauls, fishing location, vessel size, navigation, trap design and fishing strategy and expanding the coverage of surveys for lobster settlement (DFO, 2007a).

Catch rate is very widely used as a proxy for biomass and also frequently used to 'tune' stock assessments. Survey catch rates can be used as indices of relative stock size and demographic metrics such as abundance of young or females (Cadrin *et al*., 2004). For commercial catch rates, it may be preferable to standardize catch rates by, for example, species, area, season vessel size, gear type… (e.g. Hvingel *et al*. 2000). Breen *et al*. (2003) noted four ways in which CPUE based abundance indices were used in control rules in their study of New Zealand rock lobster fisheries:

- observed CPUE can be compared with a target level,
- the rate of change in observed CPUE can be calculated over 2 or more years,
- observed CPUE is used with an assumed *q* to estimate biomass for use in the rule,
- from two or more years of catch and estimated biomass, current surplus production can be estimated.

As noted in section 2.2, catch rate could be used in phase plots, as a proxy for stock abundance, with total effort data, representing the level of exploitation, to empirically identify ranges of effort associated with stock increases or declines. Cadrin *et al.* (2004) also note the use of effort data to derive relative exploitation rate. Our initial experiences with this approach have had mixed results, with a variety of different forms of trajectory, sometimes dependent on area or possibly the shape of the effort trajectory, but this could reflect the relatively poor quality of the total effort time series data, the tendency for fishers to alter behaviour to maintain catch rate and difficulties in identifying and separating effort targeted primarily at either edible crabs, or alternatively lobsters. One technical problem with historical proxies is the comparability of historic estimates to current estimates (Cadrin *et al*., 2004), as substantial changes in fishing gear, fishing areas and environmental conditions may have occurred over time making comparisons among periods difficult. However, this criticism could also be levelled at least to some extent with regards to time series of stock recruit data that are used in more sophisticated analyses.

Rago's replacement ratio (NEFSC, 2002) provides an objective approach to determining a sustainable exploitation rate, by deriving the relative exploitation rate that permits the population to replace itself. Data requirements are modest consisting of total catch and survey or fishery catch rates.

2.3.2 Empirical reference points

The empirical reference points $F>=M$ for large predators and $F<M$ for small pelagics have been suggested (ICES, 1997; 2001). Typically, large predators have low natural mortality, high longevity and are often highly fecund, whereas small pelagics tend to have higher natural mortality, lower longevity and lower fecundity. However, such reference points may be relatively imprecise, as reliable and precise estimation of M remains a problem for many species. They may thus lack the resolution needed for detailed management actions. Mace's (1994) comparative per recruit analyses found that $F=M$ was of similar magnitude to $F_{0.1}$ and $F_{35\%SPR}$. $F=M$ was sustainable for τ up to 0.3, 0.38 and 0.43 for increasing K parameters, but was greater than F_{MSY} for $\tau <$ 0.05 to 0.16, depending on K. The parameter τ (the inverse of slope at the origin of a stock recruitment relationship) provides an indication of stock resilience, which decreases with increasing τ . Other authors have suggested lower proportions of M for data poor situations, for example $F=0.8M$ (Thompson, 1993).

A number of relatively simple reference points have been proposed that take account of mortality rates in conjunction with growth and maturity schedules. These include Z* which seeks to ensure conditions that permit a 50% chance of spawning at least once in the life history (Die & Caddy, 1997; Caddy, 1998a; 1998b).

$$Z^*<K(L_{inf}-L_m)/(L_m-L_c)$$

Where Z is total mortality, K and L_{inf} are von Bertalanffy growth parameters, L_c is length at first capture and L_m length at maturity. Other authors (e.g. Tremblay & Lanteigne, 2003) have also supported the use of simple measures such as size at capture relative to size at maturity as simple reference points that could be emphasised in scientific advice to managers and the industry.

Gulland (1971) suggested that B_{MSY} might be approximated by $0.5B_0$, where B_0 is unexploited biomass. Cadima generalised Gulland's formula to MSY= 0.5ZB, where B is average annual biomass (Troadec, 1977). Although Gulland's formula has been widely used it has been criticised by a number of workers (e.g. Caddy & Csirke, 1983; Beddington & Cooke, 1983), who have concluded that it over-estimates MSY by a factor of 2 to 3 and hence $0.2B_0$ might be more appropriate (Sparre *et al*., 1989). Caddy (1999a) suggests $B_{MSY}= xB_0$, where x is significantly lower than 0.5 and draws attention to Patterson's (1992) observations that low values of x are more precautionary for small pelagics (and other stocks) with high natural mortality rates.

Rivard (1998) described an overall index of stock status and fishery performance based on the outputs of stock assessments (recruitment, biomass spawning biomass, fishing mortality, catch, catch rates and fish condition) where each indicator was scored according to whether it was 'much worse than average', 'worse than average', 'better than average', or 'much better than average' and the subsequent scores are averaged. The index performed well when the measurements for its calculation were consistent, but may not be adequate when they are divergent, as it then tends to concentrate into the middle categories of the classification. This approach has similarities to a simple version of the stock status evaluation part of a traffic light system.

Kelly & Codling (2006) suggest that a move away from reference points based on very intensive data collection and analysis is required, particularly in the context of ecosystem management, where such approaches would be prohibitive. They note that the simplest approaches to interpret indicators, such as 'eyeballing' should not be dismissed out of hand, despite the fact that they are not transparent, while more complex methods such as CUSUM (Scandol, 2005) may also provide a means to analyse indicator information.

2.4 Reference points from production models

Production models model biomass simplistically as a function that combines life processes (recruitment, growth and natural mortality) and takes no account of population age or size structure. The biomass model is linked to the exploitation history of the fishery by an abundance index, often catch per unit effort (CPUE), assumed proportional to biomass, although fishery-independent indices may be used. Two reference points, F_{MSY} and F_{crash} (the fishing mortality that will drive the stock to extinction) are frequently derived, and although possessing the same names as those derived from age structured data and stock recruit data, the reference points estimated using production models are different from those calculated using structural methods.

The Schaefer (1954; 1957) production model produces a symmetrical domed curve for the relationship between biomass and F and $F_{MSY} = 0.5F_{crash}$, while the exponential decline of the Fox (1970) model does not produce an estimate of F_{crash}, and the relationship between F_{MSY} and F_{crash} is variable for models with a shape parameter (e.g. Pella & Tomlinson, 1969).

Prager *et al.* (2003) formulated indicators and RPs as ratios, which express the current position of biomass or fishing mortality relative to an indicator value that corresponds to optima or maxima (such as the MSY, F_{MSY}, or B_{MSY}). This removes the need to specify *q*, the catchability coefficient, which is often difficult to estimate, and the problem of scaling is also reduced.

The reference point maximum biological production based on consideration of production against total mortality, rather than fishing mortality (Caddy & Csirke, 1983) provides an indication of conditions that maximise stock productivity and was considered precautionary by Die and Caddy (1997). With some knowledge or assumptions regarding the rate of natural mortality the F corresponding to MBP can be estimated from F_{MSY} (Caddy, 1998b).

$F_{MBP} = F_{MSY} – 0.5M$

2.5 Yield, spawner and egg per recruit (YPR, SPR and EPR)

2.5.1 Yield per recruit

Yield per recruit analysis (Beverton & Holt, 1957) considers the processes of growth, natural mortality and fishing mortality on a single (or cohort of) fish that has already been recruited. This removes uncertainty associated with estimating and predicting recruitment and permits the implications of changes to the level and pattern of fishing mortality to be evaluated. The method can be carried out by integration, but the way in which the mortality coefficients are varied must be kept simple if integration is not to become complex. Removing constants allows the integral to be simplified into terms representing exploitation rate (F/Z), relative size at first capture (l_c/L_∞) and the ratio of natural mortality to the von Bertalanffy growth rate parameter K (M/K). Beverton and Holt (1959) published yield tables for a series of values of M/K in the range 0.25-5.0. Modern computing methods allow numerical integration to be carried out by considering short time periods separately and this provides greater flexibility, permitting season, spatial or fleet based effects to be evaluated (Gulland, 1983). Yield is usually expressed in weight, but value by age (or size) can be included if this information is available.

Two reference points are commonly derived from yield per recruit analysis; F_{max}, the fishing mortality level at which YPR is maximised and the more conservative $F_{0.1}$, originally proposed as an economic consideration, the fishing mortality at which the slope of the YPR curve is 10% of its slope at the origin (Gulland & Boerema, 1973), or the more cautious $F_{0.2}$ (Butterworth *et al*, 1997). Yield per recruit is also commonly used to evaluate the potential effects of changes in exploitation pattern.

Yield per recruit is not related to the renewable characteristics of the population, but refers only to the processes of growth and mortality (natural and fishing) within a cohort. Theoretically, yield per recruit will peak if an infinite fishing mortality is applied at the moment that the biomass of the cohort is at a maximum. However, if that maximum occurs before the age (size) of first maturity and the cohort is instantly fished to extinction, then the population will not be able to replace itself (Pereiro, 1992). This highlights the fact that YPR provides a means to evaluate fishery output, rather than providing a conservation reference, and therefore provides a measure of potential growth over-fishing.

2.5.2 *Spawner and egg per recruit*

By including maturity data and fecundity data in the per recruit projections it is possible to calculate the spawner (SSB) and total numbers of eggs produced by each recruit. Calculated over a range of F multipliers this produces a smoothly declining concave curve. Virgin or pristine SPR (or EPR; E/R) is the level of SSB (or number of eggs) per recruit corresponding to no exploitation and provides a reference point against which levels of SPR and corresponding fishing mortalities can be gauged, i.e. percent (of virgin) SPR or EPR (sometimes referred to as relative egg per recruit, $R_{E/R}$, e.g. Tully *et al*., 2006).

2.5.3 *Providing a conservation context for per recruit reference points*

As with YPR, SPR and EPR do not take account of changes in recruitment to the population, but some authors (Cadima & Azevedo, 1998, Clark, 1991; Goodyear, 1990; 1993; Mace, 1991; 1994, Mace & Sissenwine, 1993) have carried out analyses to evaluate how these families of reference points perform for a range of combinations of life history characteristics. These authors analysed stock recruitment relationships for a wide range and fish stocks in order to capture information on their resilience provided by the slope at the origin of the stock recruitment relationship. They then examined how YPR, SPR and EPR reference points performed for stock recruitment relationships with a range of slopes at the origin. These analyses provide a basis for using the per recruit family of reference points to inform on sustainability.

Median survival ratios were calculated for 83 sets of stock recruit observations from exploited fish stocks (Mace, 1991, Mace & Sissenwine, 1993). The overall average τ (the inverse of slope at the origin of a stock recruitment relationship) was 0.19 and the 80^{th} percentile 0.3. τ =0.2 was recommended as a default overfishing threshold for stocks believed to have at least average resilience and 0.3 for stocks with poor knowledge. Clark (1991) rejected τ =0.5 as too high for any fish stock, because the stock would be driven to extinction by a fishing mortality rate less that M. The highest τ at which F=M was sustained in Mace's analyses was in the range 0.3-0.43. Most fish stocks that have sustained fisheries for long periods of time have also sustained fishing mortality rates in excess of M. Clark (1991) suggested τ =0.06 as a lower bound on the basis that for this level of τ, fishing mortalities in excess of 1.0 produced hardly any ill effect, however, 11% of cases examined by Mace (1991) and Mace & Sissenwine (1993) had 10 year average Fs in excess of 1.0. Mace (1994) concluded that there was no basis to reject τ in the range of 0.05-0.35.

Mace (1994) evaluated constant fishing strategies with the aim of achieving a long-term yield approximating MSY, while at the same time staying 'far away' from F_{crash}. She varied the growth rate (K), natural mortality (M) and the inverse of slope at the origin (τ) of a Beverton & Holt stock recruitment curve from 0.05 to 0.5, to simulate stocks ranging from highly resilient (survival at low biomass 20 times the virgin rate) to having very low compensation (survival at low biomass twice the virgin rate). The YPR and SPR reference points were not influenced by τ, but all increased with both M and K. For each M-K combination $F_{0.1}$, $F_{35\%SPR}$ and F=M were of similar magnitude. F_{max} may approach infinity and therefore is not a generally useful conservation standard (Goodyear, 1993). F_{max} was undefined for five of the nine M-K combinations analysed by Mace (1994) and for it to be sustainable, τ needed to be less that 0.15-0.25, depending on the parameter combination considered. F_{max} is always above F_{MSY} for a Beverton and Holt SRR, as was the case for a Ricker relationship with $\tau >= 0.1$. $F_{0.1}$ was sustainable for all parameters combinations with τ less than around 0.4, and was identical to F_{MSY} for $\tau = 0.1$, less than F_{MSY} for $\tau < 0.1$, and greater than F_{MSY} for $\tau > 0.1$. $F_{0.1}$ is always less than infinity and has been widely adopted a goal for fishery conservation, but because it is dependent on size at selection and not related to the spawning potential of the stock it is not well suited to the management of stocks exposed to competing fisheries with different selection and objectives (Goodyear, 1993).

B_{MSY} (B was always equal to SSB in this analysis, because identical knife edged recruitment and maturity schedules were used) was never less than 20%B_0 (a commonly suggested threshold (e.g. Beddington & Cooke, 1983), although it did approach it closely with the highest combination of growth, natural mortality and τ parameters. By contrast B_{max} was almost always less 20% B_0. Mace recommended that $F_{40\%SPR}$ be adopted as a target fishing mortality rate when the stock recruitment relationship is unknown.

Clark's (1991) calculations used a range of life history parameter values typical of demersal fish and showed that, regardless of the form of the stock recruitment relationship, yield was at least 75% of maximum sustainable yield if the SSB was maintained in the range of about 20–60% of the unfished level. This can be achieved by choosing a fishing mortality rate that will reduce the SPR to about 35% of the unfished level. This level of fishing mortality maximised the minimum yield among all of the stock recruit relationships considered ("maximin yield" rate, F_{mmy}) and was close to $F_{0.1}$ except where recruitment and maturity schedules did not coincide (Clark, 1991). Goodyear (1993) concurred with this view suggesting that Clark had selected reasonable slopes for his stock recruitment relationships.

Cadima and Azevedo (1998) analysed target, limit and PA reference points for 30 ICES stocks in terms of their percentages of virgin SSB and SPR. They found that the per recruit (long term target) reference points ($F_{0.1}$, F_{max} and $F_{30\%SPR}$) had average %SPR in the range 23%-41% and average %SSB between 47% and 67%. The family of limit reference points, F_{crash} and its proxies (F_{high}, F_{loss}, $F_{Butt} \approx F^*$) has %SPR of 6%-14%, and %SSB of 0-30%. A third group (F_{MSY} and F_{med}) had average %SPR around 18% and %SSB of 35%-38%. They suggested that levels of 20%-40% of virgin SPR and 50%-70% of virgin SSB could provide potential target reference points.

2.5.4 Application of per recruit reference points

Bunnell & Miller (2005) used an individual based per recruit model to estimate biological reference points for blue crab. This permitted the inclusion in the model of individual variation in size and growth, discontinuous growth and catchability dependent on sex, size, shell state and maturity. Natural mortality (M) was varied between 0.375-1.2 and the exploitation fraction (μ) and fishing mortality (F) that protected 20% of the unexploited spawning potential were determined. Both $\mu_{20\%}$ and $F_{20\%}$ decreased with increasing M. They concluded that commercial fishing had likely contributed to stock decline as field based estimates of μ in 64% of years were higher than $\mu_{20\%}$, assuming M=0.9.

This approach has also been applied to abalone, where it has been suggested that rates of fishing that do not reduce spawning potential below 50% of unfished levels ($F_{50\%}$) were appropriate for small stocks, while $F_{40\%}$ was considered sufficient for large stocks (Shepherd & Baker, 1998). Simulations carried out for *Haliotis rubra* suggested that stock recovery could not be assured if population fecundity was reduced below 30% of its virgin level (Sanders & Beinssen, 1998).

Caddy & Agnew (2004) note that precautionary levels of stock size for short-lived invertebrates such as cephalopods, shrimps, king crabs and abalone may be similar to those for pelagic stocks, that is spawning potential should not be allowed to drop below 30-60% of virgin stock size. Although minimum spawning stock sizes for lobsters and 'small' crabs appear to have been maintained at levels of the order of 10% virgin SPR, they suggest that for precautionary considerations, perhaps these should also be kept above 30% virgin SPR.

In the US biological reference points for scallops mandated under the Sustainable Fisheries Act have been based on F_{max} and with an SSB target based on the associated SPR for this level of fishing mortality multiplied by median recruitment (Smith & Rago, 2004).

Tully *et al.* (2006) note that the limit for $R_{E/R}$ (% virgin EPR) in the American lobster, where recruitment is strong, is 10% and they proposed this level as a limit for Irish stocks, with a target of 25%. DFO (2007a) report that in the Bay of Fundy lobster fishery the percentage of virgin EPR was as low as 1%-2% around 1995 and a precautionary target level of 5% was proposed, but after consultation it was decided instead to double %EPR. Fogarty & Gendron (2004) confirm the 10%EPR limit has been adopted in the United States and that Canada has a policy of doubling EPR relative to 1995 levels. Both countries calculate EPR using extensions to the Fogarty & Idoine (1998) model.

2.6 Spawner per recruit combined with stock and recruitment data

Where a time series of stock and recruitment data are available, the inverse of ratios of recruitment/SSB (survival ratios) can be combined with SPR functions to provide corresponding estimates of fishing mortality. This has lead to the F_{high}, F_{med} and F_{low} family of reference points, based on the 90^{th}, 50^{th} and 10^{th} percentiles of R/SSB respectively. Shepherd (1982) proposed using the 90^{th} percentile of SR points as a proxy for the slope at the origin, effectively suggesting F_{high} as a proxy for F_{crash}. However, Sissenwine and Shepherd (1987) pointed out that SR points in the upper 10^{th} percentile may reflect anomalously good conditions rather that the ability of the stock to sustain itself under average conditions and proposed the median (corresponding to $F_{med} = F_{crash}$) as a safer option. Mace (1994) notes that this is likely to be biased due to compensation or depensation unless restricted to low stock sizes. Cadima and Azevedo's (1998) analyses grouped F_{med} with F_{MSY} and found that average percentages of virgin SPR and SSB, respectively, for this group were around

18% and 35%-38%, while the corresponding values for a group consisting of F_{crash}, F_{high}, F_{loss}, $F_{Butt} \approx F^*$ were 6%-14% and 0%-30%.

2.7 Spawner per recruit combined with stock recruitment relationships

Combining stock recruitment relationships (SRRs) with spawner per recruit functions permits the calculation of equilibrium yield and biomass curves and allows the reference points F_{crash}, the fishing mortality corresponding to the slope at the origin of the SRR and with an equilibrium biomass of zero and F_{MSY}, the fishing mortality at which yield is maximised and its corresponding biomass, B_{MSY}, to be calculated from age structured data (Shepherd, 1982).

These reference points will vary according to the functional from of the stock recruitment relationship used and some authors (e.g. Kell et al., 2005a) have also included a subscript (e.g. $F_{MSYRicker}$) to specify the SRR (e.g. Ricker, 1954; Beverton & Holt, 1957) used.

Mace's (1994) analyses found that F_{MSY} was always less than 47% of F_{crash} and she therefore concluded that it can be considered 'safe'. However, although the corresponding equilibrium biomass, B_{MSY}, did not fall below the commonly used 20% B_0 threshold it did closely approach this value. Therefore if there is reason to believe stock productivity would be negatively impacted at levels of biomass in the vicinity of 20% then F_{MSY} will not necessarily be safe. F_{MSY} and F_{crash} both decreased with increasing τ (decreasing stock resilience) and increased with K and M. They were most sensitive to τ followed by M and then K. F_{MSY} was usually well below (16.4% to 43%) $F_{crash.}$ F=M was sustainable for τ up to 0.3, 0.38 and 0.43 for increasing K parameters and was greater than F_{MSY} for $\tau < 0.05$ to 0.16 depending on K, implying that F_{MSY} is lower than natural mortality for these parameter values.

As well as the traditional parametric models some other proxies for stock recruit models have received widespread use within ICES. The two-line (sometimes known as Ockham's razor, Butterworth & Bergh or hockey stick) consisting of a horizontal line above a change-point and a linear decline to the origin below it has been used to estimate S*, the SSB at which recruitment declines (O'Brien & Maxwell, 2002).

Cook (1998a) introduced the reference points G_{loss} and F_{loss}, where G_{loss} is the inverse of the ratio of recruitment to SSB at the lowest observed spawning stock as estimated by a relatively 'stiff' loess smoother that provides a non-parametric proxy for a stock recruitment relationship. F_{loss} therefore provides a non-parametric estimate of F_{crash}. Equilibrium curves calculated from the latter two types of proxies may have sudden inflexions reflecting the inflections in the underlying SRRs.

2.8 Spatially or temporally defined reference points

The majority of formal reference points are expressed in terms of biomass (or SSB) and fishing mortality (or sometimes total mortality), but for many data poor species (including many shellfish species) these metrics may be difficult to estimate and where migration and/or mixing occur, stock units may be poorly understood.

A simple index of aggregation, I_g (Gulland, 1955) has been suggested as potentially useful for mobile populations by Caddy (1999b), who also notes the potential utility of metrics such as the proportion of fishing grounds (seasons) closed as a reference point. Where the population is heterogeneously distributed in time or space (i.e. dynamic pool assumptions do not apply) then the effects of spatial (or temporal) structure need to be taken into account.

Indicators reflecting potential production per habitat area are important for invertebrates where populations are often highly spatially structured. Stock density may be critical, or at least highly influential for successful egg fertilisation in some sedentary species (McGarvey *et al.*, 1992; Botsford *et al*., 1993: Brandt *et al*., 1991) and reference points framed in terms of a minimum stock density (or catch rate) on at least some part of the stock distribution, and preferably one that acts as a source of production to other areas, may be appropriate (Caddy, 2004). Rotational closures, where a different (constant) proportion of the productive grounds are closed in consecutive years, have been suggested as an appropriate management measure for territorial and sedentary resources and implicitly account for spatially variations in density. Assuming knowledge is available regarding the extent of the productive grounds and those being fished, reference points for such systems could be the proportion of the total exploitable grounds receiving protection in any one year. Such reference points could be evaluated and set on the basis of simulation. Optimum rotation cycle, based primarily on maximum yield, for a patchy non-migratory resource varied according growth and mortality rates, but rotation cycles incorporating closures in excess of 6 years were found to be sub-optimal for very patchy recruit distributions (Caddy & Seijo, 1998). However, a major disadvantage of rotational closures, particularly where the fishing gear is destructive, is that they tend to distribute fishing effort widely throughout the area. By contrast fixed closures can be targeted to protect areas of particular value such as those with high biodiversity or where significant and successful spawning takes place. However, even in these cases wider ecosystem effects need to be considered. For example, closed areas imposed as a conservation measure for North Sea cod recovery meant that trawling effort was displaced to areas that previously had been relatively undisturbed (CEC 2007). Smith & Rago (2004) found that concentrating scallop fishing in areas of lower productivity may be an effective tool for reducing recruitment variation and improving yields.

For relatively sedentary populations that may exist as metapopulations, where the population consists of local sub-populations (e.g. beds), that may have different biological (e.g. growth and recruitment) and fishery characteristics, within a more widespread stock area, the concept of source and sink becomes important. If these two groups can be identified then sink areas should be harvested to optimise yields on the basis of the likely frequency of subsequent recruitment from a source area. By contrast source areas will need to be well protected and it may be that increasing density in these areas would increase exported productivity to other areas. In reality the situation is unlikely to be clear-cut in terms of source and sink. A knowledge of hydrodynamics and larval and settlement processes provides the background to assess the potential for reproductive import and export. Caddy (2004) suggests that regularly mapping recruitment areas may be useful for identifying source areas and an even distribution of age classes may also be indicative of source populations.

Littoral stocks of mussels are managed with reference points based on estimates absolute biomass, but sub-littoral mussel seed beds exploited for relaying have reference levels set in terms of area. High levels of extraction are permitted with a quota of 80% of the identified area in the Wash, because these beds are frequently lost due to physical scouring and predation. However, leaving a proportion of mussels in the settlement area is considered important as a source of food for natural predators such as eider ducks, crabs and starfish (EJSFC, 2008).

For migratory species such as yellowfin tuna, a 'Gauntlet model' approach that considers sequential risks (spatially and/or temporally differentiated) to determine acceptable levels of survival to maturity may be more relevant (Kleiber, 1996). Macrocrustaceans that undertake extensive systematic movements may also suffer from serial depletion in some cases (Oransanz *et al*., 1998). Survey based indicators providing information on the proportion of the stock area containing densities above some minimum value have been suggested (Caddy 2004). Identifying and protecting critical steps or habitats in the lifecycle can also give rise to reference points based on providing a given level of protection to this particular aspect. Indicators for monitoring nursery areas have been described for American lobster (Wahle & Steneck, 1991) and *Panulirus* (Acosta & Butler 1997), while egg brooding areas for cancrid crabs (Scheding *et al*. 2001) and nesting sites for *Octopus* have also been suggested.

2.9 Multispecies considerations and environmental effects

2.9.1 Multispecies considerations

Predator prey effects (Pauly *et al.,* 2001) have been suggested for a number of invertebrate fisheries; sea otter and abalone (Tegner, 1989); sparids and *Octopus* (Caddy and Rodhouse, 1998); grouper and *Octopus* sp. (Arreguin-Sanchez, 2000); gadoids and *Nephrops* (Brander and Bennett, 1989); cod and *Pandalus* (Stefanson *et al*., 1994); gadoids and *Crangon* (ICES, 2005a), birds and cockles (Bell *et al*., 2001). Brander and Bennett (1989) presented a multispecies bioeconomic yield model that suggested using predator biomass (or perhaps the predator-to-prey ratio) as an indicator in Irish Sea *Nephrops* fishery management. ICES (2001a) applied the production model of Stefanson *et al*. (1994), which included a predator index made up survey catch rates for 23 predator species, dominated by roundnosed grenadier, greater argentine, cod and saithe. Other authors (e.g. Kruse & Zheng, 1999; Hanson & Lanteigne, 2000) have found no correlation between biomass of potential predators, but these studies focused on macrocrustacea; king crab and lobsters respectively.

Bell *et al*. (2001) developed a model for cockles, which were subject to high levels of natural mortality by birds and had naturally high variability in recruitment. Given estimates of the bird populations in this estuary they projected a population of cockles forward, subjecting it to bird and human predation. Birds tended to remove many individuals, but small biomass of small cockles, while the fishery removed a large biomass, but few individuals of large size. In most years, after accounting for bird predation, the sum of fishing and unaccounted mortality suggested a compensation threshold in the region of 30%-40% fishing mortality. Not by coincidence, the management rule for the Burry inlet cockle fishery was to set the TAC to about a third of the autumn estimate of fishable biomass (Bell *et al*., 2001). In other areas the pressure by predatory birds may be different, for example in the Wash the feeding requirements of oystercatchers and knot exceed the capacity of any single resource to sustain them.

The maximum biological production (MBP) is a TRP for productivity that Die and Caddy (1997) showed to be safer than MSY, and for managing prey species, Collie and Gislason (2001) suggested keeping the total mortality rate (*Z*) below a threshold such that the total allowable catch in year *t* (TAC*t*) is defined by

$$TAC_t = Z_{MBP}B_{avt} - PC_t$$

where Z_{MBP} is the mortality rate at maximum biological production, B_{avt} is the projected mean prey biomass in year *t*, and PC_t is the prey biomass consumed by predators.

2.9.2 Environmental effects

Finfish indicators have tended to focus on monitoring fishing mortality, (spawning) biomass, and recruitment, but for many invertebrates, environmental linkages may be more predictive (Caddy, 2004); for example, rainfall, river discharge, and salinity are useful predictors of shrimp recruitment (Barrett and Gillespie, 1973; ICES, 2005a).

Some exploitable stocks are subject to episodes of mortality that may destroy large parts of the population, as a result of periodic or exceptional climatic events, such as severe storms. One example is razor clams, which tend to live in sandy substrates that are quite mobile. In such cases reference points may need to consider the likely rates of occurrence of such events, the proportion of the stock that is likely to be exposed to the damage, and the potential for subsequent recruitment from elsewhere.

Fogarty & Gendron (2004) discuss the possibility of environmental changes as one factor contributing to increasing in landings of American lobsters, and consider the impacts for reference points. They note that with respect to defining lobster BRPs, the key issue remains to determine whether environmental changes have affected density-dependent or density-independent factors (or both). However, they also note that environmental variability represents a source of uncertainty in the specification of the stock recruitment relationship, which has implications in establishing limit reference points. Current limits may seem too conservative given current favourable conditions, but might not be sufficiently conservative under adverse conditions.

3 Precautionary management frameworks and harvest control rules

3.1 Precautionary management frameworks

3.1.1 The framework

Management approaches based on target reference points (TRP) alone have proved vulnerable to over fishing. This was partly because of high levels of uncertainty in locating the fishery position relative to the TRP, but frequently exacerbated by continued over exploitation during delays in implementing recovery measures, due to the absence of pre-negotiated management plans and a lack of mechanisms for obtaining rapid consensual decisions on suitable action by managers, fishermen and scientists. Similar problems are likely to occur with limit reference point (LRP) based management systems, unless all parties agree to a systems approach, whereby the 'fishery' (as a system) reacts to approaching a LRP by adopting a pre-negotiated response (Caddy, 1998a). Such an approach removes potentially protracted negotiations between stakeholders that may take up entrenched positions and forms the basis of precautionary approach to management.

The Precautionary Approach in ICES was formulated in 1997, building on work carried out at Comprehensive Fisheries Evaluation Working Groups (Comfie, ICES, 1996; 1997b) and Precautionary Approach Study Group (PASG, ICES, 1997). The basic approach was that biomass and fishing limit reference points should be set defining unsustainable areas for the stock and level of exploitation. More conservative thresholds would then be set to reduce the risk of entering the danger areas to an acceptable level when uncertainty was taken into account (Figure 2).

The reference points defining the ICES framework were:
B_{lim} a biomass limit - SSB where recruitment is impaired or stock dynamics are unknown.F_{lim} a fishing mortality limit - associated with unknown dynamics, stock collapse or B_{lim}.B_{pa} a biomass threshold - SSB which, allowing for uncertainties, ensures a high probability that the stock is above B_{lim}.F_{pa} a fishing mortality threshold - F which, allowing for uncertainties, ensures a low probability that F is above F_{lim}.

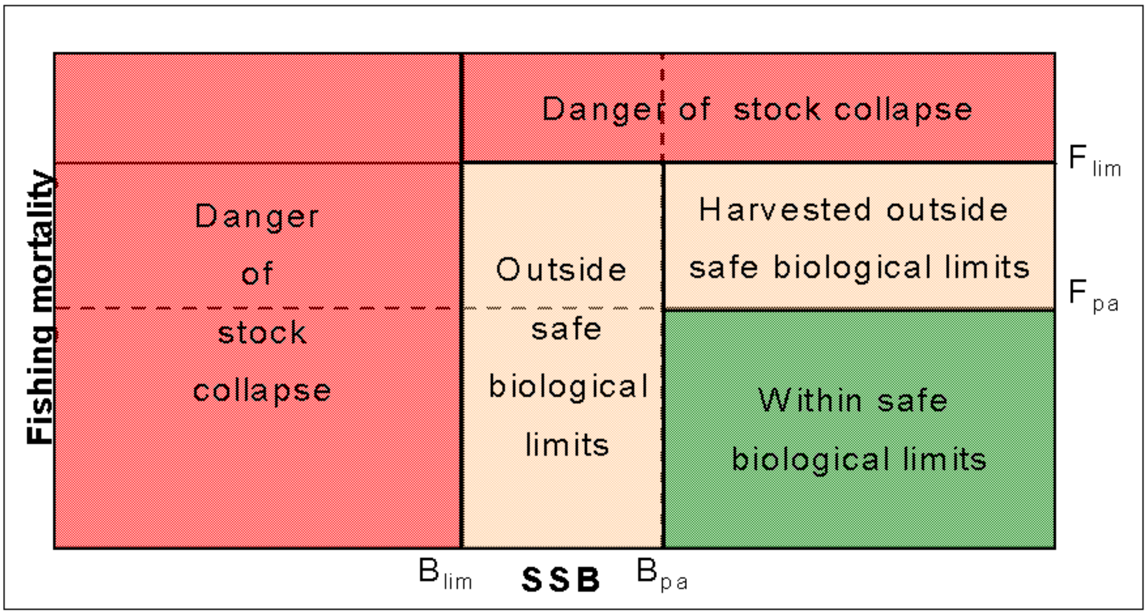


Figure 2. Graphical representation of the Precautionary Approach as implemented by ICES

A similar framework was developed by NAFO, with defined limit (B_{lim}, F_{lim}) and buffer (B_{buf}, F_{buf}) references corresponding to ICES limit and pa references, but whereas the ICES framework had no target reference points, the NAFO system also specified more conservative long-term targets (B_{tr}, F_{tr}). In the absence of explicit targets (and rebuilding plans that were put in place for over exploited stocks) many stocks within ICES have tended to be managed close to B_{pa} and F_{pa} and more recently assessment working groups have been charged with developing targets and management plans using guidance provided by the Study Group on Management Strategies (SGMAS, ICES, 2005b; 2006b) which has superseded the precautionary approach study groups. Precautionary reference point frameworks developed by other institutions and the reference points considered to populate them are compared and contrasted in Gabriel & Mace (1999).

3.1.2 Setting limit and target reference points

The UN Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks (Doulman, 1995) suggested that F_{MSY} should represent a minimum standard for limit reference points, however, ICES (1997; 2001) considered that it may also be used as a target and used more explicit limit reference levels (i.e. F_{crash} and its proxies) to estimate F_{lim}. Caddy (1998) notes that the need to formulate the buffer and pa reference points highlights the 'extreme value' limit reference points approach taken by NAFO and ICES. Establishing a set of limits at a higher stock level with a controlled probability of overshoot would be another approach (Caddy & McGarvey, 1996).

Numerous biological reference points were estimated for many ICES stocks (e.g Cook, 1998b; Smith *et al.*, 1998) and discussed and proposed as PA reference points at the 1998 PA Study Group meeting (ICES, 1998). Subsequent assessment working groups could assess the state of the stock against these reference points or propose new reference points along with supporting rationale.

Initially the ICES system used independently estimated F and biomass reference points with the proviso that F_{pa} must also ensure that in the medium to long term SSB is maintained at or above B_{pa}. However, this sometimes caused inconsistencies and the approach was modified such that B_{lim} became the cornerstone from which B_{pa} was estimated to take account of uncertainty and F_{lim} was the corresponding equilibrium F. F_{pa} was then derived from F_{lim} taking account of uncertainty, with the acknowledgement that at equilibrium it might not correspond to the B_{pa}, but should result in an equilibrium >= B_{pa} (ICES 2001b; 2003).

Biomass reference points were estimated from the stock and recruitment data according to the following procedures (ICES, 2001b):

- If the SSB-R plot clearly indicates that R is impaired at low SSB, select B_{lim} as the SSB above which R is not impaired.
- If the SSB-R plot indicates no impairment in R at low SSB, but the range of SSB values is large then the lowest observed SSB is selected as B_{lim}.
- If the SSB-R plot indicates that R decreases with increasing SSB then select the lowest SSB as $B_{pa.}$
- If the SSB-R plot has a narrow SSB range and indicates no trend then select the lowest SSB as B_{pa}.

Where stocks produce infrequent very large year classes, other procedures could be applied such as setting B_{lim} to the lowest SSB that had produced an outstanding year class. This assumes that given favourable environmental conditions this level of spawning stock is not limiting. Once either B_{lim} or B_{pa} was selected then the other reference point could be derived based on $e^{1.645\sigma}$, where 1.645 corresponded to the 5% one sided percentile and σ measures the uncertainty on SSB. Where long time series of stock recruit data were unavailable, but CPUE data were, then ICES (2001b) recommended using CPUE data as a proxy for SSB to define U_{lim} and U_{pa} as percentages, typically 20% and 60%or less, respectively, of U_{virgin} or U_{max}.

If B_{lim} or B_{pa} are reliably estimated then F_{lim} or F_{pa} could be obtained as the corresponding Fs from long term simulations. F_{pa} should be set so the lower 10-25% percentile produced B_{pa}, in order to maintain SSB above B_{pa} most of the time. However, given doubts about the utility of medium term projections F reference points could be independently estimated. F_{lim} could therefore be based on: F_{loss}, F_{med}, F_{crash}, F_{pa}, F_{lpg}, F_{MSY}, medium term simulations, F corresponding to B_{lim}, analogy with other similar stocks, F values historically observed to lead to stock decline. If F_{lim} was defined then F_{pa} could be obtained as $F_{lim}*e^{-1.645\,\sigma}$, where σ was a measure of the uncertainty of F estimates. Otherwise the following hierarchical procedure was recommended:

- If F_{med} goes through a cloud of points that appears to come from the right-hand side of the stock recruitment data then $F_{pa}=F_{med}$.
- If B_{pa} is defined as B_{loss}, F_{pa} should be below F_{loss}, with the 10-25% percentiles usually appropriate. If $B_{lim}=B_{loss}$ then F_{loss} cannot be used as F_{pa}.
- Medium term projections can be used to estimate F_{pa}, such that $B>B_{pa}$ with at least 90% confidence.
- Set F_{pa} based on historical experience.
- Choose F_{pa} by analogy with other similar stocks.

It has been suggested that because both F_{crash} and F_{MSY} increase dramatically as the slope at the origin of the SRR increases, biomass targets and thresholds should be dependent on the degree of compensation exhibited (or assumed) (Mace, 1994). She suggested using the percentage of unfished biomass (or SSB) corresponding to a level of 50% of the maximum expected recruitment from a stock recruitment relationship, or equating the threshold with the slope at the origin. Cook's (1998a) G_{loss} provides a non-parametric estimate that takes account of the slope at the origin, while O'Brien & Maxwell (2002) proposed the use of the two-line (Ockham's Razor) SRR model to define the SSB at which recruitment started to decline (S*) and use this value for B_{lim}, with B_{pa} set on the basis of the likelihood profile for S*. ICES has accepted the use of S*, but did not adopt the likelihood profiling approach for estimating B_{pa} (ICES, 2002).

3.2 Traffic light (TL) systems

Whilst the definition of reference points provides a basis for evaluation of fishery status, the presence of uncertainty in both the current stock status and in the appropriateness of the reference points themselves should be addressed. Suggested approaches include the conducting of a broad review of the biological basis for management (ICES, 1997b) and the selection of indices which pinpoint the most critical features affecting the conservation potential of the resource (Caddy, 1999b). Using a suite of measures, such as the reference point F_{Comfie}, the minimum of F_{med}, F_{MSY} and F_{max} (ICES, 1997), can improve the reliability and robustness of reference points, especially when they have a different basis and data for estimation. This may be particularly advantageous in data poor situations where the metrics used for reference may be more empirical. In the Comfie example, the minimum of the alternatives was suggested, but this need not necessarily be the case and it may be desirable, but potentially analytically difficult, to combine a variety of metrics with differing units and scales. Caddy (2004) advocated the use of a broad range of fisheries indicators and reference points to reflect life histories and fishery characteristics, ideally within a transparent fisheries harvest law understood and agreed to by managers and stakeholders. In this context the use of traffic light systems may be advantageous.

Traffic light systems (Caddy 1999a, 1999b) provide a means of considering multiple indices (and/or indicators) together in order to formulate a decision on stock/fishery status and can be extended to include potential actions to be taken in the face of particular scenarios, although this is a more complex issue. Nonetheless, Caddy (2002) stresses that it is hoped the TL approach will not just become another way of merging a series of different pressure indices into one overall index measuring the level of impact of the fishery. Although useful this would confine the concept to the realms of science, merely an index, without being clear that management should respond and by how much. As a specific type of LRP management approach, management responses are integral to the TL system. Whatever the variables used, it is necessary that the system increasingly restrict fishing effort as an increasing proportion of multiple variables move from safe 'green' values to dangerous 'red' values. Agreement from industry to appropriate responses as increasing numbers of indices move beyond their LRPs in to a red category is fundamental.

The range of indicators that can be incorporated in TL systems includes direct measures relating to the stock concerned, indices of external drivers thought to directly impact on the stock such as predator abundance or certain environmental factors, but also indicators that do not necessarily relate directly to the species under consideration, but which correlate strongly with its status or more particularly reproductive success. Caddy (1999a) provides tables of 30 qualitative or semi quantitative criteria that could form the basis for deciding on priorities for precautionary management of marine resources. These can include environment effects and the abundance of other species. An important distinction between indices and indicators is that the latter lack scientific validation and the use of several indicators does not necessarily provide a better basis for scientific advice. Therefore, indicators should not necessarily be included in the output score, but could be presented separately as supporting information (DFO, 2007). Various approaches have been explored for dealing with transitional and boundary situations involving fuzzy logic (Seijo & Caddy, 2000; Silvert, 2001;Murta & Silvert, 2002), ramp functions, etc. The problem is not only how to define reference points (or in the TL system colour boundary values) but, when using multiple indicators, more importantly how to weight them within a "characteristic" that defines the likely status of biomass or fishing mortality. No general rules can be offered at this point, but the advantages provided by multiple indicators are evident even if the TL approach is simply providing a diagnostic or index of "ecosystem health", as in impact assessment (Caddy 2004). The traffic light approach has been more used in Canada than in other areas and although it has proven useful and been generally accepted by managers and industry, it has been criticised by the scientific community for lacking scientific rigour (Koeller *et al*., 2002). In this example the TL system provides the qualitative stock status signal, but a simulation model with characteristics similar to the Scotian Shelf prawn fishery was subsequently applied to determine the next years TAC.

Traffic light systems typically involve scoring current values of the indicators against reference levels and then weighting these together such that an overall score relating to a particular characteristic can be achieved. Scores for one variable may be conditional on another, for example, low mean size could score positively in conjunction with other signals suggesting strong recruitment, or negatively where other signals suggested over exploitation of the adult stock and low recruitment. Halliday *et al*. (2001) proposed that decision rules should be based on the integrated score of indicator values measuring at least three characteristics: abundance, production, and fishing mortality. A gradation of response for the characteristic is likely to result, because not all the individual indicators should trigger simultaneously, which should provide some redundancy and "smoothing" if the proportion of indicators triggered within a management rule determines the severity of management response (Caddy 1999a, 1999b).

The management response can be expressed by assigning the overall characteristics' scores to a consideration matrix, with predetermined management actions or through a series of conditional statements illustrated by the subset presented below (Caddy, 2004):

IF Production = green AND F = green AND Stock = green THEN
    Small increase in TAC
ELSEIF Production = green AND F = amber AND Stock = amber THEN
    No change in TAC
ELSEIF Production = amber AND Stock = red THEN
    Significant reduction in TAC

Halliday *et al*. (2001) suggested that fisheries productivity be given high prominence. The TL approach has been used for characterizing shrimp fisheries (Koeller *et al*., 2000; 2002) and a similar multiple indicator approach, the 'trouble spot thermostat', (Shepherd *et al*., 2001), was applied to abalone. This protocol for managing individual fishing grounds of greenlip abalone used diver survey, and analysis of commercial shell samples and allowed a response to declines of local populations within a metapopulation. Traditional metrics such as catch-per-unit-effort, size frequency, and total mortality (*Z*) proved to be relatively insensitive indicators of population decline, while recruitment time series, total catch from, and degree of spatial contraction of, individual subpopulations emerged as more sensitive indicators.

Caddy (2004) suggested four indicators for each of a four character traffic light approach potentially suited to a macrocrustacean with two predators, a co-existing species and prey (Table 3). However, this model requires quite sophisticated data and many of the variables required for this model would be unavailable for UK macrocrustacean fisheries (e.g. trap survey catch rates, area with density > Xm^{-2}, recruitment estimates, area with recruit density >X Xm^{-2}, annual number of trap hauls,…).

Table 3. A four character traffic light approach potentially suited to a macrocrustacean (species A) with two predators (predator1 & predator2), a co-existing species (species B) and prey

Indicator	Characteristic
1. Mean survey catch per trap 2. Area with density > Xm^{-2} 3. Early-season catch per trap haul 4. Bycatch species A in trawl fishery for species B	Abundance
1. Number of recruits (carapace length < XXcm)	Production

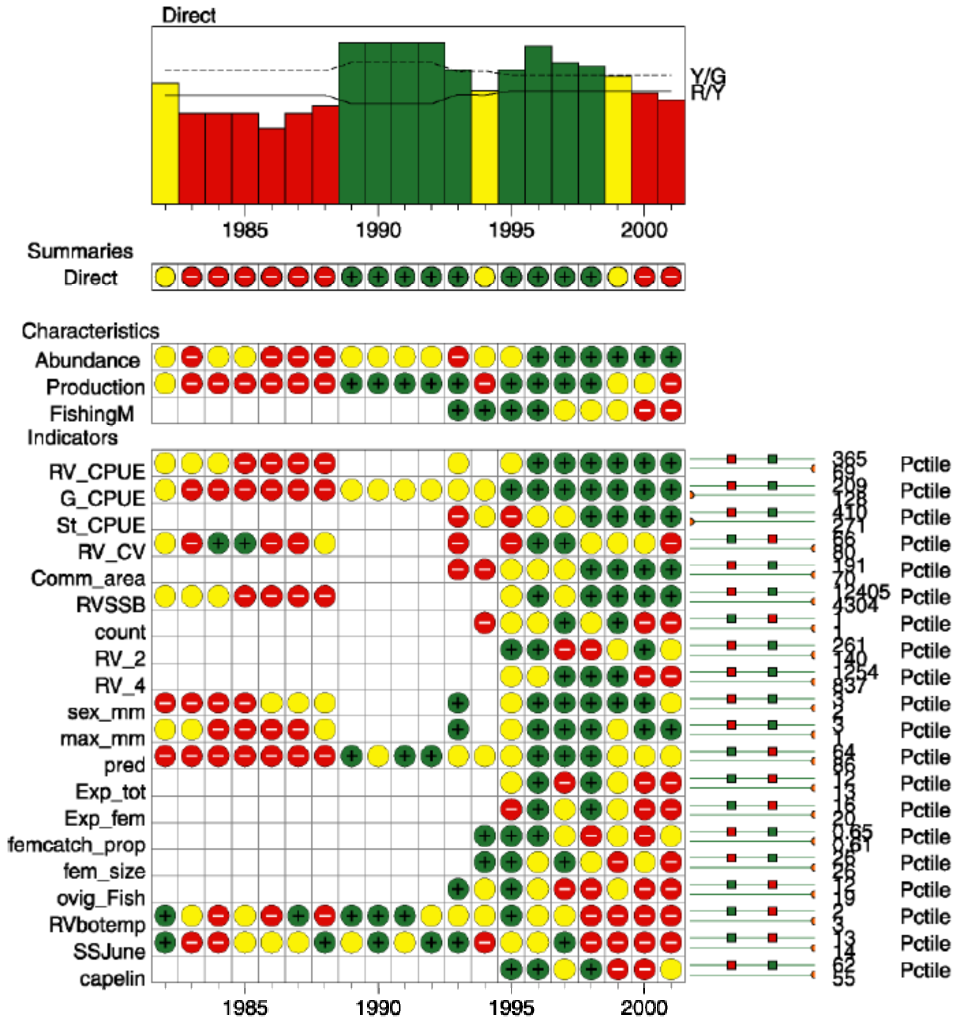
2. Area with recruit density > XXXm^{-2} 3. Mean size of mature females 4. Condition factor	
1. Mean Z_t from survey data 2. Fleet days fished per season 3. Immature individuals (%) 4. Annual number of trap hauls per area grounds	Fishing pressure
1. Abundance (predator1/species A) 2. Abundance (predator2/species A) 3. Absolute value $\vert$bottom temperature – optimum temperature 4. Prey abundance > XXXXm^{-2}	Ecosystem/environment

In the model described by Koeller *et al*. (2002) default boundaries red to amber and amber to green signals for individual indicators are the 33rd and 66th percentiles, respectively; these are reversed where increasing indicator strength is considered to correspond to declining stock health. Indicators are grouped into three categories for:

a) **abundance** (RV abundance index, Gulf vessels CPUE, commercial trawler standardised CPUE, RV CV indicating degree of aggregation, commercial fishing area, industry perspective),
b) **production** (commercial counts per pound, RV age 2 abundance, RV age 4 abundance, RV female SSB estimate, average size at sex transition, average annual maximum size, predation, RV bottom temperatures, July sea surface temperature, RV capelin abundance indicating generally favourable conditions for shrimp) and
c) **fishing mortality** (total exploitation rate, female exploitation rate, proportion of females in the catch, proportion of the catch taken during ovigerous period).

Each individual indicator is given a score (r:1, a:2, g:3) and a simple average is calculated. The average is assigned a summary colour according to limits determined by the probability distribution of possible outcomes (Figure 3). This aspect in particular has been criticised as difficult to interpret and it has been recommended that it should not be considered in advice because issues such as weighting of indicators and harvest rules associated with any particular summaries have not been resolved. In this model, as noted in section 2.8, some signals are conditional on others, for instance an increase in commercial count per pound could indicate good recruitment, or a decline in abundance of older shrimp, or a combination of the two. Consequently, this variable needs to be considered with others reflecting abundance by age. Interpretation of this type of summary measure, describing the population age or size structure (mean size, proportion small, count, etc) is normally dependent on clarification by some other information on abundance, but this example also highlights that this can also be the case for spatially structured information. In this instance CPUE indices were maintained as the stock and fishery contracted into a smaller area. Thus indicators of the area occupied by the stock and fishery were required.

Figure 3. TL output, summary and individual indicators (Koeller *et al.* 2002)



Opinions vary on the role of the TL approach, with many shrimp biologists considering the approach more reliable for stock status determination than conventional reference points. However, NAFO (1999a; 1999b) concluded that the traffic-light approach was acceptable for providing a format for discussions among fishermen, scientists, and managers, but that it could only provide short-term perspectives on stock status and could not evaluate long-term management strategies. Furthermore, they felt that the approach could not replace more conventional reference points and should only be used to supplement the traditional basis for management advice, but could provide an interim measure for evaluating status of shrimp stocks (Cadrin *et al*. 2004).

The Marine Stewardship Council's accreditation scheme shares many of the features of a TL system in that it aims to combine different signals relating to each of its three principles and come to a decision as to whether accreditation is appropriate. The principles include:

- A fishery must be conducted in a manner that does not lead to over-fishing or depletion of the exploited populations and, for those populations that are depleted, the fishery must be conducted in a manner that demonstrably leads to their recovery.

- Fishing operations should allow for the maintenance of the structure, productivity, function and diversity of the ecosystem (including habitat and associated dependent and ecologically related species) on which the fishery depends.
- The fishery is subject to an effective management system that respects local, national and international laws and standards and incorporates institutional and operation frameworks that require use of the resource to be responsible and sustainable (MSC, 2002).

The accreditation scheme therefore synthesises information relating to the resource directly, the wider ecosystem effects and the management frameworks in place providing an overall weighted score for each principle.

3.3 Harvest Control Rules (HCRs)

Precautionary management frameworks implicitly assume some general control law that could be summarised as suggested by Serchuck *et al.* (1997). For example the NAFO framework could be summarised by ensuring that:

$SSB >> B_{buf} > B_{lim}$ and $F \approx F_{tr} <= F_{buf} < F_{lim}$

If SSB is in the uncertain zone between B_{lim} and B_{buf} (or B_{pa}) then a typical control law would be to reduce the target F as a linear function of the distance between B_{lim} and B_{buf}, such that F would tend to zero as B_{lim} was approached.

However, decision rules or harvest control rules, recommended by FAO (1995; 1996) as key to the development of the precautionary approach to fisheries management, require more explicit detail of the measures required to achieve the generic control law. They aim to replace *ad hoc* provision of advice with a more rigorous management structure in which objectives, such as the avoidance of limits and the achievement of thresholds and targets, along with the actions to be taken to achieve them are explicitly stated. FAO defined HCRs as pre-agreed specifications for the management actions that will be taken to respond to estimated or perceived states of nature (FAO 1996). Similarly, the ICES Study Group on Management Strategies defined an HCR as an algorithm for pre-agreed management actions that is a function of variables related to the status of the fish population (ICES 2006b), while Cooke (1999) refers to an algorithm that yields catch limits, effort limits, season or area limits, or other means of controlling or influencing the level of harvest. Breen *et al.* (2003) propose that the term 'management procedures' be used to describe fully developed and tested procedures and that 'decision rule' be limited to rules that have not been tested or do specify what action is to be taken upon triggering.

Although HCRs are not restricted to a particular form of control, as can be seen from the above most emphasis has been to regulate the catch or fishing effort and the role of technical measures in precautionary management is less explicit, although these have formed a part of recovery plans for several ICES stocks (e.g. Northern hake, North sea cod) and changes in MLS and V-notching have formed a basis for management strategies in Canada (e.g. DFO, 2007a). However, most HCRs are designed to determine total allowable catch (TAC), by setting a target catch for the coming year as a function of estimated population size, on the basis of a fishing mortality that might be status quo F, a rebuilding target or some long term target F. In some circumstances additional criteria are introduced to require that, for example; SSB does not decline or increases, and that yield does not vary by more than given proportion.

The recovery plan for European northern hake stock introduced in 2001 following declining stock levels through the 1980s and 1990s and a series of low recruitments in the late 1990s, provides one such example. Technical measures including mesh size increases for certain fleet sectors and in certain areas were introduced along with an HCR specifying that the TACs should be set such that they will result in an increase in the quantities of mature fish in the sea of 15% and that yearly variation in TACs should not exceed 50% (ICES, 2006b). Evaluation by simulation suggested there was a high probability to achieve recovery to SSB>=Bpa within 10 years. These emergency measures were subsequently replaced by a regulation (EC Reg. No 811/2004) specifying that F be limited to 0.25 (=F_{pa}) and the maximum change in TAC be limited to 15%. Improvements in the state of the stock indicated by more recent assessments suggested that F_{sq} (the current level of fishing mortality) was just above F_{pa} and that recovery to B_{pa} was imminent at F_{sq} (ICES, 2006b) and recent assessments have suggested that SSB is now just above B_{pa} and F_{sq} is just below F_{pa}. In these circumstances the fixed F rule in the HCR would imply a significant increase in TAC, but this is constrained (to 15%) and the resultant TAC corresponds to an F below F_{pa}. More recent management strategy evaluations with a more comprehensive inclusion of uncertainty suggest that the probability of remaining above B_{pa} may decline in the future (ICES, 2007a).

HCRs may be categorised according to ‘constant catch’, ‘constant fishing mortality or ‘fixed escapement’ strategies (e.g. Butterworth & Bergh, 1993; Restrepo & Powers 1999), but are not limited to these linear functions or metrics (Hilborn & Walters 1992). The South African Anchovy fishery provides examples of all three categories over its history (Butterworth & Bergh, 1993). Target fishing mortalities (such as $F_{0.1}$ or F_{MAX}) are a special case amongst constant F strategies and have been extensively used (e.g. Rivard & Maguire 1993).

Threshold management strategies (Quinn *et al*. 1990) have been used extensively as part of the management process for the groundfish fisheries off the west coast of North America, while more recent HCRs often include precautionary reference points (i.e. to avoid limits with a high probability) for fishing mortality and spawning stock biomass in the algorithm. HCRs could also include a component linked to the ‘value of information’, where for example, the HCR provides lower TACs when there is greater uncertainty about population size (for example, as reflected by survey CVs, Cooke 1999).

Constant catch HCRs imply a low TAC with high stock biomass and productivity such as the maximum constant yield of Annala (1993) that has been used in management of New Zealand rock lobsters. Constant fishing mortality HCRs may be considered safer, but result in variable spawning size and yield. Using TACs in a fixed Fregime, rather than directly controlling effort, was considered an uncertain method for stock recovery for abalone, where recruitment was highly variable (Sanders and Beinssen, 1998). Fixed escapement has been used for short-lived and semalparous species such as squids (Basson & Beddington, 1993; Basson *et al*. 1996);

where escapement of no less than 40% is required (Agnew *et al.* 1998). Fixed escapement strategies require the fishery yield to absorb all year-to-year variation in stock abundance. Some littoral bivalve stocks, where the total biomass on the grounds can be estimated pre-season, are managed by a constant F (=proportion) (Bell, et al. 2001) sometimes in conjunction with a fixed escapement that provides a minimum level of spawning biomass. This type of approach is applied to some UK cockle stocks and has been elaborated on in some areas. For example, in the Wash, a harvest control rule is framed in terms of a number of reference points, including a minimum 11,000t total stock biomass estimate and a minimum of 3000t of adult cockles. Additional reference points include a minimum of 70% adults on the beds, no more than 10% by weight of cockles to be smashed in dredging operations. Other control measures include maximum daily quotas and a buffer zone of 100m around any mussel beds (EJSFC, 2008).

Breen *et al.* (2003) reviewed HCRs and noted a wide variety, all of which, with the exception of constant catch, required feedback from the population in the form of an abundance index, in their study, CPUE. Breen *et al.* (2003) used a 'benchmark' HCR based on a fixed F set to find an acceptable balance between mean catch and other indicators. Against this they evaluated 13 different HCRs including those suggested by Cooke (1999), Geromont *et al.* (1999), Fournier & Warburton (1988), Bentley *et al.* (unpublished), Haist (2002), Geromont & Glazer (1998), Punt & Smith (1999), De Oliveira et al. (1998), Baldursson *et al*. (1996) as well as some other options. The rules of Bentley *et al.* (unpublished), Fournier & Warburton (1988) and Baldursson *et al*. (1996) all performed very poorly in the preliminary explorations and were discarded at that point. The remaining rules were then compared through simulations of 1000 iterations for each scenario. Metrics used to evaluate performance included; mean biomass, minimum biomass, low biomass index, average annual variation in catch (AAV), biomass range, mean catch, minimum catch, percentage of crashes. Robustness testing included introducing the following scenarios: varying production parameters, a lag in productivity, variable productivity, episodic mortality, increased random error (multiple trials with error on different variables), increasing catchability, unreported catches and uncontrolled catches (4 trials investigating different aspects including increase of non-commercial catch). They concluded that the constant catch rule performed well only if the catch level was low, demonstrating the trade-off between mean catch and catch stability. Several rules showed either unresponsiveness or huge periodic oscillations and this was particularly common when lags were introduced to the system. Haist's rule did not perform as well as some others in many trials, but showed the lowest crash rate in the trial where uncontrolled catch was allowed to increase and all the rules performed badly. This illustrated the point that an overall best rule is very difficult to find except within a very narrow range of possible states of nature (and fishery behaviour), and the importance of including implementation errors in management strategy evaluation. Breen *et al.* (2003) did not consider the modeled levels of uncontrolled catch to be extreme, as estimates of the recreational, traditional and illegal catches suggested they were at roughly the same level as the commercial catch and thought to be increasing. Although noting that it is very difficult to find a 'best' rule the rule of Punt & Smith (1999) had the best overall score, excluding the %crash indicator, where it did not have the lowest crash rate. This rule is an F_n strategy buffered with minimum and maximum TACs and by additional separate limits for between year increases and decreases in TAC.

The Northern Australia prawn fishery provides an example of HCRs used to set the effort level and the fishing season length in a mixed-fishery context (Dichmont *et al,.* 2006). Management strategy evaluation was used to evaluate 3 assessment methods and two forms of decision rule. The performance of the management strategies was evaluated in terms of whether stocks were at or above SSB_{MSY}, long-term discounted catch and inter-annual variation in catch. None of the strategies achieved the SSB criterion if the target effort was set to E_{MSY}, because the control measure is total effort and the two species are found and caught together. Reducing target effort below E_{MSY} increased final stock sizes, but at a cost of reducing yield. The best strategy was one that changed the timing of the fishing season so that effort was shifted away from *Penaeus esculentus* and onto *P. semisulcatus* and to set more precautionary effort targets for *P. esculentus*.

Precautionary management frameworks require the level of risk that is acceptable to the stock to be defined, which may be the preserve of scientists, but HCRS require engagement with fishery managers and other stakeholders because the selection of a management procedure always involves explicitly quantifying, and then considering, the trade-offs among often conflicting management objectives. Such trade-offs might include those between: maximising level of, or stability in, catch, differences in costs and benefits between fleet sectors, different objectives between species taken, or minimising environmental damage. On a more pragmatic level they also need to consider the likely extent of compliance or enforcement that might be required for effective implementation.

Even though they may contain elements intended to make them precautionary, the high levels of uncertainty inherent in the fisheries systems being managed mean that HCRs cannot guarantee they will be precautionary in practice (Kirkwood & Smith, 1996, Punt 2006). Evaluation to determine the efficacy is therefore required. Such evaluation could be carried out using large-scale experimentation (e.g. Sainsbury *et al*. 1997), but this is rarely possible in practice and a more tractable alternative is to evaluate them through computer simulation (Kirkwood & Smith, 1996, Cooke, 1999, McAllister *et al*., 1999, Kell *et al*., 2005a; b), an approach often called Management Strategy Evaluation, MSE (Smith *et al*., 1999).

Most HCRs use the results from stock assessments, but this need not be the case and it has been suggested that TACs should be set by means of simulation tested management procedures and not by linking output from annual 'best' assessment to reference points (Butterworth & Bergh, 1993). Problems caused by the latter approach include that the assessment reacts to noise in the monitoring data and lags in the assessment and management process (Breen *et al*. 2003; Kell *et al*. 2005a). Empirical HCRs based on directly measurable quantities have been proposed (e.g. Hilborn *et al*. 2002). Empirical HCRs (not directly dependent on stock assessments) are in place for anchovy and sardine off South Africa (De Oliveira & Butterworth, 2004) and rock lobsters (*Jasus edwardsii*) off New Zealand (Breen *et al*. 2003).

In data-poor situations, where estimates of population size are lacking, empirical HCRs, expressed as a functions of indicators, that reflect the state of the resource (e.g. CPUE, mean fish size, egg production, etc) will need to be used. The performance, of such HCRs depends on the strength of the link between the indicators and the true resource state. If these are weak, management actions could be triggered either too early or too late (Punt *et al.* 2001a). In such cases stable harvesting regimes that only change in response to a strong signal may be preferable, but these may require a wider precautionary buffer (Roel & De Oliveira, 2007).

Indicators of stock trajectory have been explored as a management tool. Bell and Stefannson (1998) used a simple MSE in which the magnitude of change in CPUE observed in the previous year dictated the change in TAC for the coming year i.e. a 50% decline in CPUE implied a 50% reduction in TAC. This management scheme was explored for a range of stock dynamics (growth, maturity and recruitment) but was unable to prevent overfishing in a number of stock dynamic scenarios. The addition of a multiplier when converting the change in CPUE to a change in TAC aided in some situations, but for shorter-lived stocks more dependent upon recruitment the potential for large increases in TAC combined with the lag between assessment and fishery lead to highly unstable scenarios and an increase in probability of stock collapse.

The International Whaling Commission (IWC) has a long history of MSE and in 1974 implemented an HCR called the 'New Management Procedure' (NMP, Kirkwood 1992, 1997) with objectives to recover whale populations to optimum levels, to protect them below 54% of their pre-exploitation size and to provide a formal (rather than ad hoc) structure for the development of scientific management advice. Although well specified the NMP proved inadequate because insufficient data were available for its requirements, uncertainty was superficially accounted for, mechanisms to facilitate scientific agreement on catch-limits recommendations were not in place and it produced widely fluctuating catch-limits. De Oliveira *et al.* (*in prep*) suggest the following lessons were learned:

- Objectives must be explicitly stated and prioritised;
- Data and analysis requirements must be realistic and specified;
- Uncertainty must account for limitations in the advice framework and regulatory regime as well as biological factors;
- Management algorithms should be rigorously simulation tested against the agreed management objectives;
- The data, methods and metrics for assessing stock status and the management measures to take in response must be explicitly detailed.

4 Application and potential approaches for UK capture shellfisheries

Previous sections have provided background to reference points, precautionary management systems and harvest control rules in a broad context. In this section we focus on a number of species found in UK waters, but in general terms rather than considering specific stocks or fisheries. These descriptions of the stocks and fisheries are very brief and intended only to highlight particular issues associated with each species and suggest some potential options for future assessment and management. In a limited study such as this there is not the scope to consider each species in more detail. Brief details for a slightly wider range of species are tabulated (Table 4 & 5).

4.1 Scallops

The UK scallop fisheries are open access dredge fisheries carried out in coastal and offshore waters and are particularly important in the English Channel. There are multi-national aspects to the fisheries. Landings are generally stable, although there may be cycles due to variable recruitment success. The stocks consist of patches of varying scallop density and there is evidence that recruitment can be widespread over several patches. Although scallops can be aged directly from the shells, and length data are also relatively easy to collect, stock assessment is difficult because biological parameters differ considerably in space (i.e. between patches or possibly more locally). The scale of commercial data reporting is usually insufficient to determine exactly which patch the scallops are from and as a result biological sampling may not be representative. Depleted scallop stocks have been shown to recover rapidly and substantially when fishing is curtailed (Murawski *et al*., 2000). Spatially structured management regimes provide options that can protect a proportion of the stock, by either fixed or rotational closures. Reference points and harvest control rules can be framed as the proportion of the stock under exploitation, assuming that this is accurately known. Benefits in the form of additional recruitment, that may spill-over from a fixed closure, are dependent on the location and density scallop stocks in the closed area as well as the hydrodynamic regime and substrate structure. Rotational closures sequentially move exploitation around the area of stock distribution and this may prevent build up of very old (potentially senescent) scallops. However, by ensuring a wider distribution of fishing effort rotational schemes may increase the area where the environment is damaged by dredging, while fixed closures have the advantage of protecting the environment in this area from damage by dredging.

4.2 Cockles

Cockle fisheries are a mixture of open and restricted access fisheries in estuarine waters. The major fisheries (Thames and Wash) are mainly suction dredge fisheries, while many of the other fisheries are worked by hand gathering. Landings from some fisheries are relatively constant, but others can be extremely variable, due to the success or otherwise of spat settlement. In general terms cockle beds occur in well defined areas, the exact location being influenced by the density of older cockles on the bed. The presence of well defined beds enables good stock biomass estimates to be made from annual grab or shore quadrat surveys. Cockles can be aged by interpretation of external shell rings. Reporting of landings in dredge fisheries can usually be determined at the bed level, hand working often extends over more extensive areas and reporting is usually less precise. Depleted stocks are normally replenished within one or two years from surviving local adults. Spatial management regimes are employed at the bed level, to conserve adult stocks or preserve juveniles in areas where few adults are present. Relatively precise age structured statistics relating to both stock size and landings permit the use of limit reference points based on minimum absolute levels of biomass, as well as proportions of adults with additional reference levels for the proportion of cockles damaged by dredging. Cockle fisheries are often managed on the basis of harvesting a constant proportion. Taking predation of cockles by birds into account, Bell *et al*., (2001) indicated that fishing did not appear to increase overall cockle mortality provided no more than 30%-40% of the overall abundance was removed. A 33.3% harvest ratio is used as a target for a number of cockle fisheries, although in some cases this reference level was arrived at empirically by consideration of F_{max} for a number of fish stocks (*pers. comm*. C. Bannister). Control is usually exerted through limited opening (space and time) licence and TAC. Cockle suction dredges can have severe effects on local ecosystems in muddy areas, but commercial fisheries usually occur in areas of muddy sand where the effects of suction dredges have been shown to be of limited duration.

4.3 Ensis

Several species of the genus *Ensis* are present in the UK, but currently they are only exploited to any degree in the Western Isles of Scotland. *Ensis* typically live in deep burrows in sand on open coasts. They are mobile at scales of kilometres, able to vacate their burrows and move quite rapidly jetting water from the mantle or using the strong foot for propulsion. It is possible therefore that initial settlement occurs away from the adult beds, to which the animals move at a later stage (Henderson & Richardson, 1994; Fahy & Gaffney, 2001). The native species are long lived and relatively slow growing, but little is known about their recruitment processes. Many potentially commercial beds lie in areas protected by environmental legislation and so, despite the existence of established markets in Europe and the Far East, exploitation has been slow to develop in the UK because of concerns about environmental damage stemming from the use of water-jet dredges that fluidise the substrate. Other harvesting methods such as electro-fishing are under development and consideration is being given to limiting the extent of exploitation through the application of Several Order fisheries. Given that they tend to occupy discrete beds that are persistent over time, such fisheries could be managed in a similar way to cockles, but the open sea location of most populations, together with a lengthy larval stage, means that management of individual beds is unlikely to influence subsequent recruitment to them. It is likely that environmental concerns will ensure that the majority of *Ensis* beds will remain protected from fishing, so continued recruitment should be assured. Potential reference points and management approaches based around protecting a proportion of the total stock biomass or area and taking account of the episodic nature of *Ensis* recruitment and potential for catastrophic environmental damage seem most appropriate. Management approaches taking account of spatial structure of beds and utilising access, effort, TAC and seasonal controls are all possibilities.

4.4 Whelk

Whelk fisheries are distributed around the UK coastline, with the highest landings being generated from the North Western Coast of Wales, Eastern English Channel and the North Yorkshire Coast. Pots are the main method of capture, although there are minor contributions to the landings as by-catch from towed gears, mainly beam trawling. Growth of whelks is generally slow, but both growth and size at maturity can vary considerably over large spatial scales, as a result of environmental conditions and predation pressures. Whelks lay eggs masses that are attached to the substrate and hatch into miniature adults, without a wide dispersal phase. This makes them potentially vulnerable to local depletion. Currently few data are available, although length data could be collected and it is possible to age whelks using the operculum. Stock assessments are not carried out and if attempted would need to be at local levels as a result of the geographical variations in the populations. Current management is by MLS with a few local variations. The current 45mm EU wide MLS, can result in landings of immature individuals in many areas around the UK, but there are also UK populations that are mature at this size. Some local legislation has been introduced with higher size limits (e.g. Shetland, 75mm). A closed season has been put in place to protect spawning adults in South Wales. Landings are heavily dependent on market conditions, which can be volatile, with the principal markets being located in the Far East and to a lesser extent southern Europe. The crash of Asian markets in 1998 led to huge declines in total UK landings. The use of crabs as bait in the whelk fishery has been raised as an issue with these fisheries. The data poor nature of these fisheries has precluded the development of reference points, with the exception of the MLS and size at maturity. TL approaches could be seen as an appropriate first step to utilise the currently limited data available, potentially including empirical reference points such as Z* (Die & Caddy, 1997) with the flexibility to incorporate new data as they became available. Spatial management measures at a local scale could be investigated given the limited dispersal for this species. If management is applied on a wide scale it may need to be more precautionary to avoid local depletion due to the lack of a larval dispersal phase.

4.5 Cuttlefish

The cuttlefish fishery in the English Channel is the largest cephalopod fishery in Europe. International landings have increased steadily through the time series. There is a multinational dimension to the fishery with France taking the majority of the landings. UK landings are mainly by beam trawl offshore in the Western Channel, as part of a mixed fishery for demersal species, and by trap in inshore waters of the Channel. Cuttlefish growth is rapid and influenced by the environment. Although direct aging is difficult routinely, the rapid growth rate and few cohorts in the fishery mean that age in years is apparent from length distributions. They are semalparous, with most adults dying after they have spawned. As with many cephalopods, stock assessment is difficult and no ICES assessment is routinely carried out. Time series of catch rates from ground-fish surveys may provide useful information for assessment. No management (no MLS or TAC control) is currently in place for this species. In-season management based on a fixed level of escapement to provide sufficient spawning stock has frequently been applied to cephalopods, as it is suited to the semalparous life cycle (Beddington *et al*., 1990). However, this approach requires close monitoring of catch rates during the season and the ability to react swiftly to change in the catch rates. Alternatively, the fishery could be regulated on the basis of an index of recruitment strength if this was available before the start of the season. Although much of the catch is taken in traps, the major part of UK landings is taken by beam-trawl (potentially as by-catch in a mixed demersal fishery) and this may complicate effective management. Cuttlefish lay gelatinous egg clusters and find traps an attractive substrate for this. The removal and death of large numbers of eggs on traps has been raised as an additional issue for this fishery. Management measures such as closing spawning areas could be put in place to protect both the spawners and eggs. However, such measures would need to be scientifically evaluated before implementation.

4.6 Edible crab

Edible crab fisheries are widespread and important in UK coastal and offshore waters. There are international aspects to many of the crab fisheries. Landings have increased through time and the stocks are generally considered to be heavily exploited. Stock assessment is difficult for a variety of reasons (The stock identities are not well defined, crustaceans cannot be aged routinely, males and females have different seasonal cycles and catchabilities, size and sex based grading criteria vary between regions, crabs make systematic seasonal movements, commercial effort data are poor,

…). However, equilibrium based length structured assessments (LCA) do provide a relatively straightforward means to estimate size structured fishing mortality patterns that provide a basis for per recruit analyses. These may provide a basis for reference points, although systematic movements by crabs and poor sampling exacerbated by grading practices may bias length distributions and results are also sensitive to the biological parameters (especially growth and M) used. Other assessment and modelling approaches (biomass dynamics and dynamic length structured models) have been explored without great success, while individual vessel catch rates provide a useful source of abundance indices. Traffic light approaches could possibly be explored for this species as a means of combining historic times series data, equilibrium analyses and empirical approaches. Existing management is primarily by MLS and licence limitation in UK, while some other countries (e.g. France, Jersey) do limit the number of pots per vessel. Although targeted by some vessels, crabs are also taken with lobsters and estimation of effective directed effort can be difficult for some parts of the fleet. This has implications for both stock assessment and management of the fishery.

4.7 Lobster

Lobster fisheries are widespread throughout UK coastal waters, with most landings coming from the inshore zone and as a result there are not major international interactions. Landings have generally been stable or increasing in recent years. They cannot be routinely aged and total effort data are poor, but the other assessment problems listed for crabs are less severe for lobsters. LCA and per recruit analysis provide a basis to set limit and target reference points often in terms of egg per recruit (e.g. Tully *et al*., 2006), while more complex per recruit modelling taking detailed account of the life cycle can provide a useful general simulation framework with which to investigate management options and is used to estimate %EPR for US and Canadian stocks (Fogarty & Gendron, 2004). Analysis of catch rates also provides options for assessing trends in abundance, but has been limited by the availability of good quality data in the UK. Management in the UK is primarily by MLS and licence limitation with some locally applied variations to MLS and bans on landing ovigerous females. Landing of ovigerous females is banned in the US and Canada, but this together with high exploitation rates can lead to very truncated size distributions and asymmetric sex ratios with very few large males. This has lead to some concern that sperm limitation could occur (Fogarty & Gendron, 2004) as this has been observed previously in rock lobsters and spiny lobster (MacDiarmid & Butler, 1999). It has also been suggested that reference points and management that aim to ensure an increased proportion of multiparous (multiple spawning) females could be beneficial (Powles, 2001), as these tend to produce larger larvae with better survival potential than primiparous (first-time) spawners.

4.8 Nephrops

Nephrops fisheries occur on discrete patches of mud, several of which are found in UK waters, the major ones being the Farn Deeps, Fladden Ground, Firth of Forth, Moray Firth, North & South Minch, Clyde and two patches in the Irish sea. The vast majority of effort expended on *Nephrops* is through directed trawl fisheries although pot fisheries also exist in some areas. *Nephrops* are internationally managed through the European Commission via MLS, TAC, mesh-size, effort and species composition regulations. The management areas used to set TACs by the EU are amalgamations of the various fishing grounds and are therefore not capable of preventing localised stock depletions. As with other crustaceans, direct ageing of *Nephrops* is not possible and assessment models therefore depend upon length compositions either directly or by creating pseudo-ages based upon assumptions regarding size at age. Landings of *Nephrops* are comparatively well sampled for length compositions and effort data are reliable. Fishery-independent surveys, comprising underwater TV surveys, in which the burrows created by *Nephrops* are counted, have been undertaken in most of the major UK fishing grounds for several years. In recent years these surveys have become the basis for stock assessment for most of the fishing grounds, replacing pseudo-age based assessments. Limit reference points have not been defined for ICES stocks, but, although not formally framed as target reference points, some stocks are now being managed on the basis of a constant harvest ratio; with the level of harvest ratios applied, differing between stocks, dependent on considerations of potential stock productivity. By-catch of whitefish in *Nephrops* trawl fisheries can be a significant issue in some areas, and has come under scrutiny with respect recovery plans for both cod and hake in recent years.

4.9 Spider crab

Spider crab fisheries in the UK are restricted to the English Channel, Celtic Sea and Irish Sea with Pembrokeshire, the South West and south coast being the most important areas. The UK fisheries developed with an export market to Spain in the late 1970's. Spider crab are primarily taken by pot fisheries, often as a by-catch. Seasonal targeting does occur, in areas of high abundance, when the adults may form large aggregations and when there is a ready market. Other gears take some by-catch, but spider crabs can be a nuisance by-catch for fixed nets targeting demersal fish and may be destroyed during removal from such nets. Landings in recent times have been variable, often reflecting market demand, and stocks are currently not considered over exploited. Spider crabs undertake systematic stock movements with the adults moving inshore in early summer. They are at the northern end of their range in southern Britain and there is some evidence to suggest that their range may be extending further north and east in response to more favourable climatic conditions in recent years. Spider crabs grow by moult, but unlike the other commercially exploited crustaceans in the UK, they have a terminal moult at maturity, after which no further growth occurs. Size at terminal moult is variable, with adults occurring both above and below the MLS. Assessment is not carried out routinely, because of the data poor nature and somewhat opportunistic nature of the fisheries. Some data are available from ground-fish surveys, but again quality is inconsistent through the time series. Current management is through MLS and indirectly through limitation by the National Shellfish Licence (though the latter is unlikely to exert any real effect). The MLS and data on size at maturity could provide the basis for empirical reference points such as Z* (Die & Caddy, 1997), as other reference points have not been developed for this species and fisheries data are poor. Management and monitoring is complicated because spider crabs are largely taken as a by-catch in fisheries targeting other species. New world fisheries for majid crabs, which tend to be larger and have high value, frequently prohibit the landing of females. However, for effective management of spider crabs in the UK, improved marketing opportunities and clear formulation of management objectives, prioritising potentially conflicting objectives between netters targeting demersal fish and crab fishermen that might periodically target spider crabs, are required. Potential fishery control mechanisms are complicated by both interactions with the mixed macro-crustacean fishery and demersal finfisheries.

4.10 Velvet crab

Velvet crab fisheries are widespread around UK coastal areas, with the inshore zones off the Yorkshire and Norfolk coasts providing the highest recorded landings into England and Wales. The species was originally considered a nuisance by-catch in the traditional brown crab and lobster pot fisheries, but increased market opportunities and a relatively high unit price have caused a change in opinion leading to some targeting. A healthy export market, apparent changes in the distribution of velvet crab as well as increases in abundance in the North Sea have led to a sharp rise in reported landings from 1999 to 2006, although landings in 2007 appear to have levelled off. It is thought that velvet crab is currently not heavily exploited, but as more fishermen target this crab, fishing mortality is likely to rise. Velvet crabs are susceptible to poor handling, which can lead to high mortality in both landings and discards. Less is known about the biology of velvet crabs than other commercially exploited crabs in UK waters because the fishery is relatively recent. Some studies on growth and reproductive biology have been carried out for populations around the UK (e.g. Tallack 2007), but most studies have taken place in Spain and these may not be relevant to velvet crab populations at higher latitudes. Landings records together with limited LPUE and length distribution data are available for recent years, but this species is relatively data poor and routine assessments have not been carried out. Any future assessment of velvet crab is likely to be prone to similar problems inherent in assessments for other crab fisheries and a recent study (Lawler *et al*, 2006) noted marked differences in size distributions over relatively small spatial scales. Recent improvements in commercial landings reporting and biological sampling may provide better landings and effort data for the near future. Potential stock assessment methodology would include analysis of catch per unit effort trends and possibly LCA and per recruit analyses, but given the observed local variation in size distributions, deciding on a suitable spatial scale at which to carry out assessments is problematic. Reference points could be empirical or based on CPUE or per recruit reference points. A traffic light system might provide a means of combining the various available metrics for these relatively data poor nature fisheries.

4.11 Brown shrimp

The Wash fishery for brown shrimp in the Southern North Sea is an open access beam trawl fishery and is commercially the most important brown shrimp fishery in the UK. Other fisheries mainly in the Irish Sea are less significant, but include fisheries in the Solway Firth and around North Wales and Lancashire. Despite high landings of shrimp into continental Europe the coastal distributions of populations on opposite sides of the southern North Sea has restricted international exploitation of the Wash stock. Landings are highly variable and heavily influenced by market forces and environmental factors. Stock assessment is difficult because this is a fast growing, and locally migratory species with a protracted spawning period. Exploratory prediction of yield based on observed environmental conditions, including rainfall and predator abundance and swept area methods have been applied. Variable catchability in time and space can be a problem for swept area methodology. Detailed per recruit modelling including specific life history traits of shrimps has been used to explore some aspects of this and might provide a basis for reference points. Other approaches (e.g. production modelling or possibly TL systems) that take account of environmental effects and predators may also be useful. Fishing mortality may be less significant than natural mortality and over exploitation is not thought to be a problem. However, it has been suggested that targeting of small shrimps on specific banks at specific times of the year may give rise to local growth over fishing. Using closed seasons or closed areas to take advantage of the rapid growth of shrimps may be an option, but high seasonal losses due to predation may also be critical. The stock recruitment relationship is poorly understood, but the fishery has recovered rapidly after very poor years historically, suggesting that good recruitment can occur when spawning stock is low. Brown shrimp fisheries use fine meshed nets in areas that are important nursery grounds for other commercial fish species (e.g. plaice and sole), and mitigating high by-catch mortality of juvenile finfish has generally received a higher priority than managing production from brown shrimp fisheries.

5 General conclusions

There is an extensive literature on reference points, precautionary management systems and harvest control rules and it is not possible to capture all aspects in a small study such as this.

In Europe, precautionary management systems for finfish have been quite well developed and formalised through the ICES forum. Reference points for ICES finfish stocks have focussed around the provision of limit reference points based on determining the spawning stock biomass at which recruitment is impaired and the fishing mortality likely to cause stock collapse, and defining thresholds to ensure these are avoided with high probability. Typically reference points have been based on age structured analytical assessments and stock recruitment relationships. Explicit rebuilding plans were initially implemented for severely depleted stocks and management plans, including target reference points, are now being developed for stocks more generally. This follows the realisation that in the absence of explicit targets, stocks tended to be managed close the threshold level. Management strategy evaluation through computer simulation is used to develop and test harvest control rules under a range of plausible scenarios.

However, many shellfish stocks have received much less attention than finfish, have poorer quality data sets and also particular biological characteristics that complicate stock assessment. As a result reference points and precautionary management frameworks are less well developed for many shellfish stocks.

Crustacean species cannot be routinely aged and time series of stock and recruitment data are rarely available. This removes the potential for calculating most of the limit reference points commonly used for finfish stocks. However, *Nephrops* are assessed within the ICES framework, formerly using the traditional ICES age-structured approaches, but more recently with fishery independent burrow count surveys playing an important role in combination with sampled size structures. Reference points consisting of harvest ratios considered sustainable are used to set annual TACs. Equilibrium length-structured assessment (e.g. LCA) and per recruit analysis provide a basis with which to calculate exploitation rates and patterns and associated reference points. This approach has been applied for American lobsters and suggested for use with European lobsters in Ireland. Catch rate data also provide a useful indicator, but good time series are not always available and commercial effort data are generally poor. Crabs have a rather more complicated life history than lobsters, exhibiting more systematic stock movements and having widely differing catchabilities, both in time and between sexes. There is also an international dimension to many of their fisheries and data are relatively poor. Thus although LCA and per recruit approaches can be applied their assumptions are more likely to be violated and there are few examples of this approach being applied. Traffic light approaches might provide a means of utilising the data that are available, which includes some individual vessel catch rate data, in a flexible, but less formal manner. Most other macrocrustaceans are very data poor and are often taken as by-catch in the edible crab and lobster fisheries, or other fisheries. Estimation of effective effort is very difficult for all the macrocrustacean species because of interactions between the pot fisheries and more empirical methods for setting reference points, monitoring stock levels and applying management may be needed, particularly for the less targeted species.

The offshore bivalve fisheries pose different problems, largely associated with a mismatch between the scales of biological populations and the scale at which commercial data are available. Stocks are highly spatially structured and population parameters can differ at quite local scales, probably in response to local environmental conditions. Thus although they can be generally be aged routinely and length data can be collected, data are not usually available to permit stock assessment at meaningful scales. Reference points and management approaches based on the relative distributions of the stocks and fisheries, possibly in conjunction with information on stock densities (or catch rates) provide a potential means for reference and control.

By contrast, many inshore molluscan stocks, particularly cockles and mussels, have well developed management plans incorporating monitoring programmes, reference points and management controls. These typically use annual surveys to obtain absolute estimates biomass and use a variety of control measures (spatial and temporal closures, TAC, access limitation, daily quotas) to achieve the management objectives that are framed using reference points such as medium term biomass being above some limit, short term biomass being above a limit, a target harvest ratio, and a balanced age structure.

Most UK cephalopod species are taken as a by-catch in mixed fisheries and there may also be international dimensions to these fisheries. This complicates monitoring, assessment and management, which is not well developed for these species in Europe. The main species of interest to the UK (E & W) is likely to be cuttlefish for which there are major fisheries in the English Channel. The semalparous life cycle of many cephalopod species often results in precautionary management based on reference points that ensure a minimum spawning biomass is permitted to escape. However, at present international data collection and assessment programmes for European cephalopod stocks are not well developed. Further, major components of the fisheries are taken as part of mixed demersal fisheries (albeit potentially targeted at times) and this will complicate data collection, analysis and subsequent management.

In summary, shellfish species around the UK present a wide variety of differing characteristics and lifecycles and a ‘one size fits all’ approach to assessment and management is not possible. For some stocks existing management is well developed, formalised and effective, while for other species proactive management is largely absent. The highly analytical approaches applied for finfish and utilising stock and recruitment data are generally not appropriate for shellfish given the current data and knowledge bases, but length structured approaches and per recruit modelling are applied. The relatively sedentary nature of many shellfish species and spatial structuring of stocks and fisheries is important and may provide indirect means for reference and management. Many stocks are taken as by-catch and very data poor and in these instances more simple approaches may be required. At many levels of complexity there may be advantage in utilising several independent indicators and taking environmental conditions into account. Traffic light approaches can provide a suitable means to automate and formalise such data synthesis as well as the framework for making consequent management decisions.

Key considerations for assessing stock status and estimating reference points include:
- What level of stock assessment do current data support?
- Do historic data provide a reliable context from which to assess status?
- Do mixed fishery interactions obscure the data in a single species context?
- Do spatial or temporal factors prevent reliable estimation of status at the stock level?
- Are biological parameters sufficiently well estimated to provide reliable reference points?
- Are environmental effects (including multispecies interactions) more important for productivity than fishing?

FAO (1996) noted that:
- scientific standards of evidence (objective, verifiable and potentially replicable) should be applied in the evaluation of information used in analysis,
- the assessment and analysis process should be transparent, and
- periodic, independent, objective and in-depth peer review should be used as a quality assurance.

Some of the factors important for assessment also impact on management and HCR formulation where the following questions require consideration:
- What management measures are required for (re- or pro-) active control of exploitation for the target species in a single species context and are they likely to be acceptable?
- What management measures are required to control exploitation in a mixed fishery, and what priority does the species of interest have?
- What are the likely timescales for required action and what management measures are appropriate at this timescale (e.g. if action is only likely to be required infrequently then occasional changes to technical measures may suffice)?
- Can exploitation be effectively monitored and controlled by spatial or temporal measures and how will these impact upon the stocks and fisheries?
- Can management take advantage of, or mitigate, the environmental effects where these are important?
- At what spatial scale does the stock/fishery need to be managed; are there international dimensions that require EU legislation?

6 Recommendations and potential for Cefas involvement

Many littoral and inshore stocks of bivalves are effectively managed at the local level by Sea Fisheries Committees (SFCs). Cefas has involvement in monitoring and assessment as well as provision of advice for some of these and should continue to do so.

Nephrops stocks are currently managed through the ICES advisory role and EU TAC management framework. Cefas plays an active role in working groups where UK *Nephrops* stocks are important and this seems likely to continue.

Cefas is currently carrying out Defra funded R & D on scallops and developing modelling frameworks for evaluation of spatial management regimes. This work builds on previous R & D projects focussing on scallops and should provide a basis with which to evaluate spatial management options for scallop fisheries in the future. Current projects implementing and monitoring spatial closures to inshore scallop fisheries (e.g. Lyme Bay and Fal/Helford SAC) should improve the knowledge base with regards to the impacts of such closures. Cefas has been involved with these projects at various stages and is likely to continue to play an active role in the provision of monitoring programmes and advice.

Cefas is developing routine stock assessments for lobsters and crabs, primarily utilising equilibrium length structured assessments and per recruit analyses as well as analysis of subsets of individual catch rate data. These should continue to be progressed, possibly in collaboration with local SFCs, particularly where they are seeking accreditation for their shellfisheries. Crabs continue to pose significant problems for assessment and further methodological research into potential assessment and management frameworks may be useful.

At a recent Defra Inshore Fisheries Working Group the possibility of considering and managing the macro-crustacean fisheries together was suggested as one potential way forward. A traffic light approach integrating signals from the different stock/fishery components and indicating subsequent management actions would be one, albeit ambitious, approach to this. There are some advantages in considering these fisheries together, as some control mechanisms apply to all (e.g. national shellfish licence, potential pot limitation), but there are also problems, as likely stock and management scales differ between species and whilst lobsters are largely under national jurisdiction, several edible crab fisheries are international. The ICES Crab Working Group provides a forum to investigate the potential for international assessment and management. Cefas contributes to this ICES Working Group and is also actively involved in collaborative EU projects with other countries (e.g. France, Ireland & Scotland) involved in shared edible crabs fisheries.

Most cephalopod fisheries have international dimensions and there is a Working Group within ICES for consideration of these species, within which Cefas has a role. At present this WG is largely concerned with cephalopod biology and data collation and there is a lack of funding to make progress with assessment and management (ICES, 2007b). Given the international dimensions involved in these fisheries collaborative international projects would seem necessary to move things forward for these species.

Whelk fisheries are currently data poor, but quite important. They have relatively few direct interactions with other fisheries (in terms of by-catch) and the absence of a dispersal stage in the life cycle makes them potentially vulnerable to over fishing. The current EU MLS allows significant landings of immature whelks because of spatial variation in growth rates and size at maturity. Management is at a local scale is probably more appropriate and as such whelks could provide a useful and tractable case study for developing a TL system for assessment and management, subject to industry buy-in.

Table 4. Summary of data availability, current and potential reference point and pa management options for UK (E & W) crustacean species

Species	Description of fisheries	Data availability and quality	Current assessment, reference points (rps) and management	Assessment, rp and management issues	Potential / alternative rps and pa management options
Norway lobster *(Nephrops norvegicus)*	Important trawl fisheries in North Sea and Irish Sea	Landings (g), effort (m), LPUE (m), length composition (g), Burrow count survey (g)	Biomass and numbers estimated from burrow density and biological sampling. Rps - harvest ratio based on length based per recruit model Management by TAC	Inability to age, variable catchability by sex and in time, poorly known growth rates by sex Stock and management units do not correspond	
Edible crab *(Cancer pagurus)*	Major trap fisheries in North Sea, English Channel and Western Approaches	Landings (g), effort (p), LPUE (v), length composition (m)	LCA and LPUE trends, exploratory production modelling Rps - per recruit Management by MLS, vessel licensing, limited effort control	Stock identity poorly established, inability to age, variable catchability by sex and in time, systematic stock movements, sensitivity of assessment to growth and M parameters	per recruit, production models, historical effort trends, TL systems
Lobster (*Hommarus gammarus)*	Important trap fisheries in North Sea, English Channel, Celtic Sea and Irish Sea	Landings (g), effort (p), LPUE (v), length composition (m)	LCA and LPUE trends. Rps - per recruit Management by MLS, vessel licensing	Stock identity poorly established, inability to age, variable catchability by sex and in time, systematic stock movements, sensitivity of assessment to growth and M parameters	per recruit, production models, historical effort trends, TL systems
Spider crab *(Maja brachydactyla)*	Significant trap and net fisheries in English Channel and Celtic and Irish Sea	Landings (v), effort (p), LPUE (p), length composition (p)	No assessment Management by MLS, vessel licensing	Inability to age, poorly quantified biological parameters, terminal moult, systematic stock movements Nuisance by-catch in net fisheries	Empirical rps e.g. Z* TL systems Sex specific management
Velvet crab *(Necora puber)*	Significant by-catch around UK coast, with increased targeting	Landings (v), effort (p), LPUE (p), length composition (p)	MLS, vessel licensing	Inability to age, poorly quantified biological parameters	per recruit, production models, TL systems

Table 4. Summary of data availability, current and potential reference point and pa management options for UK (E & W) crustacean species (continued)

Species	Description of fisheries	Data availability and quality	Current assessment, reference points (rps) and management	Assessment, rp and management issues	Potential / alternative rps and pa management options
Brown shrimp *(Crangon crangon)*	Important local coastal fisheries in North Sea and other smaller fisheries in Irish Sea	Landings (g), effort (v), LPUE (v) (North Sea only)	Monitoring of landings effort and LPUE Exploratory specialised per recruit modelling and production modelling No rps Management by technical measures (mesh size and veil net).	Stock productivity highly influenced by environment, poorly quantified growth parameters, M > F Variable catchability (e.g. with light levels) Landings heavily influenced by market forces High by-catch of juveniles of other commercial fish species	Empirical rps e.g. F<M Per recruit and production modelling TL systems using environmental/predator indices Spatial/seasonal closures
Common or English prawn *(Palaemon serratus)*	Significant local trap fisheries in Irish Sea, small coastal fisheries elsewhere	Landings (p), effort (p), LPUE (p)	Monitoring using landings, effort and LPUE Exploratory work on trap selection Vessel licensing	Limited data poorly quantified biological parameters Static gear fishery	per recruit, TL systems
Pink shrimp *(Pandalus montagui)*	Minor UK trawl fishery in North Sea	Landings (g), effort (v), LPUE (v)	No assessment No rps Management by technical measures (mesh size and veil net).		
Northern prawn *(Pandalus borealis)*	Minor UK (E & W) trawl fishery in North Sea (nothing recorded in Farn since 1998 and Fladen since 2004)	Landings (p), effort (p), LPUE (p)	North Sea stocks have been assessed by ICES using age-structured methods and production models. Historic biomass trends (B_{loss}) suggested as rp Management by TAC technical measures (mesh size)	High assessment uncertainty and high M. Influence of predators	Production models, TL systems

Table 4. Summary of data availability, current and potential reference point and pa management options for UK (E & W) crustacean species (continued)

Species	Description of fisheries	Data availability and quality	Current assessment, reference points (rps) and management	Assessment, rp and management issues	Potential / alternative rps and pa management options
Crawfish *(Palinurus elephas)*	Rare by-catch species, high unit value Local fisheries in SW	Landings (v), effort (p), LPUE (p), length composition (p)	No assessment No rps Management by MLS, vessel licensing	Inability to age, poorly quantified biological parameters. Edge of species range.	
Stone or King crab (*Lithodes maja*)	Minor by-catch of North Sea trawl fisheries	Landings (p), effort (p), LPUE (p)	No assessment		
Shore or green crab (*Carcinus maenas*)	Minor estuarine fisheries usually trawled for use as angling bait	Landings (p), effort (p), LPUE (p)	No assessment		
Squat lobster (*Munida rugosa*)	No fishery in E & W				

Data quality codes: g:good, m:moderate, p:poor, v:variable

Table 5. Summary of data availability, current and potential reference point and pa management options for UK(E & W) molluscan species

Species	**Description of fisheries**	**Data availability and quality**	**Current assessment, reference points (rps) and management**	**Assessment, rp and management issues**	**Potential / alternate rps and pa management options**
Scallop *(Pecten maximus)*	Major fisheries mainly in the English Channel and Western Approaches	Landings (g), effort (g), LPUE (g), size and age structure	Exploratory production model and age structured assessments, no rps Management by MLS and some effort control / limited access	Spatially discrete populations with differing population parameters International dimension	Spatially structured reference points and closed areas F_{max} applied in U.S.
Queen scallop *(Aquipecten opercularis)*	N Irish Sea regular – few E&W boats. Yorkshire coast intermittent. Channel none recently	Landings (m), effort (m)	Not assessed	Spatially discrete populations with differing population parameters International dimension	Spatially structured reference points and closed areas
European oyster *(Ostrea edulis)*	Local estuarine fisheries in southern UK (e.g Milford Haven, Solent, R Fal, Thames/Essex)	Landings (p), effort (p), T-S survey abundance indices and size structure (Solent and R. Fal)	No analytical assessment or reference points. Management by MLS, licences and restricted entry, daily opening hours and seasons.	Interactions with aquaculture practises, relaying for growth or to assist marketing. Disease and competitors. Variable recruitment.	Spawning potential and recruitment indices (including spatial structure) Entry and effort control
Mussel *(Mytilus edulis)*	Important fisheries for seed and adult mussels in some areas (mainly, but not entirely estuaries)	Landings (p-g), effort (p-g), Some stock estimates with size and age structure.	Biomass estimates from surveys Rps - Minimum total biomass, minimum fishable biomass Management by MLS, TAC, daily quotas. Restricted entry. Seed quota as % of estimated stock area	Major interactions with aquaculture practises involving relaying for growth. Limited direct sale of wild stock to public. Interactions with cockles (and other molluscs) regarding effects of predators.	Existing adequate
Cockle *(Cerastoderma edulis)*	Major fisheries in Wash, Thames, S Wales, Morecambe Bay. Smaller fisheries in Solway, Dee and Solent.	Landings (p-g) effort (p-g), some total stock biomass, size and age structures from surveys.	Biomass estimates from surveys. Rps - Minimum total biomass, minimum prop. adults. Management by MLS, TAC, daily quotas, minimum cockle density, restricted entry.	Cockle/bird/fisher interactions Disease	Existing adequate

Table 5. Summary of data availability, current and potential reference point and pa management options for UK(E & W) molluscan species (continued)

Species	**Description of fisheries**	**Data availability and quality**	**Current assessment, reference points (rps) and management**	**Assessment, rp and management issues**	**Potential / alternate rps and pa management options**
Razor clam (*Ensis* spp.)	Some diving S Coast	Landings (p)	Not assessed	Periodic mass mortality due to storm damage (or life cycle events)	Total, exploitable and high risk, biomass indicators Spatial management, restricted entry, TAC, fixed escapement
Pallourde (*Ruditapes decussatus* and *R. philippinarum*)	Local fishery on naturalised *R philippinarum* in Poole Harbour and recently in Southampton Water. No fishery known on native species	Landings (g)	Stock survey, size and age structure. Management by MLS and restricted entry	Stock and management boundaries do not necessarily coincide. *R. philippinarum* - non-native species	
Surf clam (*Spisula*	No known fishery in recent years		Not assessed		
Whelk *(Buccinum undatum)*	Important fisheries in North Sea, English Channel, Celtic and Irish Seas	Landings (v), effort (m, v), CPUE (p)	Not assessed Managed by MLS	No dispersal phase Variable growth rate	Empirical rps e.g. Z* TL approaches, Control of exploitation on a local scale
Periwinkle *(Littorina littorea)*	Local fisheries on south and west coasts of E & W	Landings (p)	Not assessed		

Table 5. Summary of data availability, current and potential reference point and pa management options for UK(E & W) molluscan species (continued)

Species	**Description of fisheries**	**Data availability and quality**	**Current assessment, reference points (rps) and management**	**Assessment, rp and management issues**	**Potential / alternate rps and pa management options**
Cuttlefish *(Sepia officinalis)*	Major fisheries in the English Channel	Landings (g), effort (m), cpue (m), groundfish surveys	Not regularly assessed	Semalparous life cycle, environmentally sensitive population parameters Effect of static gear on egg survival International dimension by-significant proportion of catch is by-catch	Biomass and exploitation indicators Management by fixed escapement Control mechanism TAC or effort control
Squid *(Loligo spp.,Todarodes sp. Alloteuthis sp. Illex sp.)*	By-catch species in trawl fisheries, minor local jigging trials	Landings (p), effort (p), groundfish surveys	Not assessed	Several species, stock structures, semalparous life cycle, environmentally sensitive population parameters International dimension	
Octopus *(Octopus vulgaris, Elodone sp.)*	No directed fisheries	Landings (p)	Not assessed	May be semalparous	

Data quality codes: g:good, m:moderate, p:poor, v:variable

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