Workshop on Biological Reference Points for Invertebrate Fisheries held in Halifax, Nova Scotia, 2–5 December 2002: Abstracts and Proceedings

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Abstract

A workshop on biological reference points for invertebrate fisheries was held in Halifax from 2 to 5 December, 2002. There were a total of 59 participants from Argentina, Canada, Italy, New Zealand, the United Kingdom, and the United States.

The primary goal of this workshop was to gather Canadian and world-wide experience on determining stock status and reference limits for one or more invertebrate species within life history groups. In particular, we were interested in methods/approaches/indicators for determining whether or not fishing activities are sustainable, resulting in over-fishing or causing serious harm to the reproductive potential of an invertebrate stock. The secondary goal was to provide a forum for the presentation of new methods and concepts for determining reference points for invertebrate species that are tied to specific aspects of their life history.

The format consisted of a keynote paper given by John Caddy (formerly of FAO), six invited papers reviewing the situation for major species/life history categories and 17 contributed papers. Discussion groups were formed to summarize the papers presented, answer questions prepared by the organizers and recommend future research directions.

After examining the diversity of invertebrate species, life histories and management information required to develop reference points, it was fairly evident that there were too many species-specific details to develop a general set of reference points in one meeting. The workshop concluded with a summary discussion that focused on the most effective structure for a national invertebrate reference point working group. Participants also expressed their wish to see research focus on some of the most fundamental information requirements for reference points.

Resumé

Un atelier de travail portant sur les points de référence biologique pour les invertébrés a eu lieu à Halifax du 2 au 5 décembre 2002. Le nombre de participants a été de 59, en provenance de l'Argentine, du Canada, de l'Italie, de la Nouvelle Zélande, du Royaume-Uni et des États-Unis.

L'objectif premier de cet atelier était de mettre en commun l'expérience canadienne et internationale dans le domaine de l'évaluation de l'état des stocks et la détermination de points de référence pour une ou plusieurs espèces d'invertébrés réparties par catégories de cycle de vie. Plus particulièrement, nous nous sommes intéressés aux méthodes, approches et indicateurs permettant de déterminer si les activités de pêche en cours sont soutenables, si elles entraînent une surpêche ou causent un dommage au potentiel reproducteur d'un stock d'invertébré. Le second objectif était de fournir un forum pour la présentation de nouvelles méthodes et de nouveaux concepts pour l'établissement de points de référence biologique appropriés aux caractéristiques spécifiques du cycle de vie des espèces d'invertébrés.

L'atelier comportait un discours-programme par John Caddy (anciennement de la FAO), six présentations par des conférenciers invités portant dont le but était de faire une revue de la situation des principales catégories d'espèces ou cycles de vie, ainsi que 17 communications offertes. Des groupes de discussion ont par la suite été organisés afin de résumer les présentations et de répondre à des questions préparées par les organisateurs et recommander des avenues de recherche pour le futur.

Après examen de la diversité des espèces d'invertébrés, des cycles vitaux et des informations nécessaires à la gestion pour établir des point de référence, il est devenu assez évident qu'il y avait trop de particularités à chacune des espèces pour en arriver à développer un ensemble de points de référence commun au cours d'une seule rencontre. L'atelier s'est terminé avec une discussion générale sur la structure organisationnelle la plus efficace pour un groupe de travail national sur les points de référence biologique pour les invertébrés. Les participants ont aussi exprimé le souhait de voir la recherche se concentrer sur les questions fondamentales requises pour l'élaboration de points de référence biologique.

Acknowledgements

I am very grateful to all who took the time to contribute to the success of this workshop in so many different ways. First, I would like to thank the members of the organizing committee, Ross Claytor, Claudia Hand, Marc Lanteigne, John Moores, David Orr, Bernard Sainte-Marie and Tim Siferd, for their help and guidance. The panel discussants consisting of Michel Comeau, Louise Gendron, Graham Gillespie and David Orr took on a difficult job on short notice and managed to maintain focus and cohesion with little guidance. The speakers produced high quality presentations which gave us the information and ideas to work with. All of the participants contributed to the discussions during the presentation part of the meeting and afterwards in their respective discussion groups.

Ross Claytor, Andrew Cooper, Louise Gendron, Graham Gillespie, Claudia Hand, David Orr, Denis Rivard, and Bernard Sainte-Marie all provided very helpful comments on previous drafts of this report. Finally, I would like to thank Marie Charlebois-Serdynska for rescuing me from the financial aftermath of the workshop.

Preface

Publications on the precautionary approach to fisheries management stress the need for target and limit reference points. For example, Annex II of the 1995 UN Straddling Stocks Agreement states that there is the need to ensure that there be a low risk of exceeding limit reference points and suggests (para. 7): "…the fishing mortality rate which generates maximum sustainable yield (MSY) should be regarded as a minimum standard for limit reference points". In a number of jurisdictions, this suggestion has been interpreted to mean that the fishing mortality at MSY, or a proxy, along with the biomass at MSY can be used as limit reference points for many commercial species. Reference points have been defined for growth and recruitment overfishing in finfish using traditional stock assessment models. The very unique characteristics of invertebrate biology and their fisheries make it difficult to apply fisheries models and concepts such as yield-per recruit and MSY.

Most invertebrate species exhibit strongly spatially structured populations with low mobility adult stages but widely-dispersing larval stages. These characteristics likely result in metapopulations for which population models are still in their infancy. Other difficulties include discontinuous growth rates or spatially dependent growth rates, unknown stock-recruitment relationships and the inability to determine the age for non-molluscan species. Attributes of some management systems, such as the protection of egg-bearing females for crabs and lobsters, and the targeting of females for shrimp, can also contribute to the complexity of applying finfish ideas. In order to implement a precautionary approach to these highly valued fisheries, the definition of reference points will need to be tied very closely to life history characteristics of the species being fished.

The primary goal of this workshop was to gather Canadian and worldwide experience on determining stock status and reference limits for one or more invertebrate species within life history groups. In particular, we were interested in methods/approaches/indicators for determining whether or not fishing activities are sustainable, resulting in over-fishing or causing serious harm to the reproductive potential of an invertebrate stock.

The secondary goal was to provide a forum for the presentation of new methods and concepts for determining reference points for invertebrate species that are tied to specific aspects of their life history.

Background for meeting

Denis Rivard

Fisheries and Oceans Canada, Fisheries Research Branch, 200 Kent St., Ottawa, Ontario, Canada K1A 0E6

The development of reference points for vertebrate or invertebrate species should be done within the context of the Precautionary Approach (PA). The International community is committed to PA through treaties such as UNFA which was ratified by Canada in 1999 and came into force in 2001. PA frameworks have been developed for organizations such as ICES, NAFO, NASCO and ICCAT, amongst others. In the Canadian context, the Privy Council Office (PCO) has defined PA as being part of Risk Management within a wide range of government operations. Precaution would be invoked where some decision or action is required in a situation where there is a risk of serious or irreversible harm and there is a high degree of scientific uncertainty. In the PCO framework, Society chooses the risk tolerance but the burden of proof may be assigned.

The Department of Fisheries and Oceans has instituted a series of workshops, including this one to look at science requirements and implementation of PA for fisheries. In the context of fisheries, serious harm has been equated to the concept of impaired productivity of a target species or other components of the ecosystem. Recruitment overfishing would constitute serious harm, while growth overfishing would not, as this is related to economic performance. Harvest control rules under PA must be risk averse and ensure that there is a very low probability of serious harm. Actions designed to avoid serious harm would be initiated well above the limit reference point and rules would be more conservation-oriented as the limit is approached.

Questions that should be addressed at this workshop are:

1. What constitutes "impaired productivity" for particular invertebrate species?
2. What indicators are informative about "impaired productivity"?
3. How do we choose a position on the indicator(s), i.e., Conservation Limit?
4. How will we estimate risk of failing to stay above the Limit?

In answering these, the challenge will be to take into account the peculiarities of invertebrate species, which exhibit a wide variety of life history characteristics, and to take into consideration the uniqueness of management regimes or approaches to conservation.

Discussion Groups

After the presentations were completed, the workshop participants were organized into discussion groups corresponding to the four life history groups with each led by the leaders of the panel discussions (see page 56). These groups were asked to compare and contrast the life history characteristics of the species being discussed. Then, they were asked to answer the following three questions.

1. What metrics are applied to harvest control rules and are used to indicate good/impaired productivity?
2. What metric and actions are taken to monitor and promote recovery or adjustment within a fishing season?
3. What information and reference points (not in place at the moment) would/could/should be used as metrics of harm?

   Recommendations on where to go from here were also solicited.

Life History Group 1

These are species with high fecundity, highly dispersive larvae, mobile copulating adults that brood their eggs, and have a large sexual size dimorphism (e.g., lobster, crabs, shrimps). Fisheries either prosecute predominantly one sex or take special measures to protect egg-bearing females. Fishing operations may be disruptive of their habitat.

Chair and rapporteur: Michel Comeau

The primary goal of the workshop was to gather and share Canadian and worldwide knowledge on stock status assessment strategies and biological reference limits for invertebrate species. The overall tone of the workshop was set by asking a very important question: How can recruitment and/or growth overfishing for invertebrate fisheries be defined? To address that question, a series of presentations dealt with possible indicators that could be used to establish Target Reference Points (TRP) and Limit Reference Points (LRP). TRPs are frequently viewed as indicators to establish or elaborate management plans. They are reference points that define a target to achieve or move toward. LRPs are used as indicators to evaluate the efficiency of management plans in place and the sustainability of fished populations. These are reference points to avoid, and approaching them means that some action is required to avoid irreparable harm. These targets are usually established using models based on biological, economic, or social information and rarely on experimentation.

For the presentations and the panel discussion the species were grouped into crabs (Cancridae and Majidae), lobsters (*Homarus americanus* and *Nephrops norvegicus*), and shrimps (Pandalidae). There is a wide diversity of life histories and management regimes among crustacean species (Table 1). Presentations on crabs, lobsters and shrimps showed different growth patterns related to sex, strong sexual dimorphism, terminal molt at maturity, and short-to-long life spans. There are also various harvesting strategies (Table 2) with male-only fisheries for crabs, mainly female fisheries for shrimps, and restrictions on landing females with eggs attached under the abdomen where both sexes are commercially exploited (American lobster). Some management plans are based on a total allowable catch (TAC), while others rely solely on a minimum legal size (MLS) and restrictions on effort (Table 3). Levels of knowledge and research on the biology of crustaceans also vary among species.

During the panel discussion, it was agreed that a single currency should be used as a LRP for all crustacean fisheries, and perhaps for all invertebrate fisheries. The necessity of good egg production was recognized as the most important parameter for crustacean fisheries, and could be considered as the LRP. However, means to measure and ensure adequate egg production are still needed for these fisheries. In most crustacean fisheries, the MLS is the main management tool used to ensure good egg production, and is set according to the size at sexual maturity. Ensuring sufficient egg production in a female targeted fishery is difficult since the fishery targets the egg-producing portion of the population, while sperm limitation is a concern in a male-only fishery.

We also discussed and agreed that egg production alone cannot ensure the long-term health of a population and the sustainability of a fishery (Table 4). The egg production and larval survival are strongly influenced by environmental factors that are uncontrollable or not easily controlled. There is also a need for better understanding of the habitat and ecosystem in terms of invertebrate population requirements. Knowledge of the equilibrium between and among trophic levels is lacking, and the resiliency of the species to poor ecosystem conditions is unknown. It is believed that a large size distribution of commercially exploited animals and a diverse genetic pool are needed to achieve sustainable fisheries.

The main issue is how to establish threshold values for egg production and female condition. Establishing TRPs or threshold values must be done on a species specific basis, but the LRP could be based on the female condition in terms of egg production. We need to:

- define and understand recruitment overfishing,
- understand how biotic and abiotic factors affect populations,
- develop ecological and population models based on biological and fishery data (improve our data-based and model-based assessment tools),
- collect data to define the stock-recruitment relationship,
- establish for each fishery the range of fishing mortality values that would provide a sustainable fishery.

Table 1. Life history group 1: Comparison of life History characteristics.

	Crab		Lobster		Shrimp
	Cancridae	Majidae	*Homarus americanus*	*Nephrops norvegicus*	Pandalidae
Habitat zone	• From inshore to offshore.	• From the coastal waters to 400 m.	• Mostly coastal, but it could range from the shoreline to the oceanic plateau.	• Soft bottom habitat where the animal could dig burrows; • From 30 to 750 m; • Patchy distribution.	• Benthic mostly on soft bottom habitat in the Atlantic, and also on rocky habitat and one species is mostly pelagic on the Pacific coast; • Although depth range greatly varies by species, Pandalid shrimps are found from 50 m to 1000 m, but mostly fished between 150 m to 400 m.
Movement	• Large movement at the larval stages and very little movement at the benthic stages.	• Large movement at the larval stages and little movement at the benthic stages; • There is a general movement from shallow to deeper waters with increasing carapace size.	• Generally limited bathymetric and horizontal movement along the shoreline. More extended movement for lobsters in the Gulf of Maine and the American Eastern Seaboard.	• Sedentary.	• Diurnal vertical migrations; • Passive and active movements within water currents; • Winter “inshore” migrations for ovigerous females.

Table 1. Life history group 1: Life History characteristics, cont'd.

	Crab		Lobster		Shrimp
	Cancridae	Majidae	*Homarus americanus*	*Nephrops norvegicus*	Pandalidae
Reproduction					
	• Strong dimorphism in favour of the males; • Males have the opportunity to mate once or twice before reaching the fishery minimal legal size (MLS). Females are neither targeted nor retained in the fishery; • Egg incubation is one year.	• Strong dimorphism in favour of the males; Some males could reach maturity, hence their terminal molt, before the MLS and be permanently protected from the fishery; • Mating aggregation, and both males and females are highly polygamous; • Egg incubation could last 1 or 2 years. •	• There is a sexual dimorphism of the claws in favour of males and of abdomen width in favour of females; • MLS often smaller than size at maturity; • Males reach size at maturity earlier than females; • Egg incubation lasts 1 year and the female reproductive cycle (from egg laying to the next) is 2 years for up to 80% of females.	• Size at maturity close to the MLS; • Low to moderate fecundity.	• Protandric species, with a sex change occurring at year 2 to 4 depending on the temperature, the density and the population. The life expectancy after the sex change from male to female is unknown, but mortality after the second spawning is thought to be high.
Longevity					
	• Short life span of 6 to 10 years; • Mortality varies geographically; • No terminal molt.	• Average life span between 10 and 20 years old reaching a terminal molt at maturity; • Early benthic stages observed on a different ground than larger juvenile and adult stages.	• Long life span more than 50 years; • No terminal molt and both males and females can grow to the same size.	• Medium life span between 10 and 15 years old; • No terminal molt.	• Life span 4 to 10 years depending upon area.

Table 2. Life history group 1: Metrics applied to harvest control rules and those that indicate good or impaired productivity.

Crab		Lobster		Shrimp
Cancridae	Majidae	*Homarus americanus*	*Nephrops norvegicus*	Pandalidae
Harvest control rules				
• The minimum legal size (MLS) is set at a size larger than the biggest size reached by females. In terms of female condition, the reproductive potential of the stock is protected; • Male-only fisheries in most of cases, except for some European fisheries where both sexes are landed; • The exploitation rate is very high (up to 100%) for males larger than the MLS (for fisheries on the Pacific coast); • Total allowable catch (TAC) for some fisheries on the Atlantic coast;	• Male only fisheries with the MLS (set to protect 100% of the females) in Canada and the United States, but for other majid crabs in Europe where females are fished (e.g., female majid crabs are fished in the United Kingdom and exported to mainland Europe); • TAC with individual quotas (IQ); • Fishing season with a trap limit and a minimum mesh size; • No high grading of the catch. It is prohibited to select for more valuable crab;	• MLS is loosely set to protect a certain percentage of primiparous females; • There is no quota (except for the offshore fisheries); • Management tools are based on effort limitation in Canada but not in the U.S.A.; • Effort restriction in Canada is achieved by limiting the number of traps per fisherman and the number of fishermen per Lobster Fishing Area; • Traps are the only fishing gear permitted. There are restrictions on the trap size and traps must be equipped with escape vents;	• MLS; • TAC; • Mesh size regulation; • Undersized animals are discarded, but with a high mortality; • Mainly trawl fisheries and some small trap fisheries.	• TAC with no season (except in the Gulf of St. Lawrence fisheries with more effort control); • Limited entry; • Mesh size regulation for both pot and trawl fisheries; • Use of a bycatch separating grate; • Spawner escapement targets (BC); • F-based decision rules (used in West coast fisheries).

Table 2. Life history group 1: Metrics for harvest control rules and productivity, cont'd.

	Crab		Lobster		Shrimp
	Cancridae	Majidae	*Homarus americanus*	*Nephrops norvegicus*	Pandalidae
Harvest control rules cont'd					
	• Trap fisheries (traps equipped with escape vents); • Some areas with fishing season; • Some areas with soft-shelled crab monitoring.	• Monitoring of the percentages of soft-shelled crabs in the catch.	• Fishing seasons are also used to restrict effort; • Landing of v-notched females and females with eggs attached under the abdomen is prohibited. V-notching of females is done in some areas in both the United States and Canada.		
Good/impaired productivity					
	• Trends in landings are monitored, but there is no fishery independent indicator of productivity.	• The monitoring of the percentages of soft-shelled crabs in the catch; • Index of recruitment and abundance of different categories of crabs based on annual trawl surveys. Future recruitment can be evaluated based on these annual surveys;	• CPUE and landings; • Size at sexual maturity and reproductive cycle of females (to adjust the MLS and fishing seasons); • Size frequency of captured animals; • Egg-per-recruit model (using various biological and fishery parameters) to measure the egg production;	• CPUE and landings; • Size structure of the captured animals and of the entire population from trawl surveys; • Tuned VPA assessment; • Video surveys to assess abundance; • Yield-per-recruit model.	• Recruitment, abundance and biomass indices, and length frequency from trawl surveys; • Relationship between size at sex change and maximum size; • Changes in interannual spatial distributions; • CPUE in relation to abundance and demography.

Table 2. Life history group 1: Metrics for harvest control rules and productivity, cont'd.

Crab		Lobster		Shrimp
Cancridae	Majidae	*Homarus americanus*	*Nephrops norvegicus*	Pandalidae
Good/impaired productivity, cont'd				
	• Fecundity of primiparous and multiparous females; • Spermatheca content and egg viability (in relation to the female condition); • Shell condition; • CPUE and size structure of legal size males.	• Trawl surveys to estimate the abundance, the lobster diet and food chain information.		

Table 3. Life history group 1: Metrics and actions taken to monitor and promote recovery or adjustment within a fishing season.

Crab		Lobster		Shrimp
Cancridae	Majidae	*Homarus americanus*	*Nephrops norvegicus*	Pandalidae
• None.	• The monitoring of the percentages of soft-shelled crabs in the catches is used as a basis to close some areas within a crab fishing area if the percentage reaches 20%. This allows reducing the manipulation of weak crabs and the handling mortality; • The annual trawl surveys allow calculating abundance and adjusting the TAC based on historical proxy; • Most of the harvest controls allow evaluating and maintaining the reproductive potential of the stock.	• Virtually none, with the exception of some closed areas in limited locations.	• Monitoring the abundance to adjust the TAC; • Nephrops are normally taken in multispecies fisheries; management measures taken to protect other species may impact, positively or negatively, on Nephrops fisheries.	• The traffic light approach has been used to assess stock status; • Based upon both CPUE and the biomass/abundance from the research surveys, TAC can be adjusted; • The exploitation level is inferred from catch/biomass. The fishery could be closed if the biomass goes below an established historical proxy.

Table 4. Life history group 1: Information and reference points (not in place at the moment) that would/should/could be used as metrics of harm.

Crab		Lobster		Shrimp
Cancridae	Majidae	*Homarus americanus*	*Nephrops norvegicus*	Pandalidae
• Monitoring the sex ratio in terms of the handling mortality and female discards (TRP); • $F_{0.1}$ proxy using CPUE information; • Monitoring of the predator population, e.g., sea otter population on the West coast (TRP); • Egg-per-recruit model (LRP).	• Female condition in terms of fecundity and spermathecal content; • Sex ratio in relation to female abundance and geographical location.	• A better understanding of the reproductive dynamics of the population (with a focus on the female maturity) similar to what is now available for the snow crab; • Abundance of berried females in relation to size; • Identify the source of recruitment (source and sink) and develop a recruitment index; • Habitat index to evaluate the capacity of the ecosystem (in general terms of productivity) in relation to fishing mortality and natural mortality to generate a model based on ecology.	• F limit; • Biomass limit; • Abundance index limit.	• More long term information on the relationship between the sex change and the changes in the population are required to adequately assess the biomass; • More long term information on the relationship between abiotic (oceanographic conditions) and biotic (predators) is required to understand the natural fluctuations of shrimp populations.

Life History Group 2

This group includes species with a larval dispersal phase and with sessile adults that are broadcast spawners (e.g., bivalve molluscs, barnacles). These species occur in beds, are highly fecund, and fishing operations may be very disruptive of their habitat.

Chair and rapporteur: Graham Gillespie

This life history group includes a wide range of habitats and species from hard substrate epifaunal (oysters, mussels, barnacles) to soft substrate infaunal (largely clams; Table 5). Soft substrate infaunal animals can be further divided into inter- and sub-tidal groups. Reproductive strategies are similar; most species are broadcast spawners, although there are some complications due to hermaphrodism, and a few groups (barnacles) with internal fertilization. Most hermaphroditic species are cyclic or simultaneous, so there are no size considerations as in protandrous serial hermaphrodites (e.g., pandalid shrimp).

Most conservation strategies involve broodstock reserve areas or maintaining spawner densities at effective levels. These strategies have density-related considerations for successful fertilization; small areas of high concentration can be highly successful reproductively; many exotic species have become established from small introductions. However, these same concentrations are most attractive to harvesters, so consideration of micro-scale densities is as important as overall average density in beds.

Allocation policies can determine which management strategies are most effective. Clear definition of property rights can lead to increased stewardship, increased capacity, willingness to participate in co-management, and development of stock or habitat enhancement. Clear property rights foster better fishing practices (low impact) and are a strong incentive to avoid overfishing.

Stock-recruit relationships are relatively weak; although fecundity is high, recruitment is highly influenced by environmental factors, which makes development of overfishing definitions difficult. In many cases there is evidence for a meta-population structure, although razor clams (isolated populations) and cockles (estuarine entrainment) might have distinct populations in some localities. Large recruitment events have been recorded following significant mortality events; and there is literature discussing depensatory recruitment related to adult density. Occasional catastrophic mortality events make conservative strategies difficult to justify.

Intertidal populations have the advantage of being easily defined and surveyed. Mussel beds and oyster reefs can be defined using aerial photography. Fisheries for hard substrate epifaunal communities can have high habitat impacts, particularly when the fished organism forms habitat for other species, e.g., mussel beds or oyster reefs. Although recovery times in these systems can be long, monitoring is relatively easy. Clam beds are relatively easily delineated and surveyed at low tides. This has led to adaptive management approaches that monitor stock response to experimental harvest rates in terms of density or total abundance/biomass. This approach is intuitively accessible to harvesters, and allows collection of data for more complex modelling approaches. Because resource beds are relatively easily delimited, it was proposed to explore production and effort relationships (CPUE) on a per-unit-area basis to define reference points for overfishing.

Harvest controls generally involve effort limitation through limited entry, time and area closures, or bag limits (Tables 6 and 7). Size limits determined for size at first maturity are common, although not for fragile species or species that cannot re-bury, as effectiveness is limited by mortality of discards. Gear restrictions exist in many fisheries, limiting effort to hand picking or selective harvesting (e.g., geoduck stingers). Industrial approaches (hydraulic or dry dredge fisheries) have greater potential for rapid overharvest and habitat impacts. Some industrial fisheries have performance limits related to breakage of sublegal clams; these are designed to limit impacts of the gear on juvenile survival. Current or potential reference points to be used as metrics of harm are presented in Table 8.

Rotational harvests were strongly advocated. These have been used historically by First Nations, and are implicitly present in harvester behavior in fisheries managed over large areas or industrial dredge fisheries using highly efficient gear. They also proffer wider ecosystem benefits, particularly when considering impacts of industrial dredge fisheries. The rotational period is generally related to growth and recruitment characteristics, but these vary so much between years in bivalves that additional monitoring is required. This monitoring also allows evaluation of recovery of non-target species or habitat characteristics that may have been impacted by the harvest. Rotational harvest strategies may confer strong benefits to juvenile survival. With the possible exception of habitats that regularly suffer natural disturbance and have rapid recovery times, most rotational harvest strategies should incorporate area closures. Hatchery production techniques are known for some species and therefore enhancement is a possibility for the promotion of recovery from overfishing.

Closures for reasons other than stock concerns impact bivalve fisheries. Areas are regularly lost to contamination or allocation to aquaculture (tenures), or during periods of toxic algal blooms. Other potential closure rationales include areas of high conservation interest for other species (reserves for bird species dependent on bivalves — “predator allocation”) or areas where harvests are socially unacceptable (parks, noise or other disturbance of upland residents). Some fisheries are closed seasonally, either for YPR considerations (increased yield through growth) or to allow for undisturbed spawning and/or settlement. Some areas may have specific characteristics that would require removal from the fishery due to extended recovery periods (e.g., subtidal areas that support corals).

Generally applicable recommendations for this life history group included:

- Strong support for development of rotational harvest strategies;
- Regular surveys for stocks that are managed relative to virgin biomass;
- Continued research pertaining to critical densities and local processes necessary for successful reproduction;
- Consideration of a generally applicable limit reference point of $B_t > 0.5 \times B_0$;
- Although reserves have been advocated, guidelines as to how many, how large and where to place reserves is lacking. Research into the dynamics of larval dispersal would be of benefit;
- Explore yield-per-recruit approaches for developing reference points (e.g., maximum YPR) for sessile species.

Table 5. Life history group 2: Comparison of life History characteristics. Intertidal clams includes *Venerupis*, *Protothaca*, *Saxidomus*, *Siliqua* and *Cerastoderma*.

<table>
<tr><th>Geoducks
(Panopea spp.)</th><th>Intertidal clams</th><th>Surf clam
(Spisula solidissima)</th><th>Ocean quahog
(Arctica islandica)</th></tr>
<tr><td>• subtidal soft substrate infaunal;</td><td>• Intertidal soft substrate infaunal;</td><td>• subtidal soft substrate infaunal;</td><td>• subtidal soft substrate infaunal;</td></tr>
<tr><td colspan="4">• broadcast spawner;
• larval dispersal, adult sessile;
• aggregated in beds;</td></tr>
<tr><td>• extreme longevity.</td><td>• Short-lived to moderate longevity.</td><td>• moderate longevity.</td><td>• extreme longevity.</td></tr>
</table>

Table 6. Life history group 2: Metrics applied to harvest control rules and those that indicate good or impaired productivity. Intertidal clams includes *Venerupis*, *Protothaca*, *Saxidomus*, *Siliqua* and *Cerastoderma*.

Geoducks (*Panopea* spp.)	Intertidal clams	Surf clam (*Spisula solidissima*)	Ocean quahog (*Arctica islandica*)
• biomass estimates from surveys and stock reconstruction; • TAC with individual quotas; • closures due to toxic algal blooms (temporary); • closures due to water quality (potential reserves).	• historic production proxies; • stock abundance or biomass, density indices (stock response models); • feedback models (TACs or area thresholds); • age and growth (recruitment to fishery); • population structure (recruitment); • habitat available to fishery (area); • size at maturity (size limits); • closures due to toxic algal blooms (temporary); • closures due to water quality (potential reserves).	• initial biomass estimate; • limited entry and ITQs; • regular biomass surveys.	• initial biomass estimate; • limited entry and ITQs; • regular biomass surveys.

Table 7. Life history group 2: Metrics and actions taken to monitor and promote recovery or adjustment within a fishing season. Intertidal clams includes *Venerupis*, *Protothaca*, *Saxidomus*, *Siliqua* and *Cerastoderma*.

Geoducks (*Panopea* spp.)	Intertidal clams	Surf clam (*Spisula solidissima*)	Ocean quahog (*Arctica islandica*)
• monitor density from index patches in harvested areas; • monitor stock size or biomass from surveys; • monitor age structure from sampling; • enhancement possible to promote recovery.	• monitor stock abundance or biomass; • monitor population characteristics (growth and recruitment); • enhancement possible.	• monitor total catch and catch rates; • monitor population structure; • estimate area impacted (side-scan sonar).	• monitor total catch and catch rates; • monitor population structure; • estimate area impacted (side-scan sonar).

Table 8. Life history group 2: Information and reference points that would/should/could be used as metrics of harm. Intertidal clams includes *Venerupis*, *Protothaca*, *Saxidomus*, *Siliqua* and *Cerastoderma*.

Geoducks (*Panopea* spp.)	Intertidal clams	Surf clam (*Spisula solidissima*)	Ocean quahog (*Arctica islandica*)
• BC: target $F = 0.01 \times B_0$, limit $B_t = 0.5 \times B_0$; • WA: Target harvest rate of 2.7% determined through YPR analyses; • recovery proviso where beds must reach pre-harvest biomass before reharvest.	• density thresholds for exploitation of *Venerupis* ($< 30/m^2$ = closure, 30–70/m^2=10%, 70–130/m^2=20%, $>$ 130/m^2=40%; determined from survey); • density thresholds for *Cerastoderma* (beds closed to hydraulic dredge fishery if density $< 50/m^2$, determined from fishery catch rates); • harvest limits for Cerastoderma (33% of exploitable stock, determined from survey); • change in biomass and catch in feedback loop to direct effort in multiple subareas.	• Canada: officially $0.5 \times M \times B_0$ or $M \times B_{COM}$, which is the commercially available biomass; economic limits primarily control harvest. M = instantaneous natural mortality.	• USA: limit reference point $0.5 \times B_{MSY}$, target reference point $F = F_{0.1} = 0.042$.

Life History Group 3

Species with a larval dispersal phase and with poorly mobile adults that are broadcast spawners (e.g., sea cucumbers, sea urchins, abalone, swimming scallops, polychaetes including bloodworms — although some species do copulate). Similar to species in group 2 these species usually occur in beds, are highly fecund, and fishing operations may be very disruptive of their habitat.

Chair and rapporteur: Louise Gendron

The discussion group deliberated on the three questions posed by the Chair. However, in the absence of specialists working on abalones, sea cucumbers or polychaetes, discussions focused essentially on scallops and sea urchins. Information on scallops refers mainly to the sea or giant scallop *Placopecten magellanicus*, but also to the Iceland scallop *Chlamys islandica*, as far as the northern Gulf of St. Lawrence is concerned. Discussions on urchins focused primarily on the green sea urchin *Strongylocentrotus droebachiensis* although some information relevant to the red sea urchin *S. franciscanus* was also presented.

The topic on life history was broadly discussed and the group felt that characteristics other than the one suggested — habitat, movement and longevity — should be mentioned because of their importance and relevancy to the determination and understanding of biological reference points (Table 9). The discussion was therefore expanded to include biological and ecological traits of reproductive adults, larvae, settlers and juveniles.

The discussion on Limit Reference Points (LRP) was held considering that a situation occurring below a given limit would impair productivity in terms of the ability of the stock to reproduce itself. This refers to the concept of recruitment overfishing, as opposed to growth overfishing which was considered here not to impair productivity in the sense given above.

No clear definition of overfishing exists for these two species although some arbitrary limits to overfishing have been defined and are operational, especially for scallops in federal waters of the USA because of the Magnusen Act (Table 10). However, there is a lot of uncertainty that a given limit will prevent overfishing and assure the persistence of the populations. It is also recognized that limits may vary with different environmental regimes and that one single limit may not be appropriate for the entire range of environmental variability.

As for many invertebrates, the stock-recruit relationship is not well understood. For these semi-mobile species that have relatively long pelagic larval phase, recruitment is often sporadic and highly variable. However, the experience of temporal area closure for the scallop and the sea urchins show that egg production can be significantly increased, translating in an increase in recruitment, as recently demonstrated for scallops on the U.S. side of Georges Bank. The protection of reproductive potential is always of great importance and in broadcast spawners, there is an effect of aggregation of reproductive adults on the success of fertilization. This has been demonstrated for scallops. This implies that density is much more important than absolute abundance in setting limits.

To date, in most of the fishing areas, management measures have been averaged over space, not taking into account the patchiness of the resource and the fact that different populations (a mixture of sources and sinks) may exist (Table 11). Fishing effort is often directed towards most productive areas that end up being more heavily fished than low productive areas. The fact that these areas may be source populations constitute a concern because their depletion could affect persistence of populations at a larger scale. A spatial approach to the management of these species is indicated.

As stated by Rago and Smith at this workshop, advances in technology, in statistical and numerical models, as well as a growing acceptance by industry for this kind of management are factors that lay the basis for the implementation of appropriate spatial management measures. Moreover, sound spatial management could possibly reduce recruitment variability if known source populations are subjected to lighter exploitation rates. More work is still necessary to better understand the spatial pattern of larval dispersal and the spatial dependencies for recruitment (Table 12). Some progress is being made in the development of models coupling hydrography and biology.

Table 9. Life history group 3: Comparison of life History characteristics.

<table>
<tr><th>Scallops</th><th>Sea Urchins</th></tr>
<tr><td colspan="2">Adults</td></tr>
<tr><td colspan="2">• Adults are poorly mobile and generally considered as sedentary;
• Adults are not randomly distributed and form aggregates;</td></tr>
<tr><td>• Scallops are found on sandy and gravel bottoms, from 35 m to 120 m depth in the southern part of their range and shallower in the north;</td><td>• Urchins are found on hard substrates from the lower intertidal to 200 m depth;</td></tr>
<tr><td colspan="2">• Concentrations are targets for exploitation;
• Areas of high density are heavily fished;</td></tr>
<tr><td>• Density and proximity of adults is known to be important for reproductive success (fertilization).</td><td></td></tr>
<tr><td colspan="2">Sexual maturity</td></tr>
<tr><td>• Size at sexual maturity is generally lower than commercial size, but egg production from sub-commercial size scallops may be insignificant.</td><td>• Size at sexual maturity is much lower than commercial size in sea urchins.</td></tr>
<tr><td colspan="2">Growth</td></tr>
<tr><td>• Scallop growth rate is high especially during the first years;
• K/M is high;
• Growth is variable depending on depth, temperature and food availability.</td><td>• Sea urchin growth is extremely variable;
• Urchins can reach commercial size (5 cm test diameter in 5 to 15 years depending on food availability);
• Ageing is difficult and currently not done.</td></tr>
<tr><td colspan="2">Longevity</td></tr>
<tr><td>• Longevity is of the order of 20–25 years in the sea scallop and probably near 40 years in the Iceland scallop;
• On average, life expectancy in exploited populations for both species is 5–7 years.</td><td>• Longevity is high, easily up to 20 years.</td></tr>
</table>

Table 9. Life history group 3: Life History characteristics, cont'd.

<table>
<tr><th></th><th>Scallops</th><th>Sea Urchins</th></tr>
<tr><td>Juveniles</td><td>• There is no strict spatial segregation between adult and other life stages (sublegals, juveniles, settlers);
• It is possible to find areas with only one cohort of scallops settled, but often, several age cohorts can be found together.</td><td>• There is no strict spatial segregation between adult and other life stages (sublegals, juveniles);
• For the red urchin, spines from adults form a protective canopy for settlers and their presence determines survival of settlers.</td></tr>
<tr><td>Larvae</td><td colspan="2">• Larvae are planktonic and very mobile and have a 1–2 months duration;
• Their dispersal can be large scale depending upon hydrographic conditions;
• The pattern of larval dispersal is poorly known;
• Larvae are capable of vertical migrations;
• At settlement, they are capable of choosing particular substrates.</td></tr>
<tr><td>S-R relationship</td><td>• Historic data on S-R relationship are limited in range;
• Recent data from closed areas show that an increase of spawning biomass has translated into higher recruitment.</td><td>• Data available on S-R relationships are limited in range;
• There is no information on the slope of S-R near the origin.</td></tr>
<tr><td>Ecology</td><td>• Scallops are subject to massive mortalities mostly in marginal areas, where temperatures are near or exceed their temperature tolerance;
• Die-offs are also observed in nearshore populations;
• Diseases have also been known to induce mass mortalities.
• Catastrophic mortalities have been reported in the chronically embyssed Iceland scallop;
• Starfish species are important predators of scallop.</td><td>• Sea urchins are subject to mass mortalities caused by an amoeba. The die-offs are associated with warmer temperatures and high urchin densities;
• Urchins are subject to important depletion by predators such as seastars and sea otters, and a number of fish species;
• There is a tight ecological coupling between urchins and algae. Quality of roe depends on algal food source.</td></tr>
</table>

Table 9. Life history group 3: Life History characteristics, cont'd.

Scallops	Sea Urchins
Fishery	
• Management measures provide protection of small animals through size limits and selectivity of the fishing gear (ring size). Survival depends on handling; • In certain areas, fishing activities are prohibited during reproduction and the settlement period; • Buffer zones set to protect lobsters provide refugia for scallops; • Fishing with heavy dredges may be disruptive to the habitat and to recently-settled spat. • There could be economic refuges.	• Harvesting of sea urchin is done mainly by Scuba diving; • In certain areas, the use of drags is allowed while in others it is prohibited; • Scuba diving is depth-limited and provides refugium for urchins.

Table 10. Life history group 3: Metrics applied to harvest control rules and those that indicate good or impaired productivity.

Scallops	Sea Urchins
Harvest Control Rules	
• Biomass estimates (B); • Estimation of F; • Amount of area fished; • Commercial catch rates; • Size/age structure; • Recruitment indices; • Meat weight/meat count; • Yield-per-recuit: • Egg-per-recruit; • Probability that biomass goes above or below a given threshold (evaluated with a Bayesian state-space model, Bay of Fundy).	• Biomass estimates (B); • Commercial catch rates; • Bathymetric distribution in relation to kelp beds; • Density; • Size structure; • Recruitment index; • MSY = XMB, where X=0.2, M=0.05–0.15 and B=current biomass from survey • Lifetime egg production (EPR); • Yield-per-recruit; • Maximum sustainable yield (MSY).
In many fishing areas, these various metrics are used to set TACs or on an in-season basis (rolling TAC, e.g., German Bank). An ADAPT/VPA approach is used to determine B and F in certain regions (part of Georges Bank, Canada) Data are obtained through research surveys and commercial sampling.	In many fishing areas, biomass estimates are used to set TACs based on MSY or based on an exploitation rate varying among regions between 3.3–6.6% of initial or standing biomass. Many of these fisheries have experienced three phases of development : expansion, collapse and recovery to lower but sustainable levels. Data is obtained through research surveys and commercial sampling.
Good productivity is indicated when:	
• B is above a limit defined as $0.25B_{MSY}$ (U.S. stocks); • F is below F_{MAX} or $0.8F_{MAX}$ (U.S. stocks)[1]; • Commercial and survey catch rates are above average (time series); • Amount of area fished is above average (time series); • Recruitment indices are strong;. • Meat weight remains higher than 8 g (Bay of Fundy); • Meat counts remain low, below average; • Probability that next year's biomass declines below the threshold biomass for a specific harvest plan is less than 0.15 (Bay of Fundy).	• B is above a limit defined as B_{MSY} • EPR is over 20% or 35% of an unfished population; • F does not exceed F_{MAX}; • Bathymetric grazing fronts remains below the 6 m isobath[2]. For this species too high densities impair productivity [2]This bathymetric limit prevents destructive grazing of kelp and allows to maintain algal canopy which is essential for roe quality.
[1] A level of 0.8 F_{MAX} prevents growth overfishing and also prevents recruitment overfishing. At this level of F, EPR reaches 25% of an unfished stock. Limit for recruitment overfishing has been set in the past to 5% EPR of an unfished stock.	

Table 11. Life history group 3: Metrics and actions taken to monitor and promote recovery or adjustment within a fishing season.

Scallops	Sea Urchins
Metrics	
• Biomass survey; • Size/age structure; • Growth;. • Recruitment index; • Natural mortality (clappers);	• Biomass; • Size structure; • Growth; • Recruitment.
Actions	
• Reductions of TAC (easier with ITQ); • Area closures: In the U.S. if $B < 0.25B_{\mathrm{MSY}}$ it is required to implement a plan to rebuild to B_{MSY} within 10 years; • Rotational closures (3 years); • Effort limitations: reduction of fishing season or days-at-sea; increase in ring size; • Changes in meat count (from 52 to 44 meats per 500 g in Gulf of St. Lawrence); • Enhancement through seeding; • Develop aquaculture in areas where stocks have been strongly depleted.	• Reductions of TAC; • Area closures; • Rotational closures (5 years). Effort limitations appear difficult to implement. More caution should be taken in giving access to new fisheries.

Table 12. Life history group 3: Information and reference points (not in place at the moment) that would/should/could be used as metrics of harm.

Scallops	Sea Urchins
• Biomass limits[1]; • F limits[1]; • Average meat weight in catch; • Age/size structure; • Minimum density for successful fertilization; • Spatial dynamics of recruitment process.	• EPR; • Feeding fronts at specific depths — ecosystem-based limit; • Maximum density for better productivity;

[1] B and F limits are currently used in U.S.

Life History Group 4

Species with direct development (no larval dispersal phase) and with copulating adults that are either mobile (e.g., squid) or poorly mobile (e.g., octopus, whelk, gammaridean amphipods). These species usually have low fecundity and are prosecuted by fisheries which are usually not disruptive to their habitat.

Chair and rapporteur: David Orr

The panel discussion covered:

1. short-finned squid (*Illex illecebrosus*);
2. neon flying squid (*Ommastrephes bartramii*);
3. market squid (*Loligo opalescens*);
4. Giant Pacific octopus (*Octopus dofleini*);
5. whelk (*Buccinum undatum*).

Squid:

Limit reference points (LRPs) are difficult to develop for squid because the species are characterized by relatively short life cycles (one year), no known stock-recruit relationships, population dynamics are strongly impacted by environmental effects, and only a limited portion of the squid stocks are available in Canadian waters (Table 13). However, the panel suggested that harvest control rules (i.e., TRPs) could include TACs and target fishing mortalities (Tables 14 and 15). Estimates of residual fecundity (*L. opaslescens*) and indices of relative fishing mortality (*I. illecebrosus*) were suggested as ways of monitoring the fisheries and changes in exploitation levels. Recruitment of *I. illecebrosus* is strongly affected by environmental variation, and it is possible that environmental indices offer some potential for serving as a basis for developing target and limit reference points for annual squid species in the future. Such TRPs and LRPs could possibly be based on allowing appropriate levels of spawning escapement (Table 16). However appropriate threshold escapement levels are unknown and they would likely change annually with environmental variation.

Giant Pacific Octopus:

Currently there are no biologically based measures that could be used to manage the giant Pacific octopus. This is a territorial animal that lives in crevices (Table 13). Assessment data are obtained from divers operating in nearshore fishery (Tables 14 and 15). As octopi are removed from nearshore crevices, immigrants from deeper water replace them; therefore, the fishery is characterized by a hyperstable CPUE (Table 16). Fishery impacts will only be detected when both the nearshore and deeper water communities become depleted.

Whelks:

Line transects have been used to study whelk populations in the Gulf of St. Lawrence. However, basic biology such as fecundity, density dependence, seasonality, habitat, sex ratios and size distribution were not well understood by the panel members (Table 13). As a precautionary measure, managers in Quebec and New Brunswick have established minimum shell height restrictions (Table 14).

It was suggested that indicators of stock status could include fishery CPUE, an index of area fished, changes in mean shell height and interannual changes in size frequency.

These animals have limited mobility, therefore, it would be possible to promote recovery by seeding areas and rotating areas being fished.

In general, the panel members felt that they did not understand the biology of these animals well enough to develop meaningful target reference points (TRPs) or limit reference points (Table 15). There was no fishery independent data for either the market squid, or Giant Pacific octopus and only limited data for the other species. This group is very diverse and it is likely that each will require unique sets of reference points that can only be developed after a great deal of research and consideration.

It is doubtful that the Canadian Department of Fisheries and Oceans will have the resources to conduct research surveys directed for these animals. Therefore, efforts should be taken to make better use of fishery data such that stock status can be monitored and that meaningful reference points and harvest control rules can be developed (Table 16).

Table 13. Life history group 4: Comparison of life History characteristics.

Shortfinned squid (NL)	Neon flying squid (B.C.)	Market squid (B.C.)	Giant Pacific octopus (B.C.)	Whelks
• distribution broad from Florida to Newfoundland; • highly migratory spawning south of Canadian waters; • One year life cycle;	• Offshore distribution; • Spawn in tropics; • Feeding migration in Gulf of Alaska, return south spawn and die; • One year life cycle; • a new and emerging fishery.	• Nearshore distribution; • Localized spawning aggregations; • One year life cycle	• Territorial adults; • Terminal spawner; • pelagic paralarvae; • high fecundity ($\sim 10^6$); • 3–5 yr. life cycle.	• Poorly mobile; • 5–6 years until maturity; • 10 year life cycle • Still require basic biology pertaining to fecundity, density dependence, seasonality, habitat, sex ratios, size distribution etc.

Table 14. Life history group 4: Metrics applied to harvest control rules and those that indicate good or impaired productivity.

Shortfinned squid (NL)	Neon flying squid (B.C.)	Market squid (B.C.)	Giant Pacific octopus (B.C.)	Whelks
• Survey indices (Scotian shelf; USA and Gulf of St. Lawrence) number/tow, kg/tow, mean body weight; • Fishery catch by area; • Inshore Newfoundland size frequency; • Environmental indices (North Atlantic Oscillation, oceanic fronts, bottom temperature).	• Catch; • Effort (CPUE); • Size composition; • Reproductive maturity; • Sea surface temperature; • No fishery independent data; • Proposed a target fishing mortality; • Data was insufficient.	• Catch; • Effort (CPUE); • No fishery independent data; • Fishery not assessed or actively managed.	• Catch; • Effort (CPUE); • Size/ sex/ maturity; • No fishery independent data.	• shell height (65 mm in Quebec, 75 mm in New Brunswick); • in Quebec metrics include: 1. CPUE; 2. Density; 3. Index of area fished; 4. Mean size within each area; 5. Number of fishermen.

Table 15. Life history group 4: Metrics and actions taken to monitor and promote recovery or adjustment within a fishing season.

Shortfinned squid (NL)	Neon flying squid (B.C.)	Market squid (B.C.)	Giant Pacific octopus (B.C.)	Whelks
• Body weight; • Survey catch rates; • Ratio of catch to survey catch rate can provide an index of relative fishing mortality; • Regulated by TAC.	• Leslie-Delury depletion modelled population (proposed); • Fishery remains small; • Fishery inactive over last 3 yrs.; • Insufficient data.	• None.	• Gathering assessment data; • Currently no biologically based management measures.	• Increase minimum size; • Export restrictions; • Seeding areas; • Rotate areas being fished.

Table 16. Life history group 4: Information and reference points (not in place at the moment) that would/should/could be used as metrics of harm.

Shortfinned squid (NL)	Neon flying squid (B.C.)	Market squid (B.C.)	Giant Pacific octopus (B.C.)	Whelks
• Information stock-recruit relationship (currently unknown); • Effects of fishery unknown because of strong environmental effects; • Relative fishing mortality; • LRP could be based upon spawning escapement but appropriate threshold level is unknown.	• Information stock-recruit relationship (currently unknown); • Extremely limited portion of stock available in Canadian waters; • Should explore spawning escapement reference point.	• Information stock-recruit relationship (currently unknown); • Strong environmental effects; • Spawning escapement reference point (residual fecundity).	• Information stock-recruit relationship (currently unknown); • Continual replacement of octopi removed by fishery by immigrants from deeper water; • Hyperstable CPUE until nearshore (those that people can access by diving) and deepwater pools are depleted; • Appropriate LRP's unknown.	• Size at 50% maturity; • Comparison of size frequency in catch between years.

Summary: Next steps and recommendations

After examining the diversity of invertebrate species, life histories and management information required to develop reference points, it was fairly evident that there were too many species-specific details to develop a general set of reference points in one meeting. A number of presentations highlighted the need to determine minimal spawning densities for sessile organisms and how these could be used as reference points. For many species, stock-recruit relationships were listed as being unknown but it was recognized that knowing these relationships was vital for the definition of limits. Research on larval behaviour and the use of enhancement methods to improve productivity was also considered important issues for some species. The possibility of establishing a common metric or currency in terms of spawning potential as a reference point over the diverse life histories was raised. Finally, there was a plea for consistency over all species, in the definition and monitoring of the criteria for serious harm as required for the Privy Council Office's definition of the precautionary approach.

The participants agreed to the formation of a national working group to continue the work initiated at this workshop. In particular, participants wanted the informality of a working group structure so that it would be effective in rapidly dealing with emerging issues in the development of limit and target reference points for invertebrates.

There was a summary discussion that focused on the most effective structure for a national invertebrate reference point working group. Subgroups corresponding to the life history categories used in this workshop should be formed to continue to add to the catalogue of life history characteristics in Tables 1, 5, 9 and 13. There was substantial information lacking for many of the species presented or discussed at the workshop. In addition, a number of exploited species such as sea cucumber were not discussed at all. The notes contained herein on metrics for harvest control rules, for measuring good/impaired productivity, as well as for monitoring populations and promoting recovery represent a substantive beginning. These life history subgroups could focus on both contributing more of the information that is currently available on these metrics and proposing new research to address the gaps. Participants expressed the wish to have research focus on some of the most fundamental information requirements for reference points (e.g., egg production). Progress and issues from the subgroups could be reported to the national group. Periodic meetings of a national working group could then bring together experts from within and outside of the department to focus on specific issues, especially those that cut across life history groups such as a common definition of conservation limits and common metrics in terms of spawning potential.

Keynote Address

Current usage of fisheries indicators and reference points, and their potential application to management of fisheries for marine invertebrates

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Applications of fisheries indicators for highlighting resource conservation problems are discussed, and the actual and potential use of time series of indicators and reference points in resource management illustrated, not excluding experience from outside invertebrate fisheries. A classification of reference points and their uses is provided, and the role of Limit Reference Points (LRPs) is extended to situations where stock rebuilding is needed. Criteria for listing endangered species, as in the case of CITES Appendices are discussed, and a simple trend analysis for Mediterranean invertebrate resources discussed. The pressure, state, impact response indicator classification used in environmental assessment is contrasted with the use of indicators and reference points (within harvest control rules or stock recovery plans) for marine resources. Indicators and reference points are suggested for invertebrate resources where age composition and stock-recruit relationships (SRRs) are rarely known. Since SRRs are usually unavailable for invertebrates, other population characteristics are suggested for invertebrate fisheries in a multi-LRP context, with particular emphasis on indicators that are productivity-based, and ecosystem, spatial, habitat, environmental characteristics and regime states all require monitoring, in a broad-brush approach to monitoring that provides necessary redundancy. Reference points derived from models are compared with the direct use of empirical data values believed to represent limiting conditions or safe stock situations. The use of multiple indicators and LRPs in harvest rules and other decisional infrastructures is discussed with examples. This could take the form of a traffic light system to indicate the onset of undesirable conditions, combined with a pre-negotiated harvest rule to constrain management responses. Classification of resource states by ‘colour’ within harvest laws records the transition from a safe ‘green’ phase, through ‘yellow’ or ‘orange’ uncertain or high risk conditions, into a dangerous zone classified as ‘red’ where prompt management action should be triggered.

Life History Group 1

Review of crab reference points used in US and Canadian crab fisheries and a comparison of a referential system estimated using a length-based method for Snow Crab and Dungeness Crab

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We reviewed the Reference Points (RPs) currently used for managing crab stocks in the US and Canada. In addition, we developed harvest rate- and biomass-based RPs using specific parameters for snow crab and Dungeness crab stocks in the US and Canada. We explored the trends in threshold harvest rate and biomass ratios derived for females and combined sexes using a length-based approach which incorporated Beverton-Holt and Ricker stock-recruit (S-R) models for various parametric values. In the absence of established S-R relationship for the two species, a plausible range of values relating to the steepness of the S-R curve near the origin were considered and average RP values were determined. The recruitment was also perturbed to generate distributions of RPs. Threshold harvest rate estimates were lower for combined sexes spawning biomass than for female only spawning biomass in all the analyses. Increasing the minimum size at first capture and decreasing estimates in handling mortality resulted in an increased threshold harvest rate. However, changes in fishery duration and timing of the fishery open date did not change the threshold harvest rate appreciably. The use of a Beverton and Holt S-R model provided lower threshold harvest rates than that of a Ricker S-R model. Threshold harvest rates for the Canadian Snow and Dungeness crabs were generally higher than those estimated for the Bering Sea and Southeast Alaska stocks. Natural mortality, initial sex ratio, mating ratio, and S-R relationship have a great influence on the threshold harvest rate and biomass ratio estimates. For the Dungeness crab stocks, mortality, growth, maturity, and selectivity parameters are lacking for different components of the stocks. Thus, greater effort should be devoted to collect this information. The results of this exercise need to be treated in a precautionary manner because of the unknown parameter values.

A hierarchical approach to determining reference points for Pandalid Shrimp

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Reference points for harvesting Pandalid shrimp are categorized into four general approaches: historical proxies, biomass dynamics models, dynamic pool models, and demographic production models. Each of these approaches has different data requirements and underlying assumptions. Estimation of biological reference points from these methods can be viewed as a hierarchy, using data-poor proxies in the lowest tier to applying more informative demographic production models in the highest. Based on a review of Pandalid life histories, precautionary approach reference points, methodologies for estimating reference points and their applications to Pandalid shrimp stocks, we advocate a progression from proxies to more informative models and the requisite advancement of research programs to develop reliable reference points for Pandalid shrimp stocks.

Biological reference points for American lobster populations

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Biological Reference Points (BRPs) for setting targets and limits to exploitation for American lobster populations have been widely implemented in the United States and Canada. Current discussions concerning the appropriateness and applicability of particular BRPs to American lobster populations are strongly shaped by the large-scale increase in landings experienced in both Canada and the United States over the last three decades. This issue must be directly confronted in any discussion of lobster management strategies and reference points and we begin by exploring hypothesis concerning changes in lobster recruitment abundance and their implications for biological reference points.

We review the underlying conceptual foundations of BRPs applied to American lobster populations in the United States and Canada and examine the strengths and limitations of each with respect to data requirements/availability and biological/ecological realism. Classes of models that have applied to American lobster populations include surplus production and dynamic pool models. Reference points for surplus production models have centered on specification of MSY and F_{MSY}. Application of yield per recruit models has led to specification of target reference points (maximum yield per recruit and F_{MAX} and $F_{0.1}$) related to growth overfishing The problem of recruitment overfishing has essentially been addressed through egg production per recruit (EPR) models where limit reference points ($F_{10\%}$ in the U.S.; the level of fishing mortality that reduces EPR to 10% of its maximum) or target reference points (increasing EPR to twice its 1996 level in Canada) have been specified. We compare these approaches to others applied to lobster populations around the world.

We then address specification of Alternative Reference Points now under consideration and their relationship to current BRPs for American lobster stocks. We specifically consider (a) BRPs related to maintaining robust size compositions and multiple spawning opportunities (b) BRPs based on total egg production rather than egg production per recruit (c) minimum size limits in relation to the size at maturity and (d) trigger mechanisms related to changes in total or relative abundance with specification of minimum acceptable population levels.

The applicability of spatial management tools is next examined in the context of source-sink dynamics of lobster populations. We consider both metapopulation dynamics with implications for stability and resilience to exploitation and the application of spatial controls in the context of within-season lobster management. The potential utility of marine protected areas for lobster populations is examined.

Finally, we treat the issue of evaluating the efficacy of management actions and measurement of progress toward objectives adopted for management. The issue of coping with uncertainty in the context of biological reference points applied to lobster populations and implications for developing precautionary management strategies is explicitly considered.

Yield-per-recruit based reference points for Bering Sea Snow Crab

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The difficulty in establishing a spawner-recruit relationship using effective spawning biomass and number of recruits prompted us to employ instead traditional yield-per-recruit (Y/R) analysis method to determine useful biological reference points for the eastern Bering Sea snow crab stock. Size specific maturity; size specific molting probability; shell-age specific natural mortality; shell-age and size specific handling mortality and fishing mortality; and size selective bycatch mortality and growth were considered for Y/R calculation of males in the male-only snow crab fishery. Threshold harvest rates for males with carapace width (CW) larger than 101 mm were calculated subject to a given guideline harvest level (GHL) for the same size range and adjusted to the real yield under two hypotheses: (1) absence of terminal molt on mature males and (2) presence of terminal molt on mature males. Under hypothesis (1), the maximum Y/R producing harvest rate (HR_{MAX}) was 80% and the 0.1 level harvest rate ($HR_{0.1}$) was 57% of exploitable male ($>$ 101 mm carapace width) abundance. Under hypothesis (2), the HR_{MAX} was 99% and the $HR_{0.1}$ was 90%. Based on a precautionary approach, the lowest $HR_{0.1}$ value (57%) was recommended as a harvest rate cap for a defined component of exploitable males $>$ 101 mm CW. Variation in either handling mortality or percentage composition of old shell crabs in the GHL calculation had some effects on $HR_{0.1}$.

Yield and egg production reference points a comparison of different fishing strategies of American lobsters in nearshore Gulf of Maine

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Conventional egg production and yield per recruit models are not useful for lobster because age determination is difficult, growth in length is not continuous and the relationship between size and annual egg production is complicated. The model described in this study examines growth of a cohort of male and female for American lobster, *Homarus americanus*. It incorporates size-specific annual molt probabilities, intermolt duration, molt increments, maturity schedules, fecundities and length-weight relationships. Calculations incorporate interactions between reproduction and growth (e.g., female lobsters suspend molting and growth when they are carrying eggs) and size specific management measures for female lobster (e.g., maximum and minimum size regulations). Reference points derived from this model include relative egg production per recruit, yield per recruit (of both sexes), average number of spawnings per female recruit. Different fishing strategies have evolved in part due to variations in resources, markets and the types of management measures supported by fishers. We examine these reference points with regard to two distinct fishing strategies for lobsters that exist in the nearshore waters of the Gulf of Maine. In the Canadian portion, the fishing season is limited to a 6-month period (from late November to May), and the number of traps per fisher is limited to 400. In the United States, with a few minor exceptions, there are no regulated seasons, and limits on traps have only recently been adopted. The evolved patterns of fishing in both of these areas show a temporal concentration of effort, and subsequent high proportion of landings over a very short portion of the year. This is in part, a response to competition amongst fishers. The model allows multiple time steps during a year to incorporate these differences in life history and fishing tactics on a fine temporal scale. Additionally, the use of v-notching, as currently employed in both the US and Canada, is examined, both in terms of conservation effectiveness and as a population marker that might be used as a reference point tool.

Trap-catch based indicators following increases in minimum legal size in lobster (*Homarus americanus*) fisheries

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In the 1990's egg-per-recruit (e/r) models were used to assess Canadian Atlantic lobster fisheries. Most areas were viewed as overfished based on model estimates of current and virgin e/r. An interim target to double e/r within Lobster Fishing Areas (LFAs) was adopted by the Department of Fisheries and Oceans. Among the measures adopted, increased minimum legal size (MLS) was probably the most significant. Within a given area, MLS increases should result in more ovigerous females, particularly as the MLS approaches the 50% size at maturity ($Mat_{50\%}$). This relationship holds when looking across Maritimes LFAs — the closer the MLS is to $Mat_{50\%}$, the higher the proportion of ovigerous females in the trap catch. Egg-per-recruit also tends to be higher where MLS is close to $Mat_{50\%}$. To examine whether the changes anticipated from increases in MLS occurred, data from at–sea samples of the trap catch were examined from three areas. In western Cape Breton (LFA 26b) a 6.5 mm increase in MLS occurred from 1987–90, prior to the adoption of the doubling target. In the other two areas (northern PEI, LFA 24) and northeast Cape Breton (LFA 27) the increases in MLS (4 and 6 mm) were a response to the doubling target. The percentage of ovigerous females in at-sea samples was examined within 3 size classes (60–69 mm, 70–79mm and 80–89 mm). It was expected that the size class containing the newly protected mature females would show the largest increase in ovigerous females. In addition to indices based on ovigerous females, indices based on mean lobster weight were examined. To account for within-season changes due to removals and availability, we used samples from the first third of the season to represent a given year. While variability in the indices was high in our analyses, they responded as expected in each of the 3 areas. For example in northern PEI, where the MLS increase was from 63.5 to 67.5 m, the percentage of ovigerous females increased in the 60–69 mm size class but not in the 70–79 mm size class. Overall these data provide evidence that the increases in MLS were positive in terms of egg production. The indices have the advantage of being easily obtained and readily understood by fishermen.

Using length-based models to generate biological reference points for managing the Dungeness crab, *Cancer magister*, fishery in Fraser Delta, British Columbia

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The Dungeness crab fishery in British Columbia has been passively managed through sex and size limits. Only male crabs larger than or equal to 155 mm in carapace width may be harvested. The fishery is intensive with exploitation rates well over 90%. We developed length-based models to generate biological reference points to be used for managing the fishery. We incorporated handling mortality into the analysis to calculate yield, revenue and profit-per-recruit, after some important biological parameters, such as natural mortality rate, vulnerability of different sized crabs to traps, probability of moulting, survival rate for newly moulted crabs, were estimated based on scientific surveys in an unfished area within the Fraser Delta. The current high exploitation rate should be reduced to 65–75%, based on the calculated biological reference points, such as $F_{0.1}$. Such an intensive fishing also results in a great deal of catch-and-release of sub-legal sized crabs. Continuing fishing at a high ratio of sub-legal to legal sized crabs in the catch will result in a net loss in yield in the long-term, as some sub-legal sized crabs will die of handling mortality and could not contribute to the future yield. We conducted a length-based analysis on gain-or-loss in yield for continuing fishing at different ratios of sub-legal to legal crabs in the catch to determine threshold points (biological reference points), at which gain is balanced with loss in yield in the long term. To avoid losing yield in the long term, the ratio of sub-legal to legal crabs in the catch should not be allowed to rise above 19:1, 9.5:1, 6.5:1 or 5:1, if the handling mortality rate is, respectively, 5%, 10%, 15 or 20%.

Exploitation rate as an indicator and reference point for lobster fisheries

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Three key elements of successful frameworks for fisheries management are objectives, indicators, and reference points. Objectives for a fishery may be based on biological or non-biological considerations. Indicators are established to assess whether or not objectives are being met. Reference points identify specific indicator values that trigger fishery management decisions. Two goals are important in the development of a reference point. First, the reference point should be evaluated with respect to indicators that are directly based on field sampling. Second, the reference point is most likely to be accepted by industry if it links biological and non-biological objectives. Reference points based on exploitation rates that maximize long-term catches are one way to achieve these goals. In this paper, a model is developed that incorporates lobster life history characteristics and hypotheses on stock-recruitment relationships. The purpose of the model is to provide a structure for investigating exploitation rate as a reference point for lobster fisheries. Three Beverton-Holt stock-recruitment hypotheses are investigated to determine their relationship to long-term catches at various exploitation rates. Reference points based on long-term catches link biological and non-biological objectives. It is argued that this approach is more likely to receive acceptance by industry than reference points relying strictly on biological objectives. Exploitation rate estimates can also be based on industry sampling programs. The estimation of exploitation rate from sampling concurrent with fishing demonstrates how the goal of evaluating reference points with field indicators can be achieved.

Fecundity, abundance and spatial distribution of mature females and sex ratios in snow crab, (*Chionoecetes opilio*) population: Hypothesis for recruitment fluctuation in the southern Gulf of St. Lawrence, Canada

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Since 1989, a trawl survey has been conducted in the southern Gulf of St. Lawrence to provide a direct assessment of the snow crab population dynamics. The abundance, distribution and size composition of females (preprimiparous, primiparous and multiparous) and adult males $\geq$ 95 mm of carapace width (CW) has been estimated using data from the trawl survey to allow an assessment of the reproductive potential of the stock. Preliminary results showed that the sex ratio between adult males $\geq$ 95 mm CW and mature females, especially in the case of primiparous females, was not constant over time. During the last decade, high abundance of mature females was observed during low abundance of adult males $\geq$ 95 mm and vice-versa. During this period, about 95 % of mature females carried fertilize eggs and highest population fecundity was observed during two periods from 1990 to 1992 and from 1997-2001. The high abundance of mature females observed during 1990 and 1992 produced a peak of new recruits of instars V to VII (2–3 years old after settlement) that we observed during the 1994 and 1995 trawl surveys. The scarcity of these new recruits observed during the 1998 to 2001 trawl surveys may be due to the low abundance of mature females during the 1993 to 1996 periods. A new wave of recruits, instars V and VII, may be observed in 2 or 3 years from now in our trawl survey based on the high abundance of mature females since 1997. However, a decrease in the abundance of mature females is anticipated starting in 2002 based on the sharp decline in preprimiparous females in the population. Based on these analyses, we discuss the feasibility of sex ratio based stock management in the southern Gulf of St. Lawrence snow crab fishery and its limitation.

An investigation of the sources of variability in American lobster eggs and larvae size: Maternal effects, and inter-annual and inter-regional comparisons

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The objective of the conservation plan for lobster throughout Atlantic Canada is to double egg production from recruit spawners relative to 1996 levels. In the Quebec Region, the objective will be achieved by increasing the minimum legal size. An increase in the minimum legal size would result in a higher proportion of the population's total egg production coming from primiparous females. Measures to increase egg production from larger females that have spawned two or more times could also be recommended since it has been suggested that these females might produce better quality eggs (higher energetic content). However, a comprehensive assessment of the relationships between female size and egg size/quality in lobster is currently lacking.

During the Canadian Lobster Atlantic-Wide Studies (CLAWS I & II) initiative of Fisheries and Oceans Canada, we were able to investigate the effects of female size and reproductive status on egg size (diameter, dry-weight), and larval size (cephalothorax length — CL) at hatching in the Îles-de-la-Madeleine (southern Gulf of St. Lawrence) lobster population from 1997 to 2001. The objectives and the sampling effort have varied through the years. From 1997 to 1999, under the premise that small females produce small, lesser quality eggs, the study was designed to compare eggs size and the size, development and growth performances of hatching larvae from small ($<$ 80 mm CL) and large ($>$ 100 mm CL) females. Therefore, limited number of berried females were captured for each groups, i.e., 4 (replicates) for each female type. In 2000, the sampling effort was specifically designed to describe the full scale of variability in eggs and larvae size at hatching over the entire size range of the reproductive (females) population at three locations: Îles de la Madeleine (also in 2001) and Anticosti Island (Gulf of St. Lawrence) and Grand Manan (Bay of Fundy). Data on stage I larvae size at hatching were also available from Gulf of Maine (Boothbay–Pemaquid Point) lobsters between 1999 and 2001. The estimated size at 50% maturity was used to identify primiparous (first-time spawners) females for each population. Multifactor, mixed-hierarchical, analyse of variance models were used to investigate inter-annual variability in lobster eggs (diameter, dry-weight) and stage I larvae size (CL) in the Îles de la Madeleine population, and among populations in 2000. All levels of variability were included in each ANOVA model with Female and Population as random effects. In addition, linear regression models were used to examine the relationships between mean stage I larvae size and females CL.

In all comparisons, the main source of variability in the eggs and stage I larvae size was among females. Nevertheless, in the Îles de la Madeleine population, each year except in 2001 eggs and larvae from primiparous females were significantly smaller ($p < 0.05$) than eggs and larvae from the larger females. However, when the entire size range of reproductive females are considered, females size (CL) explained very little of the variance in egg size and mean larval size at hatching ($r^2 = 0.23$, $p < 0.05$ and 0.12, $p = 0.22$ in 2000 and 2001, respectively). Among populations, lobster mean egg diameter and mean stage I larvae CL at hatching (for both first-time and multiple spawners) were similar between the two populations of the Gulf of St. Lawrence (ANOVA, $p > 0.05$). Moreover, in diameter, eggs from the Gulf of St. Lawrence populations were not different of eggs from lobsters in the Bay of Fundy (outside the Gulf). Finally, mean stage I larvae size at hatching was not related to females CL in the Bay of Fundy (estimated stage I size) and Gulf of Maine lobsters.

To summarize, in two populations of the Gulf of St. Lawrence where for some reasons growth rate may be lower and maturation earlier (at smaller size), the small females (first-time spawners) tend to produce small eggs, and hatching larvae that are smaller relative to larger (multiple spawners) females. However, this effect is not observed in lobster populations where size at maturity is larger; e.g., Bay of Fundy, Gulf of Maine. For each year and population, the principal source of variability was among females. Especially, the differences among females were important in the mid-size range (85 to 95 mm CL) in the Îles de la Madeleine sample in 2000. This may have been caused by a mixture of females with different reproductive cycles (spawning/molting on alternate years, or the same year) in that portion of the population. However, the real causes of that variability and its impact on the survival potential of the larvae is unknown. These questions should be addressed in order to fully assess the production potential of the lobster populations.

Female American lobster, *Homarus americanus*, maturity and reproductive cycle: Its implication in the fishery management of the southwestern Gulf of St. Lawrence

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A good knowledge of the female size at the onset of sexual maturity (SOM) and reproductive cycle is essential for a sound management of the lobster (Homarus americanus) fisheries. The SOM is often used as a biological reference point to define the minimal legal size (MLS). The SOM for female lobsters can be established by the observations of the ovarian condition, either color or weight, and cement glands staging, but cannot be detected by the morphometry of their abdomen. Based on the ovarian condition (the most accurate technique), females from various locations within the southwestern Gulf of St. Lawrence (sGSL) reached 50% maturity (SOM_{50}) between 68.7 and 73.3 mm of carapace length (CL). Before 1990, the MLS of 63.5 mm CL only protected 11% of the young mature females, and since the risk of recruitment failure can be related to young mature animals, an acceptable level of protection of that group to survive the fishery is recommended by adjusting the MLS above the SOM_{50}. To study the reproductive cycle of females, molt stage, ovarian development, and egg spawning were monitored by dissections at the laboratory and tagging studies in the field. The majority (80%) of small mature females ($CL < 120$ mm) from sGSL had a typical 2-year reproductive cycle with molting (with copulation) and spawning in alternating years. However, up to 20% of primiparous and multiparous females ranging between 65 and 109 mm CL could spawn in successive years instead of the generally accepted 2-year cycle. A small percentage (5%) of small mature females could also skip molting or spawning for a year. In term of conservation, berried females are fully protected where spring fisheries are operating in the sGSL. However, in the Lobster Fishing Area 25 (early August–early October) fishermen can catch females with a 1-year reproductive cycle in early postmolt, before extruding their eggs, and multiparous females that have the ability to spawn in successive years but before they can release another clutch of eggs. Hence, a portion of the potential egg producing females are caught and kept before they have the time to extrude their eggs and get “legal protection”. This situation is specific to fishing seasons that coincide with all or part of the spawning period. As such, adjusting the fishing season to avoid this critical period in the lobster life cycle would be a very useful conservation measure.

On the use of clutch size and spermathecal content to detect recruitment overfishing in brachyuran crabs: the snow crab (*Chionoecetes opilio*) as a case example

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Orensanz et al. (1998) proposed that investigation of clutch size variability as a direct indicator of sperm limitation caused by excessive fishing of males should receive priority over the development of traditional 'reference points' for crabs. Additionally, for the Brachyura, the analysis of the contents of the female sperm storage organs (the spermathecae) may offer insight into her past mating history. We review extensive laboratory and field investigations of snow crab, *Chionoecetes opilio*, to evaluate the relative merits of variability of clutch size and spermathecal content as indicators of possible male overfishing. We focus on primiparous females, which are first-time spawners, to avoid confounding effects of senescence and multiple mating periods experienced by multiparous females (repeat-spawners). Snow crab has a highly complex mating system including the possibility for females of polyandry and repeated mating with the same male, before and after oviposition, in the course of a single breeding season. In the laboratory and field, analysis of spermathecal content reveals that the number of stored sperm and the number of mates for individual primipara increases sharply with increasing sex ratio (adult male:female). Limitation or exhaustion of paternal sperm can be detected by comparative microsatellite analysis of spermathecal content and clutch. Clutch size alone is not a good indicator of female reproductive success, because unfertilized eggs may be extruded and remain attached beneath the female's abdomen for several months. Potential fecundity, the product of clutch size by the proportion of fertilized eggs, is a convoluted function of (i) sperm allocation by dominant males that may influence the number of extruded eggs and the proportion fertilized, and (ii) frequency of post-oviposition matings that may result in egg loss. Both processes tend to co-vary, with dominant males allocating more sperm and females mating more often after oviposition as the sex ratio increases, but they operate antagonistically. We conclude for snow crab that spermathecal content offers a better record than potential fecundity of sociosexual context at mating and the possibility of sperm limitation. However, assessment of spermathecal content is not straightforward and this may limit its utility as an indicator of stock condition.

Application and relevance to *Nephrops norvegicus* of the ICES approach to biological reference points

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The setting of reference points under the auspices of the International Council for the Exploration of the Sea (ICES) has followed the lead given by the ICES Study Group on the Further Development of the Precautionary Approach to Fishery Management. It typically involves age-structured assessment and estimation of biomass and fishing mortality reference points based on stock history, stock-recruitment data and spawner-per-recruit relationships.

The only invertebrate species for which these ideas have been considered is the Norway lobster, *Nephrops norvegicus*. We consider whether *Nephrops* is simply "a fish with a shell on it", and if it is possible to suggest candidate precautionary (limit and threshold) reference points bearing in mind the particular characteristics of *Nephrops* biology and stock assessment. Reference points for southern *Nephrops* stocks, which are severely depleted, are compared with those for a northern stock, which is seemingly healthy.

Special characteristics of *Nephrops* which cause problems for assessment include differences in biology, behaviour and exploitation by sex, the inability to determine age directly, spatial structure in stock distribution, changes in catchability and poor quality of discard and landings data. These have resulted in separate sex assessments and the use of length slicing to infer age structure. These features are not unique to *Nephrops*, but are generally less severe and do not all occur together in finfish species.

Candidate reference points for two stocks examined were consistent between and across sexes and seemed plausible despite wide differences between geographical location, stock status and exploitation history. However, in a third stock the perspectives on stock status differed between sexes.

Estimates of uncertainty in limit reference points inferred from variability in assessment outputs do not take into account other sources of uncertainty inherent in the biological, sampling and modelling processes that underlie the assessment. It would seem prudent to use simulation to investigate the effects of the special features shown by *Nephrops*, mentioned above, on the performance of candidate precautionary approach (PA) reference points before recommending them for management.

We conclude that technical difficulties do not preclude application of the ICES PA framework to *Nephrops*. The approach may be useful in formalising consideration and definition of stock status and/or in identifying inconsistencies in assessment. However, some caution is required and we recommend further work to elucidate the effects of biases and errors, in parallel to evaluating alternative assessment methods and stock-recruit indices.

Be-all-you-can-be target reference points for Canadian lobster fisheries

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Lobster fishery scientists measure rates of growth, mortality, egg production, and catch per unit effort and use these to derive other rates for management targets. I propose that targets be based instead on annual fisheries yield; not as quotas to limit catch, but as optimistic objectives to be achieved. These would be positive and easily understood by stakeholders. Landings history or landings from other areas with similar habitat could be empirical guides for choosing target yields. Levers for achieving targets include several methods of increasing egg production, preserving habitat, and preventing waste during fishing. These would be chosen by stakeholders and adjusted on a trial-and-error basis. Much effort is expended trying to answer the very difficult question of how many lobster eggs are enough. How many eggs are more than enough is a larger target and is as affordable because eggs are inexpensive. Monitoring abundance of ovigerous females, larvae, early benthic stages, or juveniles would provide feedback on the success of lever adjustments.

Are reference points necessary?

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The population dynamics of many invertebrate stocks are often driven by environmental factors. Traditionally and most frequently, environmental data have been used in stock assessments by first conducting some form of correlation analysis linking key factors to the abundance of the population and then incorporating the most influential factor(s) as a term in a population model (e.g., surplus production, environment-recruitment relationship). Almost as frequently the identified environment-population relationship will break down after a time as the system enters a new "regime" and various previously unidentified environmental and/or intrinsic factors interact. Eventually, a new overriding factor(s) may be identified. Changing environmental regimes are easily identified as they happen by existing monitoring programs, however, quantifying their influence on a stock and developing an assessment model using traditional scientific standards will usually take too long to prevent catastrophic events such as stock collapses which for short-lived species such as shrimp can come in 2–3 years of apparent good stock health. Key to overcoming this problem is a clear definition of the boundaries between traditional science, stock assessment and management. A medical analogy provides the operational framework and ethical standards to translate existing (albeit reductionistically inconclusive) scientific knowledge into management action. The traffic light method can be used to martial disparate monitored indicators into an overall assessment of stock health which is intellectually transparent for all stakeholders. The method is used to manage the Scotian Shelf shrimp stock and, within a co-management framework, has been persuasive enough to result in a 40% precautionary decrease in the Total Allowable Catch when spawning stock biomass and commercial catch rates have been among the highest recorded. There are no clearly articulated reference points for the Scotian Shelf shrimp stock.

Life History Group 2

Precaution in the harvest of Methuselah's clams — the difficulty of getting timely feedback from slow-pace dynamics

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Geoducks are extraordinary animals: the largest living infaunal clams (individual weight up to 4+ kg), they are among the longest-lived animals of non-modular structure. Because they live buried deep in the substrate (down to 1 m), size limits are not an option as a management instrument. The existence and nature of density-dependence mechanisms are virtually unknown.

Main fisheries operate in Puget Sound (Washington, USA) and British Columbia (Canada). While in both cases, precautionary and very low harvest targets (1–3%) are in place, the management systems are radically different — auctions in Washington and individual vessel quotas (IVQs) in British Columbia.

Given the geoduck's extreme longevity and stability, the sustainability of their fisheries could possibly be more apparent than real. A re-examination of age frequency distributions obtained during a short period (1979–1983) suggests that geoduck recruitment had been declining steadily for ca. 60 years. Those data were originally collected to estimate growth and mortality parameters, then used to derive biological reference points (BRPs) and associated precautionary harvest levels. However, the long-term trends revealed by the age data indicate that BRPs are not sufficient to foster sustainability, even if stock decline occurs over an unusually long time horizon.

We discuss the merit of approaches that rely on monitoring and feedback, using decision rules driven by data rather than mediated by models and assessments. In this approach, alternative management procedures are evaluated through complex simulation models of the entire system (biology, fishing process and data gathering), but decision rules usually depend on simple calculations. The problem here is what kind of data would provide appropriate short-term feedback of value to management — not estimates of total abundance, given the low harvest rates, nor age frequency distributions, which reveal long-term trends in recruitment and abundance but change little from year to year.

A network of monitoring sites (plots) with variable histories of exploitation are a possibility. An investigation conducted in Washington is discussed as an example. In this case, plots were monitored before and shortly after fishing, and then at variable time intervals. Data from these "recovery plots", which had received little attention, seem to indicate improved recruitment over the last 20 years. Recent ageing data are consistent with this short-term perception.

Setting biological reference points for cockles (*Cerastoderma edule*) in UK estuaries in relation to bird-cockle interactions

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Setting biological reference points for management of cockle (*Cerastoderma edule*) fisheries in estuaries in the UK is complicated by the need to consider the impact of cockle fishing on bird species which feed on cockles. In the Burry Inlet in South Wales, for example, there are internationally important concentrations of shorebirds, notably oystercatcher (*Haematopus ostralegus*), an important predator of adult cockles. A ‘rule-of-thumb’ for management of the Burry Inlet cockle fishery has been to set the total allowable catch at about a third of the fishable biomass estimated in autumn. This rule was derived from the observation that harvest levels over a number of years of apparently sustainable fishing were all within this limit. A model of fishing and bird predation is constructed using data on cockle stock abundance, fishery removals and bird numbers, and incorporating information on seasonal patterns of cockle growth and flesh content and feeding requirements of birds. The model is used to obtain estimates of the numbers of cockles at size and age taken by both birds and fishermen. The model predicts that there is a relatively small overlap between bird predation and fishing in the size of cockles taken — birds take a relatively large number, but small biomass of smaller cockles. Fishing and bird predation appear to be additive to each other as sources of mortality, but to be compensated for by changes in other (unknown) sources of mortality. The model predicts that after accounting for bird predation, fishing does not increase overall cockle mortality provided that it takes no more than 30-40% of the overall abundance. We conclude therefore that the current management strategy for the Burry Inlet cockle fishery has a sound biological basis. Finally we discuss the implications of these results for other cockle fisheries, such as those in The Wash and Thames Estuary, where the relative abundance of cockle-eating birds may be very different.

Life History Group 3

Biological reference points in the management of North American sea urchin fisheries

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The world's sea urchin fisheries are clearly in need of better management. Typically they develop rapidly, then are fished down to a recruitment-only or overfished state with little early management. Here we first note the essential functions of both target and limit reference points (TRPs and LRPs, respectively). Because LRPs should reflect whether a population can continue to persist, we briefly discuss current understanding of the conditions necessary for persistence of both single populations and metapopulations. We then discuss the unique characteristics of sea urchin fisheries, including tight ecological coupling, roe fisheries, protection of juveniles under spine canopies and broadcast spawning. We then briefly review the management history and rationale of North American fisheries and characterize the reference points among them. These include several examples of familiar TRPs, a unique TRP involving direct monitoring of ecological conditions and an LRP based on the fraction of lifetime egg production.

Review of biological reference points for scallop species: The benefits and costs of being nearly sessile

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Seminal work by Caddy (1975 and later) defined basic principles for the exploitation of sessile marine resources. He noted that exploitation is a function of the spatial distribution of the resource and the spatial dynamics of the fishery. Under these circumstances, many of the basic tenets of fisheries science become inapplicable. We review the biological attributes of scallop populations relevant to the development of biological reference points. To date, managers of scallop resources have made limited progress toward implementation of appropriate spatial management measures. Advances in technology, improved statistical and numerical models, and a growing acceptance by industry for these kinds of measures, lay the basis for substantive improvements in management. We highlight a number of such improvements in this paper. Nonlinear mixed effects models can be used to define the spatial distribution of growth rates and their implications for the definition of growth overfishing. We develop a heuristic metapopulation model to illustrate that the typical “boom and bust” effects, often attributed to environmental factors, are explained equally well by spatial variations in habitat quality, spatial concentration of fisheries, and dispersal of larvae among areas. Results suggest that incentives to concentrate fishing effort in lower productivity areas may be an effective tool for reducing recruitment variation and improving yields. While the evidence for recruitment overfishing is equivocal, analyses of marked biomass increases of USA sea scallops in closed areas suggest that egg production may have increased as much as 50 fold in the last 8 years.

Vessel Tracking Systems have been required on the USA offshore scallop fleet since 1998. The Canadian offshore fleet began using these tracking systems the same year. This comprehensive census of fishing effort at very fine spatial and temporal scales, lays the basis for an improved understanding of fleet dynamics, responses to management measures, and resource distribution. Finally, results of coupled biological-hydrodynamic simulation models are coherent with spatial patterns of the resource. Moreover, such models can begin to define the reproductive footprint of local populations and inter-area dependencies for recruitment. Collectively, these biological and technological advances suggest that comprehensive spatial management plans, based on principles defined nearly 30 years ago, are possible if perceived social and economic obstacles can be overcome.

Using probabilistic models to derive risk-based reference points for invertebrate fisheries: a case study involving red sea urchins (*Strongylocentrous franciscanus*)

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Reference points can be defined in terms of risk. Risk benchmarks have two components, consequence and probability. As an example, there could be a required 95% confidence level that a fishery will not cause biomass to decline by more than 25% of the virgin value. Probabilistic computer models are effective for addressing the probability-component of risk. Probabilities are approximated from the frequency of occurrence in the simulations.

However, the predictions of computer models are subject to various types of error. For fishery models, the impact of error can be reduced by incorporating a pairwise-comparison strategy. Each simulation is performed twice, once with harvest and again without harvest. The predicted impact of harvest is the difference between these two simulations. As long as the modelling errors have similar impact on both members of a pair, then the difference between harvest and no-harvest simulations will be relatively unaffected. The strategy also helps to distinguish the impact of harvest from random variability incorporated into the model.

This type of risk-analysis has been applied to the red sea urchin (*Strongylocentrous franciscanus*) fishery on the British Columbia coast. The probabilistic computer model is called Probabilistic Urchin Population Simulator (PUPS). Simulations of 100 years were used. One thousand harvest simulations were performed and then repeated as no-harvest simulations. The simulations allow a comparison of the predicted impact of harvest against a benchmark of risk. The comparison illustrates how risk-based reference points could be used as a tool in managing an invertebrate fishery. The risk based reference point considered in this case is generic and may be applicable to other fisheries. More specific risk-based reference points could be developed to address specific concerns. The major advantage of using risk-levels as references points is the flexibility to address specific issues and to use models that are applicable to those issues. The major disadvantage is the added effort required to specify the reference points and develop suitable models.

Which way is more reliable to compute reference points for the green sea urchin fishery — observation error approach with Monte Carlo simulations or state space modelling with Bayesian methods?

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Quotas for green sea urchin fisheries in British Columbia are based on maximum sustainable yield (MSY) calculated from a biomass dynamic model. Two methods, the process error estimator and observation error estimator (time-series fitting), have been used to estimate MSY. The former method only models the random errors in the state equation and assumes the observations are deterministic given the states, while the latter only models the random error in the observations and assume that the state equation is deterministic. The observation error estimator is generally regarded to be the better one when only one of the two sources of randomness is modelled. In reality, both process and observation errors exist. They can be simultaneously modelled using the state-space modelling approach with parameters and the degree of uncertainty estimated using Bayesian methods. This paper evaluates which approach generates more reliable estimation: the observation error approach with Monte Carlo simulations or the state-space modelling with Bayesian methods? Two commonly used Markov chain Monte Carlo simulation techniques, Metropolis algorithm and Gibbs Sampler, were used for the Bayesian analysis. As true values for the biological parameters were unknown, 100 simulated data sets were independently and identically generated. The time-series of observed fishing efforts were used for each data set, while the time-series of biomass and of commercial catch per unit effort were randomly generated based on the biological parameters and observation error variance estimated using the observation error approach and the observed data. Biological parameters and MSY were calculated for each of the simulated data sets using the observation error estimator with Monte Carlo simulations and the state-space modelling with Bayesian analysis. The degree of bias, the absolute difference between the estimated mean and the true value, was found to be similar for both approaches. However, the latter approach is significantly more reliable in calculating the degree of uncertainty about the estimation in the sense that the confidence intervals based on the estimated variance achieves a better coverage of the desired probability.

Overfishing definitions for sessile stocks with rotational fishing or area closures

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Rotational and long-term closures cause special difficulties for defining reference points for relatively immobile stocks. When substantial biomass is contained in areas closed to fishing, growth overfishing can occur in open areas even when spatially averaged fishing mortality is below a conventional reference point such as F_{MAX} or F_{MSY}. For example, currently 80% of the sea scallop biomass in the U.S. portion of Georges Bank is in areas closed to fishing, while fishing mortality in the open areas is about $F_{open} = 0.4$. Thus, the overall fishing mortality of this stock is well below the reference point of $F_{MAX} = 0.24$, even though a reduction of effort in the open areas would improve yield-per-recruit in those areas. In fact, as long as the current closures continue, the overall fishing mortality rate will be below F_{MAX} no matter how hard the open areas are fished. The current whole-stock reference point therefore gives managers no guidance as to the appropriate fishing mortality that will maximize yield, but suggests instead that open area fishing mortalities can be increased arbitrarily. On the other hand, after a closure, the mean size and age of the stock in that area will be larger than if the area had been fished at the reference point. For this reason, fishing mortality needs to be greater than F_{MAX} after the reopening of a rotational closure in order to maximize yield-per-recruit. The following principles are proposed for fishing mortality metrics that would overcome the above difficulties and would be compatible with standard reference points: (1) Closed areas should not be included when comparing fishing mortality to a yield-per-recruit reference point in order to prevent growth overfishing of the open areas. (2) Fishing mortality in areas that have been recently reopened to fishing should be time-averaged over an appropriate period in order to maximize yield-per-recruit from that area. Even when area closures are not used, similar difficulties in fishing mortality metrics can also happen in sessile and sedentary stocks when fishing effort is highly non-uniform spatially. "Individual-based" yield-per-recruit analysis can be used in these situations to help prevent loss of yield due to localized growth overfishing.

Life History Group 4

A new reference point approach for California market squid, *Loligo opalescens*

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We use mean "residual" fecundity (eggs remaining in the eggs and ovaries) of squid in the catch as an index of fishing mortality, in the same way that Beverton and Holt used mean size of fish in the catch. Both size and residual fecundity are monotonic functions of age, although they have opposite slopes. Moreover, we generalize per recruit models to include mean residual fecundity per squid in the catch so that both the reference point and the status variable can be based on residual fecundity in catch samples. The generalization from per recruit to per individual in the catch is interesting and a somewhat novel twist on the old conventional modelling approaches. Also, in principle at least, both the reference point and status variable can be gleaned from catch samples without resort to a survey, stock assessment model, etc. This is fortunate because there are few data and no reliable model for the stock involved.

Appendix 1: Agenda

Workshop on Biological Reference Points for Invertebrate Fisheries, Halifax. 2–5 December, 2002. Delta Halifax Hotel

2 December	09:00	Welcome	S.J. Smith
	09:15	Background for meeting	D. Rivard
	09:30	Key Note Address	J. Caddy
	10:10	Questions/Discussion	
	10:30	Coffee	
		Life History Group 2	
	10:50	Invited paper - geoduck	L. Orensanz
	11:40	Contributed paper - cockles	M. Bell
	12:00	Lunch	
	13:10	Panel discussion	G. Gillespie
		Life History Group 3	
	13:40	Invited paper - sea urchins	L. Botsford
	14:30	Invited paper - scallops	P. Rago
	15:20	Coffee	
	15:40	Contributed paper - sea urchins	W. Hajas
	16:00	Contributed paper - sea urchins	Z. Zhang
	16:20	Contributed paper - scallops	D. Hart
	16:40	Panel discussion	L. Gendron
	17:10	Adjourn	
	18:00	Reception	Hotel
3 December		Life History Group 4	
	09:00	Contributed paper - squid	L. Jacobson
	09:20	Contributed paper - octopus	Cancelled
	09:40	Panel discussion	D. Orr
	10:10	Coffee	
		Life History Group 1	
	10:30	Invited paper - snow crab	M.S. Siddeek
	11:20	Invited paper - shrimp	J. Boutilier
	12:10	Lunch	
	13:20	Contributed paper - crab	M.S. Siddeek
	13:40	Contributed paper - lobster	D. Pezzack
	14:00	Contributed paper - lobster	M.J. Tremblay
	14:20	Contributed paper - crab	Z. Zhang
	14:40	Contributed paper - lobster	R. Claytor
	15:00	Coffee	
	15:20	Contributed paper - crab	E. Wade
	15:40	Contributed paper - lobster	P. Ouellet
	16:00	Contributed paper - lobster	M. Comeau
	16:20	Contributed paper - crab	B. Sainte-Marie
	16:40	Adjourn	

4 December	09:00	Invited paper - Lobster	M. Fogarty
	09:50	Contributed paper - nephrops	M. Smith
	10:10	Coffee	
	10:30	Contributed paper - lobster	R. Miller
	10:50	Contributed paper - shrimp	P.A. Koeller
	11:10	Panel discussion	M. Comeau
	11:40	Form Discussion groups	
	12:00	Lunch	
	13:10	Discussion groups meet	
	15:00	Coffee	
	15:20	Discussion groups meet	
	16:30	Adjourn	
5 December	09:00	Plenary	
	10:00	Coffee	
	10:20	Develop research recommendations	
	12:00	Close meeting	

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