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A Review of Rotational Management of Fisheries and its Application to Canadian East Coast Arctic Surfclam (*Mactromeris polynyma*)

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ABSTRACT

The quota-regulated fisheries for Arctic Surfclam (*Mactromeris polynyma*) on Banquereau and the Grand Banks have been managed under one plan since 1986 and 1989, respectively, with license holders having access to quota in both areas. Previous assessments indicated that the status of the resource was generally healthy with fishable biomass close to virgin conditions, and catch below the Total Allowable Catch (TAC) (based on F = 0.33M). A 2015 review of the management plan concluded that it would ensure the maintenance of high spawning stock biomass although it was recommended that a spatial or rotational management approach be explored to ensure greater commercial viability of the fishery. In support of the examination of rotational management for Surfclam, this paper provides an overview of the theory of rotational management and an examination of case studies of its application to benthic sessile invertebrates to develop best practice in application of this management approach. Preliminary analyses of the appropriate recovery period for Surfclam were undertaken, which suggest that there are limited benefits to the rotational management of the Surfclam fishery, at least over a range of 2 – 20 years of rotation. This may be due to the current fishery's optimal exploitation of the age/size groups in the stock. This document concludes with observations on the application of rotational management to Arctic Surfclam in Atlantic Canada.

Examen de la gestion rotationnelle des pêches et son application à la mactre de Stimpson (*Mactromeris polynyma*) sur la côte Est du Canada

RÉSUMÉ

Les pêches régies par le système de quotas pour la mactre de Stimpson (*Mactromeris polynyma*) sur le Banquereau et les Grands Bancs sont gérées dans le cadre d'un seul plan depuis 1986 et 1989, respectivement, les titulaires de permis ayant accès aux quotas dans les deux zones. Les évaluations antérieures ont indiqué que l'état de la ressource était généralement en bonne santé, la biomasse exploitable étant proche de l'état vierge, et les prises étant inférieures au total autorisé des captures (TAC) (basé sur F = 0,33 M). Un examen du plan de gestion en 2015 a permis de conclure que le plan garantirait le maintien de la biomasse élevée du stock reproducteur, même s'il a été recommandé qu'une approche de gestion rotationnelle ou spatiale soit explorée pour accroître la viabilité commerciale de la pêche. À l'appui de l'examen de la gestion rotationnelle pour la mactre de Stimpson, le présent document fournit un aperçu de la théorie de la gestion rotationnelle et un examen des études de cas de son application aux invertébrés sessiles benthiques afin d'élaborer des pratiques exemplaires dans l'application de cette approche de gestion. Les analyses préliminaires de la période de rétablissement appropriée de la mactre de Stimpson ont été entreprises, ce qui laisse entendre qu'il y a des avantages limités à la gestion rotationnelle de la pêche à la mactre, du moins sur une période de 2 à 20 ans de rotation. Cela peut être attribuable à l'exploitation optimale par la pêche actuelle des groupes d'âge et de taille dans le stock. Ce document présente en conclusion des observations sur l'application de la gestion rotationnelle à la mactre de Stimpson au Canada atlantique.

INTRODUCTION

The quota-regulated fisheries for Arctic Surfclam (*Mactromeris polynyma*) on Banquereau Bank and the Grand Banks have been managed under one plan since 1986 and 1989, respectively, with license holders having access to quota in both areas. The most recent assessments of the stocks (DFO 2010 for Grand Bank, DFO 2012a for Banquereau Bank) indicated that the current status of the resource is generally healthy with fishable biomass being very high. However, given the absence of precautionary Reference Points (RPs) and the high uncertainty in the biomass estimates, along with an inability to evaluate stock temporal trends, it was unclear what the stock status was more precisely. These assessments, therefore, recommended the development of precautionary approach RPs. Roddick (2013) subsequently provided these RPs, which indicated that extant fishable biomass is close to virgin conditions, and that catch is below the Total Allowable Catch (TAC) (set according to fishing the stock at a target fishing mortality of 1/3 natural mortality).

In 2015, DFO commissioned two reviews (Hoenig 2015[1], Orensanz 2015[2]) to evaluate whether or not the Surfclam management plan was consistent with a precautionary approach and sustainable fishing. These reviews concluded that the plan and associated harvest strategy would ensure the maintenance of high Spawning Stock Biomass (SSB), thus guaranteeing future recruitment. However, a concern was raised that under a constant fishing mortality strategy, localized fishing on high Surfclam concentrations could lead to marked decadal fluctuations in catch rates (Catch per Unit Effort [CPUE]) and annual landings (and thus profitability). A recommendation was made to consider spatial or rotational management coupled with on-going monitoring to estimate depletion and recovery rates of high density clam beds which would in turn lead to greater commercial viability of the fishery.

On 18 December 2015, the DFO Fisheries Minister announced that prior to any change in either the TAC or decision on new entrants, scientific and related work associated with spatial management of the resource was required. In response, during June 28-29, 2016, Fisheries and Oceans Canada (DFO) Science conducted a Regional Advisory Process (RAP) review of a preliminary risk assessment of spatial management options for implementation in the 2017 fishery.

This document was developed to provide input and support to the June 2016 RAP meeting. It first provides an overview of the theory of rotational management based upon a number of significant scientific contributions that have been made since the early 1990s. It next examines case studies of the application of rotational management to benthic sessile invertebrates in various regions of the world to both take lessons from this experience and develop best practice in application of this management approach. The potential benefits of rotational management for the Arctic Surfclam fishery are then examined using the Rotational Yield per Recruit model of Hart (2003). This model has been used in the evaluation of rotational management as applied to the United States (US) Georges Bank Sea Scallop fishery and is well suited as an analytical tool for the Arctic Surfclam fishery.

This document concludes with observations on the application of spatial management to Arctic Surfclam in Atlantic Canada.

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[1] Hoenig, J.M. 2015. Review of the Scientific Basis for Managing Stocks of Arctic Surfclam on Banquereau and Grand Bank: Data, Analysis and Overall Inference. Unpublished Manuscript.

[2] Orensanz, J.M. 2015. Review of Arctic Surfclam Fishery Management. Unpublished Manuscript.

THEORY OF ROTATIONAL MANAGEMENT

Rotational management is implemented in situations under which restricting access to portions of a stock for a period of time provides a more optimum result than if it were managed under continuous access. Rotational management has been used as a fisheries management tool at least as far back as 10,000 BC (Bartlett et al. 2009). It is most commonly used for fisheries on sedentary species, as rotational areas (herein termed 'zones') provide a relatively straightforward way to regulate access to a portion of a sedentary stock. The most common concept of a rotational management plan is where the stock distributional area is divided into zones, only a subset of which are open to fishing at any one time to allow stock recovery in the closed zones. The fishery rotates through the open zones, the rotation period being a determinate set of open and closed intervals that repeat (e.g. 3 years, British Columbia geoduck, Bureau et al. 2011), or an indeterminate period during which zones are opened and closed based upon some criteria, (e.g. biomass hits high and low trigger levels for that zone, US Georges Bank Sea Scallop, NEFMC 2003). In the case of determinate periods (relevant to the rotational management of Arctic Surfclam), the number of fishing zones has to be a multiple of the rotation management plan period, i.e. with a rotation period of *n* years, there must be *n* zones for one of these to be open each year, or a multiple of *n* for many zones to be open each year. A number of rotational harvest strategies can be employed, common ones being pulse rotation in which only one zone is fished and then closed for the remainder of the rotation period, and symmetric rotation in which there are an even number of zones, half of which are closed for half the rotational period (Hart 2003). Hybrid rotational patterns containing elements of different rotational strategies, and incorporating permanent or temporary reserve areas are also possible.

There are life history characteristics that make a species amenable to a rotational management strategy. For species with fast growth at early ages, the fishery can benefit if harvesting is delayed until individuals have had a chance to grow. Excess harvesting of individuals before they have had a chance to grow can lead to what is referred to as growth overfishing; a target exploitation rate based on a Yield per Recruit (YPR) analysis is designed to help prevent this. While this applies to all species, there can be situations for sessile species in which different zones of the stock distribution can have different age composition, making rotational management a good option, particularly if the selectivity of the gear catches individuals at a size less than the optimal size for maximizing YPR. In this case, not fishing individuals during this period of growth through the use of rotational zones will increase stock yield (Hart 2003). This benefit is further enhanced when there is a price differential on species size - larger individuals being worth more per unit weight than smaller ones - which adds to the value of the delayed yield.

There may be situations in which incidental mortality is high. Although pre-recruits are not being retained by the fishery, they are being killed by the fishing gear, and thus represent a loss of potential yield. Protecting a fast growing year-class of pre-recruits from the gear until they reach a larger size will increase yield (Hart 2003). However, to protect a year-class of pre-recruits for a period of time, there must be a means to fish groups of similar aged individuals. Sedentary species that recruit in patches are ideal candidates for this form of rotational management as recruitment patches can be closed to fishing until the year-class reaches its optimal biomass (Caddy and Seijo 1998, Hart 2003).

There may be situations in which the maximum Eggs per Recruit (EPR) is not achieved at exploitation rates that achieve maximum YPR (Sluczanowski 1984). If the target size/age based on an YPR analysis occurs at low EPR, then recruitment overfishing becomes a concern as the reproductive capacity of the stock will be reduced over the long-term. Allowing a year-class to reach an age of higher reproductive output would alleviate this, although this may reduce yield.

At the other end of the growth spectrum are those species whose growth rates are very low, such that the rate of biomass increase in an exploited population is less than the effective discount rate for the fishery (e.g. Red Coral; Caddy 1993). In this case, if there is no effective control, the stock aggregations are "mined" with the fishery moving to unexploited zones as those fished are depleted. A pulse fishery can develop on these stocks with the unfished recovery period for a depleted zone being very long. There may be situations in which all zones have been depleted and none have recovered, forcing closure of the fishery until recovery takes place. A rotational management strategy can be an effective management tool for these species.

There may be practical reasons for using a rotational management strategy that are unrelated to the biology of the species. Rotational management may be employed to reduce fishing, management or enforcement costs, and increasing the overall profitability of the fishery. There are fisheries for very high market value species harvested by divers in shallow water (e.g. abalone, urchins, corals, geoducks). Harvesting can be very efficient in removing all individuals of legal size from a localized area before fishing moves on. A rotational fishing pattern on localized areas emerges even if it is not an explicitly adopted stock-wide management strategy; there is no incentive to return to an area until growth and recruitment have replenished the supply of legal sized individuals. In these cases, rotational management can be an effective tool to prevent overfishing, synchronize effort on a larger scale and reduce the fishers time spent searching for unexploited areas.

Rotational management is applicable when little is known about the biology of the harvested species. An example of this is sea cucumbers, species which have high market value, but lack age structures (e.g. scales or otoliths), making growth and mortality estimation difficult (Plaganyi et al. 2015). There are many examples of sea cucumber fisheries that have collapsed due to high market value stimulating fishing pressure combined with an inability to establish effective quotas or other controls due to an inability to estimate stock productivity. A rotational fishery with multiple open and closed zones allows time to monitor the impact of the fishery and stock recovery. In some cases, it may be prudent to additionally employ reserve areas that are permanently closed zones as an additional precautionary measure. This is particularly the case if there are zones that serve as a source of recruits for so-called sink zones. In this case, the source zones need to be identified and afforded more protection from fishing than the sink zones.

Finally, if the fishery is pursued over a very large stock area with a multitude of landing sites, then having only part of the grounds open at any one time can make enforcement easier and reduce management costs (Hand et al. 1998).

While the above features highlight the benefits of rotational management, there may be disadvantages. If stock densities build up in zones during the recovery period, growth rates may decline and mortality rates increase as the stock in the zone becomes more susceptible to biological process associated with high stock density (e.g. disease, competition amongst individuals). These effects could counteract the potential gains from increased YPR predicted under rotational management.

The opposite effect may also occur. As indicated above, if a rotational management strategy is to generate comparable yield to a continuous fishery, the open zones must be fished more intensively while they are open than if fishing is temporally continuous. This implies that the fishing mortality (F) in the open zone is a multiple of the F in a continuous fishery and the rotation period or F**n*. Fishing the open zones at such high F can reduce the stock in these zones down to a biomass that increases the risk to the stock. Such low densities may endanger fertilization success. In the case of Australian abalone, there is evidence that high local density has a positive effect on fertilization success (Sluczanowski 1984). Abalone and other sedentary species are broadcast spawners; eggs and sperm are cast into the water with limited time to co-mingle for fertilization to succeed. It is estimated that individual abalone have to be closer than two meters for fertilization to succeed (Babcock and Keesing 1999). The risk of recruitment failure increases as the stock is fished down to densities that create a greater degree of separation amongst the spawners. It is evident that local stock density of a sessile organism can have important implications for overall stock dynamics, and thus yield, and has to be carefully considered in a rotational management approach.

While the habitat effects of fishing are a consideration of any management regime, fishing in open zones at the high fishing mortalities implied by rotational management may have particularly undesired impacts on by-catch species or on structure forming epifauna that is habitat for benthic species.

In relation to management considerations, large fluctuations in stock density during open periods could lead to wide variations in catch rates, fishing costs and the supply of catch to processing plants and the market. Multiple open zones with overlapping rotations can be used to reduce this variation but increases the complexity of management. Further, higher fishing mortality in the open zones implied by rotational management increases the risk that an overestimate of stock biomass will result in a quota that causes over-exploitation and reduces stock numbers to a critically low level. This risk can be reduced by having multiple open zones with separate evaluations of biomass, although this also increases management complexity and would probably require intensive monitoring surveys. Further, the incentive for illegal fishing, and, thus, surveillance costs increase as the closed season progresses and biomass builds up in closed zones. This is especially true for high market value species.

There may be other adverse consequences if there are unofficial ‘territories’ for groups of fishers. A rotational harvest strategy could force them to fish in unfamiliar areas and may require more steaming time from home ports. This effect primarily occurs when spatially distinct fishing grounds are closed, which would not be an issue in the Canadian East Coast Arctic Surfclam fishery.

For rotational management to be feasible, there needs to be a management authority in place that can allocate fishing rights by zone with effective prevention of illegal fishing in closed zones. It must be possible to divide the stock into zones of comparable biomass and/or productivity between which there is limited movement with the number of these zones equal or exceeding the period of harvest rotation (Caddy and Defoe 2003, Caddy and Seijo 1998). Fishing regulations by DFO cover the authority and enforcement requirements of rotational management, and the sedentary nature of surfclams should make the division into zones possible.

In considering the advantages and disadvantages of rotational management, it is important to keep in perspective the management objectives of the fishery. From a biological perspective, avoidance of recruitment overfishing, through the definition of a low biomass limit, has been noted above, as has avoidance of growth overfishing through limiting fishing mortality to some maximum rate (i.e. F_{MAX}) and controlling fishery selectivity. The economic objectives of a fishery can also take many forms. The most obvious goal is to maximize the yield of the fishery (e.g. Maximum Sustainable Yield or MSY), which is often also expressed as Maximum Economic Yield (MEY). In addition to these performance metrics, which are used in many non-rotational fisheries, some rotational management fisheries have taken into account harvesting costs and price differentials (Caddy and Seijo 1998, Hart 2003, Valderrama and Anderson

2007) through the use of maximum Net Present Value (NPV) over a certain period (e.g. 20 to 30 years), assuming an annual discount rate (e.g. 10%) as a definition of optimal discounted yield. Additional performance metrics include temporal variation in yield and catch rates.

It is evident that management needs to consider trade-offs between a number of competing biological and socio-economic goals, as well as, consider additional factors, including market supply, enforcement costs and effects on other species and habitat. This is true of rotational management as it is for any management approach.

GLOBAL CASE STUDIES

The theory on rotational management above provides a taste of the issues that this approach can address as well as confront. A full consideration of the benefits of rotational management for Surfclam would require evaluation of the performance of the approach, using a range of biological and socio-economic performance metrics, in relation to management objectives and in the face of stock and regulatory uncertainties. This is beyond the scope of this paper. However, much can be learned from the application of the approach elsewhere in the world. This section thus explores the global experience in the practical application of rotational management to better evaluate its applicability to Canadian East Coast Arctic Surfclam. Case studies of rotational management in the North Atlantic, North Pacific, South Pacific, Caribbean, South America and Mediterranean were evaluated. Each of these case studies involves examination of different components of rotational management, often at different levels of detail. Some provide an examination of the strengths and weaknesses of rotational management, whereas, others simply report on its implementation in the case study. To ensure that the reviews are comparative and comprehensive, the following components of each management system were considered:

- Operating (Stock) model that describes stock dynamics (stock spatial structure, abundance and density processes, age/size – specific growth/mortality, etc.) along with the observation (fishery and survey activities) and implementation (surveillance and enforcement) processes.
- Management model that describes the assessment of the stock along with the rules (operational objectives with Performance Indicators and Reference Points) and tools (e.g. rotational zones) of rotational management.

The reviews are general in nature and while each emphasized different aspects of rotational management, it was possible to discern trends across all case studies, which allowed discrimination of best practices.

NORTH ATLANTIC

Myers R.A., S.D. Fuller, and D.G. Kehler. 2000. A Fisheries Management Strategy Robust to Ignorance: Rotational Harvest in the Presence of Indirect Fishing Mortality. Can. J. Fish. Aquat. Sci. 57(12): 2357-2362.

Synopsis

Myers et al. (2000) discuss the potential advantages and disadvantages of rotational management, as applied to the US Georges Bank Sea Scallop (*Placopectin magellanicus*) fishery. Consideration was given to rotation periods, crowding which could decrease the growth rate, intense fishing during open periods effecting both groundfish stocks and structure forming epifauna, and longer rotational periods requiring areas with greater spatial separation. The use of a rotational period of less than 7 years was suggested for this stock. It was also stated that with Vessel Monitoring System (VMS) monitoring, rotational fishing would be easier to enforce than individual vessel quotas.

It was concluded that in fisheries with a high incidental mortality rate, rotational fisheries can reduce overall mortality on the individuals that are not yet fully recruited. This tends to increase Y/R and SSB/R. It also broadens the peak of the yield curves, reducing the impact of over shooting a target fishing mortality (F).

Operating Model

This was a modeling exercise of a rotational management system using stock and fishery parameters available in extant stock assessment and related literature. The biological features of the stock relevant to rotational management are described in the review below of Hart (2003). Myers et al. (2000) do not draw attention to any specific biological features of Sea Scallop which suggest an imperative for the spatial management of this resource.

Management Model

The study used maximum YPR and Spawning Stock Biomass per Recruit (BPR) to determine the optimal rotational period. YPR was at least as high as in the non-rotational case under all rotational period as long as the ratio of incidental to target fishing mortality (F) was high and F was greater than 0.2. This approach also maintained a larger stock biomass than in a non-rotational system. The yield curves for the rotational strategies had very broad peaks compared to the non-rotational case, indicating that the precise target F was not as important as in the non-rotational case. This broad peak also occurred at a higher F than in the non-rotational case.

Rotational periods of 1, 3, 6 or 9 years were examined. There was no consideration of separate (from rotational zones) quota controls. Rather, the study considered whether or not rotational harvesting could achieve management goals without additional harvest controls.

Hart, D.R. 2003. Yield- and Biomass-per-Recruit Aanalysis for Rotational Fisheries, With an Application to the Atlantic Sea Scallop (*Placopecten magallanicus*). Fish. Bull. 101: 44-57.

Synopsis

Hart (2003) presents a general theory for any type of periodic or rotational fishing strategy for a mixed-age sessile or sedentary species such as abalone, corals, sea cucumbers, geoduck clams, sea urchins, sea scallop and Surfclam. The strategic benefits of the rotational management of sea scallops on Georges Bank, are provided based upon yield (YPR) and biomass per recruit (BPR) analyses. The focus of the paper is the optimal management strategy to employ in rotational management, although there are lessons for other aspects of the management system.

The main conclusions of the paper were that rotational fishing slightly (<10%) increases both YPR and BPR for sea scallops fished at F_{MAX}. These quantities decline less quickly as fishing mortality is increased beyond F_{MAX} compared to non-rotational fishing. The improvement in BPR appears to be independent of the selectivity pattern, but increased size-at-entry can reduce or eliminate the YPR advantage of rotation. Further, closures and rotational fishing can cause difficulties with the use of standard spatially averaged fishing mortality metrics and reference points. The concept of temporally averaged fishing mortality is introduced as one that is more appropriate for sedentary resources when fishing mortality varies in time and space.

Operating Model

Hart (2003) notes the stock dynamic features that are important to consider in rotational management. Meta-population structure is important to consider when designing a rotational strategy. If recruitment is limited by the supply of settling larva, an area that is a source of larvae might need to be fished less than that required to maximize YPR in order to ensure larval supply. Areas that are closed for several years may allow these animals to form dense aggregations (that would likely be heavily fished if not closed), thereby improving fertilization success. Such an effect would mean that rotation could produce greater benefits in reproductive success (i.e. successful egg/sperm contact) than would be suggested by biomass- or eggs-per-recruit curves.

Rotational management will improve YPR under a broad range of biological productivity conditions provided that:

1. the ratio of growth to natural mortality (K/M) is sufficiently high (greater than about 0.5), and
2. size-selectivity is suboptimal in producing yield per recruit.

Thus, with its fast growth and low natural mortality, Sea Scallops are an ideal candidate for rotational management. Hart (2003) assumed low age and/or density-invariant M, thus producing long optimal rotational times. Increasing M with age or size would shorten the optimal rotational period. Density-dependent adult M due to accumulation of biomass in closed areas would also lead to shorter rotational periods.

Sea Scallops are recruited into the US Georges Bank fishery at a size that is well below optimal from a YPR perspective. Rotational management increases the effective size-selectivity of the fishery, therefore inducing an increase in YPR. However, in those fisheries where the size-at-entry to the fishery is much larger, rotational management would not be expected to produce gains in maximal YPR. On the other hand, rotation increases BPR regardless of the size-selectivity of the fishery, a situation also found in Red Sea urchins. In this case, the minimum legal size for landing the urchins was already near-optimal and, thus, the rotational benefit was for BPR, not YPR.

Management Model

Hart (2003) does not explicitly address the operational objectives of rotational management other than state that it can alleviate the impact of both growth ($F_{AVG}>F_{MAX}$) and recruitment (increasing BPR) overfishing, and in doing so represents a precautionary approach to management. Growth overfishing under rotational management induces a substantially smaller reduction in YPR than would occur with constant fishing. Rotation also increases BPR for sea scallops, especially for levels of F above F_{MAX}, thereby reducing the impact of possible recruitment overfishing. Hart (2003) used the following Performance Indicators (PI) for these operational objectives:

- YAVG, which is the expected long-term mean YPR (averaged over year-classes) during the rotational period. This is important as year-classes experience different age-specific fishing mortality, depending on whether or not they enter the stock and fishery at the start, middle or end of the rotational period.
- BAVG, which is the expected long-term mean BPR (averaged over year-classes) during the rotational period.
- FAVG, which is the average annual fishing mortality during the rotational period. Hart (2003) considers that it is important to use an average fishing mortality when comparing rotational and constant harvest strategies to ensure comparison of equivalent long-term survival rates. If not used, the effects of rotation would be confounded with variation in the overall level of fishing mortality.

Two rotational harvest scenarios are defined although others are explored:

- Pulse Rotation, which consists of closing an area for p-1 years and fishing for one year (e.g. in nine year rotation period, area fished one year and closed eight years). The implication of this pattern is that, to allow fishing in the stock area each year, the stock area needs to be divided into at least p areas. True Pulse Rotation is when all exploitable biomass in a stock area is removed at periodic intervals (see Sluczanowski 1984).
- Symmetrical Rotation, which consists of closing an area for p/2 years and fishing at a constant rate for the next p/2 years. Hart (2003) determined that this scenario gave less benefit than Pulse Rotation.
- Hybrid Rotation, which consists of closing an area for half the time and then gradually increasing effort during the opening second half. For example, an area might be closed for three years and then fished for the next three years at F_{MAX}, $2F_{MAX}$, and $3F_{MAX}$, respectively. Other than mentioning this approach, Hart (2003) did not explore Hybrid Rotation scenarios.

Hart (2003) does not propose any implementation-related performance indicators other than referring to the costs of administrating and enforcing such a system, and to the socioeconomic costs from temporary closures of traditional fishing grounds. The latter might be significant if closures force fishermen to make long distance steams to unfamiliar areas. Because the optimal F_{AVG} under rotation is only slightly greater than the non-rotational F_{MAX}, the amount of effort and fleet capacity required to optimize YPR under rotation is about the same as that needed under constant fishing.

Valderrama, D., and J.L. Anderson. 2007. Improving Utilization of the Atlantic Sea Scallop Resource: An Analysis of Rotational Management of Fishing Grounds. Land Economics 83(1): 86-103.

Synopsis

Valderrama and Anderson (2007) examine US management of the Georges Bank Sea Scallop stock, which employs a system of zones (10 minute squares) opened to fishing when there is a predicted increase of biomass of 30% or more and closed when the predicted increase falls to 15% or less. Valderrama and Anderson (2007) state that although there is agreement that the system would lead to more rational utilization of the resource than an open fishery, the small spatial scale of management presents difficulties given existing government surveys. In lieu of adaptive rotation based upon opening and closing areas based upon survey biomass estimates, a more scheduled rotation is employed with one of the three areas closed and two open each year (but see Hart 2009 comment below). The paper uses a biomass dynamics model along with cost and revenue data to identify optimal exploitation rates for the fishery. The main performance indicator is maximum Net Present Value (NPV) of the fishery over a period of 30 years (NPV_{MAX30}). A constant recruitment was assumed in the simulations but tested the effects of stochastic recruitment. It recommended 6 and 8 year area closures followed by 2 years of fishing for Georges Bank and the Mid-Atlantic Bight, respectively, with a target F of 1.0 during the open periods, which equates to a time averaged F of approximately 0.3, compared to a Y/R target of 0.2.

The authors ran Monte Carlo simulations with variable recruitment and came to the same conclusions as the original model. They also point out that by increasing Landings per Unit Effort (LPUE), rotational management reduces environmental impacts by reducing the dredging time required to catch a given amount, and also will probably ensure recruitment as egg production relies on more older scallops.

The authors state that Hart (2003) found that maximum discounted YPR was obtained with uniform fishing and that gains from rotation would be modest except under overfished conditions or if the closure is timed to exploit a large year-class. The authors suggest that this result was due to the lack of inclusion of economics in the model, especially the lack of a premium paid for larger scallops.

Operating Model

Sea scallops are fast growing and relatively long lived. They can increase meat weight by 30% per year in the early fast growing years. Sea Scallops tend to recruit in "patches" of single year classes, making closed areas with a high density of pre-recruit scallops an attractive and effective conservation and economic strategy. Valderrama and Anderson (2007) use the biomass dynamic model developed at the Northeast Fisheries Science Centre (NEFSC) of National Marine Fisheries Service (NMFS) in the study. Stock dynamics on Georges Bank and in the Mid-Atlantic Bight are modelled over 30 years. The model includes discard and incidental mortalities, different prices for scallop sizes, and a LPUE correction for extra time to shuck large scallops. Other than this correction, LPUE is determined by biomass. The starting population structure was that of Closed Area I in 1990 for both modeled populations. This is a depleted population with high numbers of small scallops. Fishing costs were taken from published data and were dependent on crew size, vessel GRT (Gross Register Tonnage) and vessel days at sea.

Management Model

Valderrama and Anderson (2007) explore a range of rotational periods for maximizing NPV_{30}. The existing (2004-2007) system of three year rotational closures was used as a benchmark. The paper only examines the optimal rotation period; it does not examine any other changes to the regulations of the fishery.

The paper was critiqued by Hart (2009), which led to a further exchange by the authors. These are outlined below and further illuminate specific aspects of the application of rotational management to the US Georges Bank scallop fishery.

Hart, D.R. 2009. Improving Utilization of the Atlantic Sea Scallop Resource: An Analysis of Rotational Management of Fishing Grounds: Comment. Land Economics 85(2): 378-382.

In a reply to Valderrama and Anderson (2007), Hart (2009) states that the use of fixed premiums for larger scallops is unrealistic, showing that these price premiums were reduced during 2005-2007 with the increase in supply of the larger size categories and, in 2006, were in fact negative. Hart (2009) points out that the starting population used by Valderrama and Anderson (2007) was an overfished population with an incoming strong year-class. Hart (2009) argues that most of the gains cited were due to the initial closure period, although the authors stated that it was shown closures did not have to coincide with strong year-classes. Hart (2009) states that the suggestion that the approach recommended in Amendment 10 is not feasible is incorrect, and that it has already been implemented with 2 rotational closures using blocks of 10 minute squares. Hart (2009) states that the rotational management implemented through the groundfish closures on Georges Bank is a compromise to address issues in the scallop and groundfish fisheries. Scallop gear catches considerable groundfish bycatch, especially Yellowtail Flounder, and the closures are an attempt to build up these stocks. A large bycatch in the scallop fishery would undermine these efforts. Hart (2009) points out that Valderrama and Anderson (2007) did not include any external costs in their model such as the impacts in other species or their habitat, and that these would further reduce the benefits claimed in the study. Hart (2009) says that other effects such as distance from port and variability in landings are important and also excluded from Valderrama and Anderson's model. Hart (2009) also points out that with the large F recommended, any overestimation of biomass used in setting the quota would result in extreme overfishing of the population. Biomass estimation is not exact and such overestimations will occur. Hart (2009) states that management always involves a trade-off between different objectives and modeling a single species with a single objective function ignores interactions and competing objectives.

Valderrama, D., and J.T.Anderson. 2009. Improving Utilization of the Atlantic Sea Scallop Resource: An Analysis of Rotational Management of Fishing Grounds: Reply. Land Economics 85(2): 383-389.

In a reply to Hart (2009), Valderrama and Anderson (2009) state that the price premiums for larger scallops had remained in place during 2005-2008 and used the data available in the US scallop management framework document to support this. The authors said that a pricing sub-model would be good but that it would unduly complicate the model, and did not have enough data on which to base a price-demand model. Valderrama and Anderson state that the most recent NEFMC ex-vessel price models include variables for scallop size and a premium for the under 10 mm size category. They say that a price differential will exist over time and, although a reduction in this differential will decrease the benefits of rotation, it is still the best choice. The authors refute the claim by Hart (2009) that the initial stock conditions had a large effect on the results, and that rotational fishing emerges as a global solution regardless of initial conditions. They agree that the relative benefits of the approach will change with initial conditions, but consider that rotation will emerge as optimal unless the price premium disappears or the scallops fail to grow. As to the existing plan for 10 minute square openings and closings, they argue that the plan suggests the need for surveys of scallop biomass on this fine scale over the whole area which they consider is not feasible. For the bycatch issue, they argue that the higher LPUE and closures will result in a lower effect on bycatch than a fishery that operates continuously. As to the practical issues of implementation, such as steaming time and the risk of overestimating abundance, if several areas are open at any given time and the fishers are engaged in the consultative process, they have time to change their fishing practices. They conclude that the risk from overestimation of biomass is inherently reduced under rotational management, as areas are spatially and temporally separate. Overall, they consider that if there is a desire to reduce risk then optimal rotation periods can be shortened, which will result in reduced exploitation rates.

Department of Marine Resources (DMR), State of Maine (2013) Sea Scallops

Synopsis

The US Maine Department of Marine Resources is responsible for fisheries within state waters (three miles from shore). The inshore scallop fishery in the state of Maine consists of three zones, with Zone Two, which consists of approximately half the coast, under a rotational management plan for ten years, starting in 2012/2013. The fishery is pursued by both divers and vessel based draggers and has a recreational fishing component. While Maine scallop landings have increased since 2009, it is difficult to discriminate whether or not this is due to the effects of the management plan or to natural fluctuations of the stock.

Operating Model

The biology of sea scallop relevant to rotational management is described above in the review of Hart (2003). In relation to monitoring, pre-season surveys provide biomass estimates for each area and in-season closures take effect if it is determined that 30-40% of the fishable biomass in an area has been removed. In-season surveys can be conducted to see if the removals have reached 30-40% and areas may have the season extended or be reopened if the additional analysis indicates that less than 30% has actually been removed.

As in most fisheries, catches are monitored through logbooks.

Management Model

Other than the surveys noted above, there is no additional assessment (e.g. analytical model) of the stock used to inform management.

All three zones have daily catch limits, seasons, minimum size and gear restrictions. There are also specified areas closed to fishing for conservation, pollution or conflicting uses.

For the rotational fishery in Zone Two, the coast is divided into 21 areas split alternately down the coast into 3 groups. In any 1 year, 7 areas are open and 14 closed, so each area will go through a rotation of 1 year open then 2 years closed. As noted above, during the fishing season, if it is determined that 30-40% of the fishable biomass has been removed (based on evaluation of pre-season survey biomass versus in-season catch), then that area is closed to fishing. Thus, rotational management is a combination of a determinate schedule supplemented by adaptive changes based on area-specific biomass.

NORTH PACIFIC

DFO. 2012b. Status Update of Wild British Columbia Geoduck Stocks, 2011. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2011/081. See also Geoduck Clam (*Panopea abrupta*) and DFO. 2009. Proceedings of the Pacific Scientific Advice Review Committee (PSARC) Invertebrate Subcommittee Meeting: Stock Assessment Framework for the British Columbia Geoduck Fishery; November 26, 2008. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2009/008.

Synopsis

The Geoduck fishery off the coast of British Columbia (BC) is a good example of rotational management on the west coast of Canada. The fishery is conducted by divers harvesting individual geoduck beds in the waters inside of Vancouver Island and north using a three year rotation strategy. The west coast of Vancouver Island fishery has retained an annual fishery as it was felt concerns over Sea Otter predation and closures due to Paralytic Shellfish Poison (PSP) needed greater flexibility in harvest management. Rotational management is conducted using bed-specific estimates of biomass along with overall management by TAC and effort regulations. The fishery is considered data rich and is managed on a fine (bed) spatial scale. The quotas are considered conservative and the population biomass is within recommended limits.

Operating Model

Geoducks are long lived (>100 years) and grow rapidly in the first 10 to 15 years of life. Geoducks begin to recruit to the fishery at age 4, are fully recruited by ages 6 to 12, and generally reach maximum size by age 20. Sexual maturity can occur as early as 2 years of age. Geoducks are broadcast spawners with a long pelagic larval period resulting in complex spatial recruitment dynamics at a range of spatial scales. Recruitment is highly episodic and coast wide. These features make BC Geoducks a good candidate for rotational management.

Diver surveys collect geoduck counts in 5 m intervals along transects laid perpendicular to shore. The divers also record depth and substrate type. Fifty-nine percent of the bed area has been surveyed, with 21% being surveyed more than once.

On-Ground Monitors (OGMs) during fishing operations for West Vancouver Island (WVI) and the North Coast (NC) collect anecdotal information and monitor and direct fleet activities during harvest operations. Logbooks record harvest area; these are imported into a Geographic Information System (GIS) system to map the harvest areas, which help define the boundaries of the geoduck beds at the small scale. Substrate mapping using acoustic backscatter (QTC

View) analysis has been done for 45.5% of the area. This informs decision-making on the habitat impacts of the fishery. Comments and feedback from OGMs and harvesters on locations and sizes are collected at regularly-held meetings and from logbook comments.

The fishery has moved from an open access competitive fishery in 1976 to the present system. In the last 20 years, the effort to conduct surveys and bed mapping has resulted in a data rich fishery that is assessed and managed on a fine spatial scale (by bed). Verification of landings and OGMs help enforce the management strategy.

Management Model

The diver surveys provide the data used to estimate the biomass in each geoduck bed. The boundaries of the bed are estimated based on logbooks, diver surveys, QTC View mapping and comments from harvesters and OGMs. There are approximately 2,400 beds identified, but the number of beds and sub-beds changes each year as new beds are discovered and beds combined as the fishing areas expand. Extant biomass for each bed is estimated as the bed area x density x mean Geoduck weight. Mean Goduck weights are estimated from commercial landings (landed weight divided by number of geoducks harvested by bed) and biological sampling. When there are no data available for a bed, the mean geoduck weight for the overall area is used and corrections are applied for differences between commercial and biological sampling weights. Density is estimated from diver surveys when available (59% of area). When there is no survey data, density is estimated from surrounding beds within a category (i.e. high density) incorporating OGM and logbook.

Uncertainties are recognized in the parameters used to estimate biomass (area, density and mean weight), which are presented to management as a range of harvest options. Gaps in knowledge include factors affecting recruitment and natural mortality, the show factor (variable percentage of siphons visible to divers during the survey and to harvesters) and the predation effects of an expanding Sea Otter population.

One of the main reference points used in management is the bed-specific virgin biomass, the estimation of which is subject to high uncertainty. There is a desire to find alternatives due to the problems in calculating virgin biomass and the difficulty in monitoring closed beds.

The target exploitation rate for the beds under rotational management is three times a specified annual rate. The Limit Reference Point (LRP) is 40% of virgin biomass, and beds are closed when they fall below this level (in 2011, 6.7% of harvestable area was closed under this rule). There is no bed-specific biomass target (termed Upper Stock Reference point or USR) which is implicitly defined by the target exploitation rate. The reference points are considered to be conservative as there is an unquantified portion of the stock in refugia (deep water, substrate unsuitable for harvesting method, park, research and contamination closures, and beds of low market value).

Besides the rotational areas, management tools include the regional TACs, limited entry licenses, Individual Vessel Quotas (IVQ), dockside validation and OGMs. TACs are based on regional exploitation rates applied to estimated biomass of all beds within that region. There are ongoing bed enhancement efforts in the Strait of Georgia that are supplying a small but increasing portion of the TAC. Allocation of beds to subtidal aquaculture has reduced available bed area and increased the possibility of unreported wild harvest.

DFO. 2015. BC Giant Red Sea Cucumber Integrated Fisheries Management Plan.

Synopsis

The management regime has evolved since 1991 when limited entry was introduced (85 license restriction). Since then, the management approach has changed a few times. A rotational approach was used during 1993-1996, with each license receiving an equal share of the TAC. During 1997-2007, the fishery changed to an Adaptive Management Plan (AMP) with all but 25% of the coast closed to commercial fishing. The fishery reverted to a non-rotational quota fishery. An additional 25% of the coast was used for experimental fisheries that examined the effects of a range of exploitation rates on the population. The closed areas were not meant to be permanent, and after the 2008 review of the 10 year AMP, DFO started to reopen areas closed under the AMP. The fishery has again been managed in a rotational manner, with each sub-area harvested one year in three. However, the fishery on the West Coast of Vancouver Island has retained the non-rotational system as it was felt there was not enough quota available to support a rotational fishery. In addition to rotational areas, no-take reserves are introduced as needed dependent upon information from the fishery.

The exploitation rate is felt to be very conservative and sustainable, and the process of reopening areas closed under the AMP is on-going. The management approach is designed to allow time to determine sustainable harvest levels for a species of which little is known.

Operating Model

Stock spatial structure is not well understood, but given the larval stage duration of 2 to 4 months, recruitment dynamics are interpreted to be at a larger scale than the sub areas. There are a large number of protected areas where no fishing can occur, thus providing reproductive reserves to ensure future recruitment. In addition, the deep-water component of the distributional area acts as a reserve, as the depths are beyond that accessible to the divers.

Surveys are done annually to provide estimates of the density of Sea Cucumber per metre of shoreline and population biomass for each Subarea. These indicate that Sea Cucumber abundance is relatively constant over time. There is no indication of concern about overall abundance, with the stock considered to be healthy. The surveys indicate that many areas have densities higher than the initial conservative estimate of 2.5 cucumbers per metre of shoreline.

Concerns have been raised about sustaining sufficiently high densities in the fished areas such that sexual reproduction is not compromised. However, this is not thought to be critical given the presence of the reproductive reserves and the deep water component of the stock being unfished.

Due to the lack of ageing data, and the relative uniformity of size within the adult stock, there is limited information on age/size specific fishing mortality.

Dockside validation is a key component of the fishery, with validation of offloads undertaken by DFO. In addition, there is air surveillance to enforce boundaries between open and closed areas, as well as to conduct gear and vessel counts. Underwater harvest activities are also monitored by fisheries officers using SCUBA gear. The issues addressed by this monitoring include licensing verification, closed areas and times, provision of accurate information on fishing activities, accuracy of logbooks, and validation of landings information.

Management Model

Other than the surveys of area-specific biomass, there are no additional analytical assessments. There is no description of how the subareas were specifically defined, and it appears these are delimited in a pragmatic manner.

A biomass limit RP is in place (50% of unfished biomass), although its use in management at the local scale is unclear. It appears to be only applied at the broad scale.

Target exploitation rate reference points have been defined in a variety of ways for different time periods and locations. The current target RPs are:

- West Coast annual exploitation rate is 4.2% of extant biomass; and
- rotational sub-areas have target exploitation rate of 10% per bed (over 3 years), resulting in an annual average rate of about 3.3% for the inside stock area.

In addition to the rotational areas, the fishery is controlled by quotas that are based on each license having an equal portion of the TAC, the latter defined by the survey biomass estimates and the target exploitation rate.

Endreny, P.A., and G. Silvia. 2006. Mapping a Path to Sustainable Utilization of Bay Clam Resources in Oregon's 21st Century Estuaries: An Investigation into the Potential of Oregon's Commercial Bay Clam Fishery. Report to the Oregon Department of Fish and Wildlife and the Oregon Commercial Bay Clam Industry. College of Oceanic and Atmospheric Sciences, Oregon State University. 105 p.

Synposis

The Oregon Bay Clam fishery harvests (by hand and diver) five species: Gaper or Empire (*Tresus capax*), Cockle (*Clinocardium nuttalli*), Littleneck (*Venerupis staminea*), Butter (*Saxidomus giganteus*), and Softshell (*Mya arenaria*) clams. In 2005, it transitioned from "developmental" status under the management of Oregon's Developmental Fisheries Program (DFP) to "developed" limited entry (rights-based) status. This was considered premature as the State of Oregon requires developmental fisheries to meet a number of scientific and management standards, which had not been met before transitioning to developed status. A study was thus commissioned (Endreny et al. 2006) to fully explore the requirements of a sustainable Bay Clam fishery. While many of the recommendations do not apply to the Canadian Surfclam fishery, the comprehensive nature of the review provides insight on the needs of spatial management.

Operating Model

The five clam species share a number of biological characteristics including suspension feeding, ability to live in comparable substrate types, lifetime longevities of about 15 years and generation times of 1.5 to 3 years, corresponding predators, and sexual spawning by broadcasting their eggs and sperm into the water column. All bay clams are important contributors to the ecological health and function of estuaries, improving water quality and providing nursery habitat for many organisms. These bivalves play essential roles in the recycling and filtering of nutrients and energy in estuarine ecosystems. This information is used only in a general sense by Endenry et al. (2006).

Endreny et al. (2006) consider that rotational harvesting can work in conjunction with a rotational surveying schedule. When an area is "rotated-out," or set aside from harvest pressure for some time period, a post-harvest survey can occur in the area to help determine when it should be harvested again. This post-harvest survey method is successfully practiced in Washington's commercial Geoduck (*Panopea abrupta*) fishery.

Endenry et al. (2006) discuss the capacity of GIS to assist managers in the on-going monitoring of a rotational management system. Geographical Information System technology is well developed and would be a valuable tool in facilitating the assimilation of spatial information on CPUE and control of harvesting amongst areas.

Management Model

Endreny et al. (2006) propose that through an intensive baseline survey of the Bay Clam resource, and the establishment of strategic methods for future fishery dependent surveys, it may be possible to determine the sustainability of harvest levels of this fishery without expensive, ongoing traditional stock assessments. A 4-part assessment process is proposed:

- Perform a comprehensive baseline stock assessment of bay clams in all major harvesting bays, particularly Tillamook and Coos bays.
- Design a rotational spatial dive harvest strategy that considers CPUE in order to update baseline assessments.
- Implement a rotational spatial dive harvest strategy with the industry and employ a scientific analyst to evaluate the resource data and help set harvest levels.
- Employ operational observers to monitor system protocols of the strategy a few times per year with fishermen during field harvest.

Endreny et al. (2006) do not state how optimum harvesting would be defined other than in a general sense. An adaptive rotation strategy is discussed, which is based on empirical data of clam bed recovery time to the average pre-fishing density. It is noted that if a stock is experiencing positive environmental conditions, good recruitment may shorten the rotation time between harvest areas, whereas if conditions turn adverse (e.g. warming sea temperatures, hypoxic waters, increase in diseases, etc.), recruitment may be affected and stock recovery time may be extended. In order to decide on appropriate harvest rates and rotations for a stock, knowledge of stock parameters including natural mortality, growth, and recruitment needs to be used along with baseline abundance data and abundance trends through time. When bed recovery does not occur as expected, managers need to respond by changes to the established harvest rotation plan. Endreny et al. noted that the number of designated fallow areas is dependent upon the interplay between harvest rate and stock recovery time. If there are many fallow areas, longer recovery times are permitted, implying that the harvest rate can be higher in the open areas, reducing biomass to a lower level than if there are fewer designated areas, in which recovery times would need to be short to achieve pre-harvest levels.

Two potential issues are raised with rotational management:

1. there is not enough harvesting area to set aside from harvesting pressure, and
2. managers assume that the set aside areas will not suffer losses from pollution, disease, or weather.

While not raised by Endreny et al. (2006), an additional potential issue involves the so-called move-on rules. Fishing in open areas would focus on high density beds, generating high CPUE, which would decline precipitously once the fishery fishes out these high density beds. Catch per Unit Effort may be non-linearly related to exploitable biomass, through a hyper-stable function. In setting move-on rules, a relatively high CPUE may have to be established as a Performance Measure (PM) in a move-on rule to ensure that area-specific biomass is not reduced to an unsustainable level.

Kalvass, P.E., and J.M. Hendrix. 1997. The California Red Sea Urchin, *Strongylocentrotus franciscanus*, Fishery: Catch, Effort, and Management Trends. Mar. Fish. Rev. 59: 1-17.

Synopsis

Kalvass and Hendrix (1997) address management of the California Red Sea Urchin fishery. The main utility of this review is that it provides an example of recruitment over-fishing in a sedentary invertebrate fishery which may have occurred under effort management without spatial restrictions. Size limits and effort control were not sufficient to sustain the resource (at least up until the mid-1990s at which time the paper was written). Until the mid-1990s at least, there was no spatial rotational management system in place. The authors recommend either/or quotas and periodic harvesting (i.e. rotational approaches).

Operating Model

The species is distributed broadly along the West Coast of North America from Baja California to Alaska. The focus of the review is predominantly on the California component of the coast-wide Red Sea Urchin fishery. Although relative abundance varies within the distributional area of the species, there is no evidence of spatial stock structure, the species being ubiquitous in rocky habitats.

In California, catches increased steadily from the inception of the fishery in the early 1970s, followed by major declines starting in the late 1980s due to fishing down of the virgin stock. The abundance trends indicated by CPUE, which are limited to 1986-1995, show a general decline.

Two density-dependent mechanisms (“Allee effects”) are felt to be important; juvenile refuge from predation under adult spines, and a minimum adult density for successful spawning.

There have been several studies addressing natural mortality in reserves (ranging from 5% to 15% annually). However natural mortality rates have been interpreted to be higher in southern California (as high as 30%) due to greater predation by several fish and invertebrate species. Natural mortality has been assumed to be 0.16 in a stock assessment.

Observation on the resource is mainly from fishery data: the fishery is prosecuted by divers (usually 2 per boat) using a short-handled rake for scooping the urchins into meshed bags along a relatively narrow strip along the coastline (low intertidal to about 22 meters depth). In addition, there are observations made by biologist divers. There have been three categories of surveys that provide some fishery-independent information on sea urchins: localized investigations by university researchers, annual benthic surveys in National Parks, and some surveys by the State of California around the Channel Islands.

Other than the need for a license or permit, there appears to have been no on-ground enforcement.

Management Model

Abundance trends are assessed predominantly based on the fishing effort data, although there has been information on abundance collected by “biologist divers”. At the time of the review, there was very limited fishery independent data. An estimate of pre-1988 fishable biomass for Northern California was 76,290 t, implying a fishing mortality rate of about 8%.

The control rules in the fishery have addressed fishing effort in an increasingly restrictive manner. The fishery was experimental from 1971 to 1980s, and not managed other than the stipulating the need for a license and use of voluntary logbooks. The rules evolved beginning in 1985 when permits were required (with a moratorium on new permits in 1987). A minimum sea urchin diameter was established in 1989. The size limit increased in 1990, followed in 1991/1992 by a July closure, shorter fishing weeks, a one week a month closure, and limited entry.

The technical measures for the fishery have been predominantly size limits and seasonal closures. There has been no spatial management during the time period of the review.

Rogers-Bennet, L., P.L. Haaker, T.O. Huff, and P.K. Dayton. 2002. Estimating Baseline Abundances of Abalone in California for Restoration. CalCOFI Rep. 43: 97-117.

Rogers-Bennet et al. (2002) discuss long-term baseline abundance of sessile bottom invertebrates in the Pacific. Much of the work is not relevant to Surfclam except for some comments on abalone stock dynamics relevant to the operating model, which are summarized below.

Rogers-Bennet et al. (2002) note that Sea Urchins may be vital for the survival of small wild abalone in the 5–20 mm size class, suggesting that marine protected areas where Red Sea Urchins are not fished may be essential habitat for Abalone and could play a crucial role in restoration efforts. Further, abalone may be a good indicator group when identifying marine reserves that could benefit multiple species. Areas that at one time had high numbers of abalone may indicate productive subtidal sites that could be set aside as no-take reserves for multiple species. Rogers-Bennet et al. (2002) also indicate that benthic invertebrates such as Abalone, sea urchins, Queen Conch, and scallops must occur in dense patches to successfully reproduce, suggesting that Allee effects, (or depensation) are important. In addition to abundance, aggregation size and distance between neighbors play important roles in the population dynamics of Abalone. Experiments have shown that fertilization may be limiting in populations of *H. laevigata* when distances separating spawning individuals are greater than 2 m. Minimum viable population density for *H. laevigata* has been estimated at 2,000 animals per hectare, below which recruitment collapses.

SOUTH PACIFIC

Plaganyi, E.E., T. Skewes, N. Murphy, R. Pascual, and M. Fischer. 2015. Crop Rotation in the Sea: Increasing Returns and Reducing Risk of Collapse in Sea Cucumber Fisheries. PNAS Vol. 112, no. 12: 6760-6765.

Synopsis

Plaganyi et al. (2015) estimated the benefits of the Rotational Zone Strategy (RZS) which has been applied to the data-poor, multi-species sea cucumber fishery within Australia’s Great Barrier Reef since 2004. They developed a simulation model to investigate the benefits of the rotational management strategy versus a non-rotational fishery. The modelling approach tested the efficacy of the RZS for 9 species during 1995-2012. Zone size and the rotation periodicity were determined by industry using a common sense approach to suit their operations. Each of 154 zones for 9 species had 20-year population projections with a range of harvest scenarios with different periodicity and magnitude of effort i.e. 3-year rotation through 154 zones (with a range of rotation time periods up to 6 years) starting in 2004. Protected areas, and a minimum size for the nine commercial species, as well as overall landings and effort caps were also considered. Risk management and MSE approaches were used to assess the trade-offs and risks of over-exploitation under alternate management strategies for the 9 species. The overall conclusion is that the RZS achieves the objectives of reducing localized depletions and reduces the risk to the overall fisheries sustainability.

Operating Model

Plaganyi et al. (2015) used an age structured production model simultaneously applied to each of the nine major species, with subpopulations simulated in each of the rotational zones. They employed 16 biological models made up of different combinations of two levels of each of the four primary uncertainties. These uncertainties include natural mortality (run at average estimates for each species and at lower bounds of the mortality estimates), steepness of the stock-recruit function (fixed at 0.7 and at a more conservative 0.5), recruitment frequency (stochastic, with random fluctuations around the stock-recruit curve, and deterministic using the stock-recruit curve), and initial biomass (using the estimated 1995 biomass which was largely before fishing, and at 50% of the 1995 value). For each of the 16 combinations, Plaganyi et al. (2015) ran 10 replicates with stochastic variation in recruitment, resulting in 160 population projections for each zone.

Management Model

The fishery is managed with a 3-year rotation period through 154 zones so each zone is fished for a short period (i.e. 15 days) once every 3 years. Other management measures include fishing limits within each zone, minimum size limits and a TAC.

The performance metrics examined were:

- B_{2032}/B_{1995}, the ratio of spawning biomass at the start and end of the runs for each species;
- B_{2032}/B_{2012}, the ratio of spawning biomass at the end of the run versus the present (2012) spawning biomass for each species averaged across all zones;
- risk of local depletion measured as the percentage of all individual runs that ended below B_{LIM} = 0.2 of the comparable no fishing reference case at the end of the projection period;
- risk of depletion measured as percentage of runs below a more conservative B_{LIM} = 0.4 of the unfished state;
- average catch over 2012-2032 for each zone, the entire area, and three groups of species based on value (very high, high and medium value); and
- average annual revenue computed as landed weight times current average market prices.

The 1995-2012 populations in the runs were also compared with survey indices where available to ensure the model agreed with what had been observed during this period.

The model was sensitive to slight changes in age of maturity with the current minimum size restrictions. Runs with higher TACs and conservative age at maturity estimates resulted in several local populations crashing and overall population depletion. To choose an optimal strategy, they conducted runs with rotational periods of 1 to 6 years. They considered total revenue versus risk measured as the median risk of biomass falling to less than 40% of the unfished biomass across all species. Risk declined with increasing rotation periods but so does revenue. There were differences based on life history (lifespan and growth rate) of the different species. Species with shorter lifespans and higher growth rates favoured shorter rotations and longer lived species favoured longer rotation periods. They concluded that the 3-year rotation period gave the greatest revenue with lowest risk overall, and thus was the most optimal given the mix of species, their life histories, management regulations and relative value. They concluded that a rotational strategy substantially reduces the risk of localized depletion with similar overall catch, particularly for slow growing species, compared to a non-rotational strategy.

They make recommendations for rotational strategies for data poor fisheries where more complex management controls are difficult to implement:

1. use a rotational cycle with longer cycle times for longer lived species;
2. a minimum legal size enhances benefits and should be selected to protect at least the first age of maturity; and
3. use a cap on total catch or effort per locality.

Sluczanowski, P.R. 1984. A Management Oriented Model of an Abalone Fishery Whose Substocks are Subjected to Pulse Fishing. Can. J. Fish. Aquatic Sci. 41(7): 1008-1014.

Synopsis

This paper considers Beverton and Holt yield per recruit dynamics in the South Australian Abalone fishery under rotational management. This diver-based fishery exploits two species, the Greenlip Abalone (*H. laevigata*) and the Blacklip Abalone (*H. ruber*) in about equal portions. Variables examined include age of recruitment (controlled by minimum size) and rotation period. With the current minimum size, biomass yield is near maximum, but egg production is only 16 - 32% of unfished. Sluczanowski (1984) uses existing fecundity at size relationships, but goes on to reference unpublished studies that suggest that abalone under 4 years of age contribute little to egg production. If this is the case, it is shown that under present conditions, egg production may be 1% of optimal for reefs fished more than once every 2 years.

Support for rotational management appears to be a combination of a high market value shallow water diver fishery efficiently harvesting the immediate fishing area, and species characteristics that produce optimal biomass per recruit at an age/size that has low fecundity compared to older/larger animals. It is an important case study, as the benefits of rotational fishing are not an increase in Y/R but rather decreased risk of recruitment overfishing. This involves a trade-off between immediate tangible returns and potential future stock growth.

No specific recommendation is given for which combination of rotational period and minimum size should be used in the fishery.

Operating Model

Abalone are sedentary and found in shallow waters over about 2000 km of coastline, usually in dense aggregations, often on isolated reefs that have been delineated into 217 management areas. Although there is not a well-defined stock-recruit relationship, it is thought that recruitment from adjacent beds is limited given that the larval stage has a pelagic period of only a few days.

Sexual maturity starts at about 2 years, which is younger than the age at the minimum size (Age 4) used by management. Thus, it was felt that the abalone fishery was insensitive to recruitment overfishing. However, there have been a number of abalone stocks that have never recovered after intensive fishing (Australia, California and BC). It has been suggested that abalone younger than Age 4 produce relatively few eggs compared to older abalone, and so the present controls result in a large reduction in egg production of the stock.

The paper does not discuss stock monitoring activities and uses published stock parameters in its yield per recruit analysis.

Management Model

Sluczanowski (1984) states that ideally each substock would be fished using a minimum size and rotation period tailored to the sub-stock parameters. It is likely more practical to divide the stock area into zones with similar population characteristics and use the appropriate minimum size and rotation period for each zone. The rotational plan assumes that a zone containing abalone is fished intensively over a short period of time until almost all abalone over the minimum size have been taken. The zone is then left to recover. The recovery period ranges from 6 months in highly productive stocks to 3 years for others.

A target reference point for egg production is not given, likely because it remains low for all but large minimum sizes or rotational periods. It is indicated that targets for egg production should be increased as longer term closures increase egg production while only slightly reducing average annual production. It is suggested that there would also be reduced fishing costs as the number of trips would be reduced.

In additional to the rotational zones, extant (1984) regulations in the fishery included limiting the number of divers, and a minimum size (near the peak biomass/recruit, and approximately Age 4). No overall TAC is in place.

Regarding disadvantages of rotational management, it is stated that there may be enhanced opportunity for poachers and economic consequences of longer term closures, but these are not discussed further.

CARIBBEAN AND SOUTH AMERICA

Liu, O. and J. Kritzer. 2013. Management Approaches for Small-Scale, Spatially-Structured, Sedentary Stocks. Unpublished Manuscript.

Synposis

Liu and Kritzer (2013, unpublished manuscript) consider eight case studies that together represent a collection of management tools effective in promoting the sustainability in S-fisheries (small-scale fisheries that target spatially-structured, sedentary stocks). Each case study is profiled, including its history, management structure, and current resource status. Although the case studies incorporate a wide range of target species involving a wide range of locations, governance regimes, and levels of data-richness, common themes emerge. The toolbox for effective management of S-fisheries includes some combination of limited entry or more extensive property rights, no-take reserves, rotational harvest systems, and stock enhancement strategies.

Operating Model

S-species are largely sedentary with highly spatially structured populations. Oysters and clams, for instance, are completely sessile after the planktonic phase, and feed by filtering the surrounding water column. The range of movement of all S-species is extremely small. These species exhibit patchy distributions with localized populations or spawning groups forming over scales of 10s to 1000s of meters, often associated with specific habitat. Another important determinant of the spatial distribution is density-dependent reproduction. Fertilization success is maximized when individuals are aggregated. This patchy distribution gives rise to meta-population structure, where a larger-scale population consists of discrete sub-populations that can exhibit independent demographic rates (e.g. growth) but are connected with other sub-populations through larval dispersal. The spatial dynamics of the meta-population are determined not only by the number of larvae produced by the meta-population as a whole, but also by the larval duration (i.e. amount of time spent floating in the water column, the direction and speed of ocean currents and fronts, the location and distance between suitable settlement habitats, and the behavior of the larvae themselves).

Although sub-populations within a meta-population are connected via larval dispersal, the demographic contribution of each sub-population to the whole is not always equal, giving rise to “source” and “sink” populations. For instance, larvae produced from the upstream area will drift and settle on the downstream area, whereas the downstream area’s larvae may drift further downstream and be lost if no suitable settlement habitat is found.

Meta-population structure and source-sink dynamics are thus important considerations for management. Because S-species tend to aggregate into patches, they can be vulnerable to serial depletion of important beds, as was the case in the British Columbia geoduck and Chilean sea urchin fisheries prior to management reform. It is easy for the most productive beds to be fished out entirely, having a disproportionately negative impact on the overall stock. If enough nodes of a meta-population network are removed or depleted to the point of ineffectiveness, connectivity between sub-populations can be severely limited and the overall resilience of the stock will decline.

Management Model

In one of the case studies (BC geoduck), explicit spatial management measures are in place. Licenses are assigned to one of three areas (North Coast, Georgia Strait, or South Coast) along the coast every year. Fishermen can fish different zones from year to year, but only if they trade with another license. Also, as TACs for the three management areas have changed, the number of licenses assigned to each zone has fluctuated in order to keep an equal distribution of the total TAC assigned to each license. There is a mandatory three-year rotation among fishing areas within each management area. This reduces pressure on the target species, increases resilience, and makes monitoring easier because catches are landed at a reduced number of ports.

No-take reserves are a commonly-used tool to manage S-fisheries, and they are incorporated in some form or another in almost all of the successful case studies reviewed. Reserves are often effective because of S-species' limited mobility and potential for protected sub-populations to seed downstream populations. In placing reserves, it is often most effective to identify sub-populations that are important sources but that also exhibit self-recruitment. If those self-recruiting source populations are protected, they will be able to persist on their own, while also providing larvae to fished populations.

Liu and Kritzer (2013, unpublished manuscript) examine Territorial User Rights Fisheries (TURFs) in some of the case studies. These are somewhat of an alternative to rotational management as it is difficult to envision these two management approaches used together, although Individual Transferable Quotas (ITQs) in the BC Geoduck fishery represents a combination of these. On the other hand, marine reserves are an important aspect of both approaches.

MEDITERRANEAN

Caddy, J.F. 1993. Background Concepts for a Rotational Harvesting Strategy with Particular Reference to the Mediterranean Red Coral, *Corallium rubrum*. Mar. Fish. Rev. 55: 10-18.

Caddy (1993) considers the concepts underlying rotational spatial management in general, using Mediterranean Red Coral as an example. Rotational management is considered to be an alternative to quota management, although Caddy (1993) discusses the use of quotas within the spatial rotational management regime. The approach is to be used when the “dynamic pool assumption” of mixing of age groups between successive harvests is not occurring within the fishery (i.e. for most sedentary invertebrate fisheries), and the mixing (geographical dispersal) occurs at the early life history stages.

The approach promotes “serial depletion” of high density subunits of the stock in a sustainable manner, and is well suited to species with a slow growth rate. Although the “dynamic pool” assumption is inappropriate for sedentary species, “dynamic pool” yield per recruit models are considered useful for exploring minimum size for harvesting and the impacts of various levels of fishing effort.

Using a simple model, Caddy (1993) addresses the methods for defining the number of sub-units, and the proportion of the stock biomass that can be harvested annually (thus the link to quotas if the overall biomass can be estimated). The model assumes that all of the biomass accessible to the fishing gear is removed from the subunit during the open period for that area (i.e. complete serial depletion). The parameters of the model are:

- recovery period;

- number of sub-units or zones (minimum of the recovery period plus one); and
- annual harvest from open sub-unit (biomass of stock divided by number of sub-units, taking into consideration that there are some reproductive reserves set aside).

There is some contradiction in that rotational management is cast as a non-quota regime although it can employ a quota for an open sub-unit. The model only requires estimates of natural mortality and von Bertalanffy growth parameters, and uses a single year-class model to represent a steady-state population of multiple year-classes.

Caddy (1993) addresses the importance of identifying unfished areas as reproductive reserves. Rotation periods must exceed the age at maturity, and the approach assumes that recruitment to the stock is at the bank scale. For the size of the sub-units, Caddy (1993) suggests taking a pragmatic approach based largely on operational considerations. An additional advantage of the approach is that genetic selection for fast growing strains, which Caddy (1993) considers to be inevitable for the “common-pool” quota managed fisheries, is attenuated.

BEST PRACTICE IN SPATIAL MANAGEMENT AND ITS APPLICATION TO SURFCLAM

While a number of the case studies were not directly applicable to the Canadian East Coast Surfclam fishery, all had lessons which can inform potential adoption of rotational management in this fishery.

Most of the studies indicated that rotational management was best suited for sessile benthic species in which mobility is limited after larval settlement, growth was initially rapid and natural mortality low, such that the K/M ratio is greater than 0.5 (Hart 2003). This is certainly the case for Surfclam (K/M = 0.08/0.08 = 1.0), making it a candidate for rotational management. Given the sessile behaviour of these species, greater consideration needs to be given to the spatial structure of the population. Many of these species comprise meta-populations in which smaller sub-populations are relatively independent for much of the life cycle except for when spawning occurs and contributes recruitment to these sub-populations. Upstream ‘seed’ areas provide recruits to downstream ‘sink’ areas, and/or there are re-circulation features that enhance local persistence. Further, there can be growth and mortality differences across these sub-populations that are important to take into account in rotational management. While Surfclam may form a meta-population structure on Banquereau and Grand Bank, seed areas are not clearly delineated, and spatial growth differences are not apparent. The findings of physical oceanographic models, and the information on the duration of the Surfclam larval stage, infer that recruitment occurs at relatively large spatial scales. A distribution map of Surfclams 50 mm or less from the 2010 survey shows a somewhat aggregated distribution, but it would take more analysis to determine if protecting areas with higher numbers of pre-recruits would be desirable. Also, with very long lived species such as Surfclam, recruitment events can be very infrequent. Thus, the opportunity to protect high density patches of recruits may only happen occasionally.

Many of the studies, as well as the 2015 Surfclam reviews, highlighted the need to consider small-scale spatial effects of population density on productivity. There have been no studies of density effects on growth rate of Surfclam, although it may be expected that there would be some unknown level of density that would result in lower growth. In support of this, there were anecdotal reports that the high recruitment patch below the eastern shoal on Banquereau was growing slower than expected.

Fertilization success at low densities is another issue raised in some of the papers (Plaganyi et al. 2015; Sluczanowski 1984). The concern is that at low densities, not only is egg production reduced, but that declines in fertilization success imply that larvae production may be reduced even further. Levitan and Sewell (1998) reviewed laboratory, natural and modeling studies and concluded that an Allee effect of reduced population growth at low densities may have a higher population threshold for broadcast spawning invertebrates. Claereboudt (1999) modeled the Bai de Chaleur sea scallop population and concluded that a 50% reduction in population resulted in a 90-95% reduction in larvae production. With high densities, while it is not clear that this is an issue with Surfclam, since clams are filter feeders, there may be a loss of larvae, through cannibalism, trying to settle in a high density area (Hancock 1973).

Regarding survey monitoring and assessment, several benthic invertebrate management systems described in the case studies use estimates of biomass from a survey to inform decision-making. Some studies use this information to control harvesting at the stock level while others also use it at the rotational zone level (e.g. BC geoducks). If the latter is pursued, it raises issues as to the most appropriate analysis and use of the analytical outputs at a small spatial scale. The case studies generally do not provide specific guidance on the appropriate assessment analysis to undertake. While the Surfclam survey conducts a relatively large number of sets (approximately 200), it still provides only a low resolution map of the distribution of Surfclam, implying increasing uncertainty of biomass within zones as these decrease in size. Spatial analyses such as kriging could be used to map biomass distribution over which rotational zone grids of different sizes could be placed, and their strengths and weaknesses to support decision-making explored.

The case studies provide considerable guidance on the rules and tools of rotational management. It is clear that there is a need to link the design of a rotational management system to the management goals being pursued and the operational objectives (i.e. rules) used, the latter consisting of assessed status of performance indicators (e.g. biomass) relative to some reference point (e.g. virgin biomass). Typically, operational objectives are based upon per-recruit considerations, which is consistent with the meta-population structure of these species although this is not always the case. Some studies have rules defined at the stock level (as is currently the case with Surfclam) while others also have rules defined at the rotation zone level. Whether or not some rules apply at the stock or zone level depends somewhat on the objective being pursued. In the case of biological objectives, at the stock level, it is possible, as in the case of Surfclam, to set limit biomass reference points (B_{LIM}) to avoid low egg production and ensure overall stock sustainability. It is also possible to establish a zone-specific B_{LIM} to avoid serial depletion (e.g. fishing moves from one zone to the next, reducing biomass to a low level in each but still allowing overall stock biomass to be above the stock-level B_{LIM}). Having a zone-specific B_{LIM} also addresses the possibility of an Allee effect. Zone-specific B_{LIM} reference points could be based on the spatial distribution of biomass from the surveys. As noted above, the uncertainty in these biomass estimates would be dependent on the size of rotational zone grid for a given sampling intensity.

Some of the case studies developed both stock and zone-level fishing mortality reference points, such as F_{MAX} associated with YPR although these analyses can lead to very high, risk prone, fishing mortality rates. In the case of Surfclam, the current plan's target fishing mortality ($F_{TR} = 0.026$) has been set at a more conservative level than either F_{MAX} or $F_{0.1}$ from an YPR analysis. An important conclusion of Hart (2003) is that when organisms are harvested at smaller than their optimum size from an YPR perspective, rotational management can result in shifting of the fishery selectivity at size curve to older individuals, thus providing YPR benefits. This is also important when larval settlement is spatially patchy, resulting in a mosaic of beds with a range of individual sizes. These yield benefits are less evident when harvesting of individual sizes is optimal. Such is the case with Surfclam; commercial dredges select for clams near their maximum Biomass per Recruit (BPR) and above age of 50% maturity (DFO, 2010).

Also, incidental mortality on pre-recruits is about 17% and is taken into account in the YPR analysis.

In an analogous manner to biomass reference points, it is possible to define fishing mortality reference points for both the stock and rotational zones (in aggregate). The stock and zonal reference points would be different, as the first would apply to the total stock area while the latter would apply only to the open areas (e.g. BC geoducks). For Surfclam, these are useful metrics to consider, dependent upon whether or not other metrics (e.g. B_{LIM} for rotational zones) are adopted.

Some of the case studies (e.g. Hart 2003, Plaganyi et al. 2015) highlight the need to consider ecosystem objectives in addition to those for the target species. This is particularly relevant for benthic invertebrates given the potential negative impacts of dredging on bottom habitat. In the case of Surfclam, habitat impacts studies over an extended period on Banquereau indicate that there are immediate impacts on both the epibenthic fauna and the mechanical properties of the sediments. The non-target fauna recover on a relatively short period, but the sediment recovery time is dependent on the frequency and intensity of storm events, and increases with depth (Gilkinson et al., 2015). Notwithstanding this, in designing a rotational management system, attention will need to be given to sensitive habitat in the stock areas. For instance, on the Scotian Shelf, there are a number of ecologically and biologically significant areas that DFO has identified as sensitive habitat (King et al. 2016).

Only a few of the case studies (e.g. Valderrama and Anderson (2007)) considered economic metrics in their consideration of an optimal rotational harvest strategy, and yield stabilization was not one of them. The maximization of Net Present Value (NPV) over a 30-year period, assuming a 5% discount rate and constant price with size, was used as the economic reference point in some of these studies. If market forces lead to size-dependent pricing, NPV could change significantly. The 2015 Surfclam review recommended that examination of an optimal rotational management strategy for Surfclam should consider economic metrics that operate at the stock level.

At the zonal level, consideration needs to be given to how best to manage harvesting in a zone to ensure achievement of the operational objectives. One could define which zones are open and closed and let the fishery proceed for a proscribed period; but this may lead to serial depletion. In one of the case studies (BC Geoduck), B_{LIM} reference points were established for each rotational zone with surveys indicating the probability that biomass being maintained above this level. An alternative means to maintain zone-specific biomass above a certain level is to set a zone-specific quota, which, upon being met, would lead to closure of the area (Plagányi et al. 2015). A more complex system is used in the US Georges Bank Scallop fishery where beds are open and closed dependent upon the projected biomass growth in each bed (NEFMC 2003). Performance metrics of biomass in each rotational zone to govern this management need to be relatively precise, which may not be available for Surfclam. An alternate performance metric is CPUE – when a defined minimum average CPUE is achieved over a specified period of time, dredging is moved to another location in the zone. This metric would also be subject to high uncertainty. Also, CPUE may not be proportional to zonal biomass and may remain high while biomass is reduced below a desired level (i.e. hyper-stable CPUE-biomass relationship). There is little guidance in the case studies on how best to define 'move-on' rules within zones. In the case of Surfclam, metrics based on size/count do not appear practical as there is a large distribution of age at specific size for fully recruited individuals. The fishery is not currently targeting a few incoming year classes as in the Georges Bank sea scallop fishery. Fishing down of sizes has not been evident in the commercial length frequency data, although it may be more evident in zones that have been fished heavily enough to remove accumulated biomass. A strategy may be to consider the percent of bottom dredged within the zone, and close the zone once it reaches a certain percent (e.g. 75% not accounting for overlap of tows). These issues require further exploration and discussion with DFO and the industry.

Rotational management is ultimately about allocating fishing mortality and thus yield to zones within the total stock area. Except for the serial depletion issue noted above, it involves fishing a zone for a certain period and then closing it for an additional period to allow biomass to recover. Hart (2003) explored various configurations of closed versus open periods (pulse, symmetric, hybrid), and determined that a relatively straightforward pulse rotational harvest system (in which a zone is closed for a period and then opened for a period) was best for scallops and similar species. Critical to this approach is the determination of recovery time - from some reduced biomass state, the greater the depletion of biomass in a zone, the longer the recovery time. The number and the size of each zone are thus based on the recovery time. For instance, if the recovery time is 6 years, there would need to be at least 6 + 1 zones (assuming one year fishing followed by 6 years recovery). A 3-year recovery time would require at least 3 + 1 rotational zones. Based on the K/M ratio, although growth to market size is estimated to be approximately 15 years, Caddy and Seijo (1998) working with long-lived corals, determined that there could be benefits from rotation periods (open + closed years) as short as 6 years. This is consistent with the estimate of Hart (2003) for scallop. Other case studies suggested longer rotational periods (8 – 10 years).

Preliminary yield and biomass per recruit analyses were conducted to explore the potential benefits of rotational management for Arctic Surfclam under a range of rotation periods. These analyses were based upon the Rotational Yield per Recruit Package (ROTYPR) of Hart (2003), which allows examination of the performance of YPR and discounted YPR under rotational management plans of varying duration and annual intensity with input assumptions on Surfclam biology and fishery parameters (Table 1). Details of the algorithms are provided in Hart (2003). The original package was re-written in R to extend its functionality.

Assuming rotational periods of 2 – 20 years, fishing at F_{MAX} only marginally increased YPR (1.97%) at a rotational period of 20 years over that assuming no rotational period i.e. one year (Table 2). Discounted YPR at F_{MAX} was 2.85% higher than that assuming no rotation for a 14-year rotation period. Reducing the discount rate from 10% to 5% did not change the results significantly and moved the maximum discounted YPR from a 14 to 16 year rotation period (results not shown). Total and fishable biomass increased for an eight year rotation period by 0.15% and 0.07% respectively compared to no rotation. Fishing at a lower F than F_{MAX} resulted in relative (to no rotation) yield declining and biomass increasing with increasing rotation period. However, these changes were small. Fishing at $F_{0.1}$ showed a slight decrease (-0.32%) and increase (4.09%) in yield and fishable biomass respectively (Table 3) for a 20 year rotation period while fishing at the current plan target of 0.33M showed a slight decrease (-1.09%) and increase (0.82%) in yield and fishable biomass respectively, again for a 20 year rotation period (Table 4).

Overall, these results illustrate limited yield benefits to the rotational management of the Surfclam fishery, at least over a range of 2 – 20 years of rotation. These findings are seemingly at odds to those of Hart (2003) and others in the rotational management literature. However, Hart (2003) reported that if fishing was optimal for the age/size groups in the stocks, per recruit gains from rotational management would be minimal. The age at 50% selectivity in the Surfclam fishery is 85.6 mm, which is well above the size of maturity (45 mm) (and well up the growth curve). Thus, these results are not inconsistent with those of Hart (2003) although they are preliminary and require confirmation by DFO Science.

If rotational management is pursued for Surfclam, guidance from the case studies suggests that having multiple zones spreads out the risk to the resource. If a zone that is scheduled to be reopened has not sufficiently recovered, having multiple zones allows alternates to be opened. On the other hand, too small a zone could lead to both impacts on fertilization success and enforcement challenges. Specifically for Surfclam, with modern VMS systems, it is possible to divide the banks into zones between which there would be little migration.

The productivity of the zones is a consideration. Maps of Surfclam fishing distribution indicate that the eastern shoal area was fished heavily and then left unfished on the period of decades; the survey indicates that this was due to recruitment and recovery of the biomass in the area. This is the only large area where it appears removals were complete enough to force the fleet to move, but anecdotal reports indicates that it happens on a local scale. The eastern shoal area was also an area with the highest initial density of clams, and so could probably sustain catch rates at an economically viable level for a longer period of fishing that would be the case for other areas of the banks. Thus, the exact configuration of the rotational zones is a balance of issues which requires input from managers, scientists and industry.

Enforcement cost under rotational management would most likely be higher than under a continuous fishery, but the increase should be slight, as there will likely still be a low number of vessels involved in the fishery. Some case studies noted that the distribution of open zones could result in greater steam time and thus higher costs. If the separate management areas (Banquereau and Grand Bank) are retained in a rotational strategy, this would not be a concern for the Surfclam fishery.

Finally, the precise configuration of open and closed zones may need to incorporate reserves that are permanently closed to safeguard spawning. Whether or not this is the case of Surfclam requires further examination, as noted above.

CONCLUSIONS

Several of the case histories concluded that, for sedentary invertebrate species such as scallops (but not without controversy), geoduck, sea cucumbers, sea urchins, abalone and red sea coral fisheries, rotational spatial management is a useful approach for attaining both conservation and economic objectives. Three general guidelines emerge for rotational management regimes:

- use of a rotational period which is longer for longer lived species;
- inclusion of a minimum legal size for the target species; and
- use of a cap on total catch and effort per zone.

In many of the case histories, the decisions on the definition of rotational zones and the period of rotation were based on pragmatic factors related to the interests of the industry participants. Only in a few cases (e.g. scallops) was the rotational plan guided by analysis. The simulation results on Surfclams indicate that, in comparison with the present harvesting approach at the spatial scale of the management units, rotational management does not provide significant benefits. At F_{MAX}, there is about a 3% increase in discounted YPR using a 14 year rotational period. At lower fishing mortalities (e.g. $F_{0.1}$ and $F_{0.33M}$), the yield gains are negligible. The percent gains in biomass in general occur at longer rotation periods than those for yield. This modeling work leads to the conclusion that yield benefits (as a function of fishing effort) within a rotational scheme are limited. This may be due to the fact that the fishery exploits Surfclam near that for optimal Y/R.

The complex meta-population structure of sedentary invertebrate species results in susceptibility to recruitment over-fishing (two examples are the California Red Sea Urchin and abalone fisheries). There are potential benefits for ongoing recruitment success of rotational management if stock density levels are not reduced below a critical level. That said, the rotational approach can also lead to recruitment overfishing. The case studies illustrate several examples where the density of the target species has been reduced below a critical density for successful reproduction. Diverse categories of management (e.g. annual fisheries with ongoing access to the overall management unit area, and rotational management) have led to critically low densities impairing successful reproduction. As such, it would be prudent for management plans of sedentary invertebrate species to adopt a spatial network of reproductive reserves that are not harvested. Whatever the harvesting approach put in place for the future Surfclam fishery, it is necessary to consider the issue of the minimum density required for successful recruitment. It is to be noted that both the external and internal reviews concluded that recruitment dynamics are robust under the present harvesting approach.

Overall, in the design of a rotational management approach, if it were to be adopted for Surfclams, the following issues need to be considered:

- number of zones (equal to the recovery period plus one) and ratio of open and closed zones;
- consideration of having multiple open zones in a given year to spread the risk of stock density declines; and
- consideration of a network of reproductive reserves.

In addition to the above, economic analyses need to be undertaken in collaboration with the license holders, including the new licenses which may have diverse fishing strategies. Given that there appears to be limited stock sustainability benefits for moving to a rotational spatial management regime, the economic efficiency issues appear to be the critical ones. The main issues that needs to be considered are the profitability of fishing at minimum stock densities to inform move-on rules (in consideration with the reproductive constraints), and the relative benefits of area dredged versus minimum density with respect to these rules. Further, the costs of rotational spatial management relative to the approach presently in place need to be considered (including costs to both industry and DFO). The case studies reviewed here imply that the costs will be higher, as there would be an additional layer of control on the fishery. Also monitoring of the resource and enforcement of the rules would likely need to be undertaken at a finer spatial scale than is currently the case.

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TABLES

Table 1. Input Parameters to Rotational Yield per Recruit Package (ROTYPR) Arctic Surfclam simulations; biological and fishery parameters provided by D. Roddick. (n/a = no comment)

Category	Parameter	Value	Comment
Plan Simulation	Duration (years)	60	n/a
	Age step	0.01	n/a
	Rotation period (years)	1 to 20	F multiplier in each year of period can be specified; in clam runs, all years except last set to 0 with last set to period length
	Surfclam start length	30 mm	n/a
Biology	Alpha (meat wt – sh ht)	-9.7317	n/a
	Beta (meat wt – sh ht)	3.203	n/a
	K	0.084	n/a
	L_{INF}	111.7	n/a
	Mature size	45 mm	50% length of maturity
	Natural mortality	0.08	n/a
Fishery	Discard size	0 mm	Size below which clams discarded; 0 assumes no discarding
	Discard mortality	0	Fraction of F for discarding
	Incidental mortality	0.15	Fraction of F due to clams caught but not retained
	Selectivity (logistic alpha)	6.3415	n/a
	Selectivity (logistic beta)	0.07576	n/a
	Discount rate	0.10	n/a
	Fully recruited fishing mortality (F)	0 – 1 in steps of 0.005	n/a

Table 2. Results of Rotational Yield per Recruit Package (ROTYPR) Simulations of Arctic Surfclam under rotation periods of one to 20 years, fishing at F_{MAX} assuming input parameters of Table 1; top panel: estimates of parameters (indicated in column heading); bottom panel: percent change in parameter compared to one – year rotation; YMAX (yield at F_{MAX}); Y_DIS_MAX (discounted yield at F_{MAX}); B_MAX (total biomass at F_{MAX}); BFISH_MAX (fishable biomass at F_{MAX}).

Period	FMAX	YMAX	Y_DIS_MAX	B_MAX	BFISH_MAX
1	0.13	17.32	5.08	310.53	128.74
2	0.13	17.32	5.07	310.62	128.79
3	0.13	17.31	5.07	310.69	128.82
4	0.14	17.31	5.07	310.74	128.83
5	0.14	17.31	5.08	310.80	128.83
6	0.14	17.32	5.08	310.84	128.82
7	0.14	17.32	5.08	310.91	128.82
8	0.14	17.33	5.09	310.99	128.82
9	0.14	17.33	5.11	310.90	128.71
10	0.14	17.34	5.13	310.70	128.52
11	0.14	17.36	5.16	310.40	128.26
12	0.14	17.38	5.19	309.71	127.73
13	0.15	17.41	5.22	308.71	126.97
14	0.15	17.45	5.22	307.56	126.08
15	0.15	17.49	5.20	306.44	125.17
16	0.16	17.53	5.17	305.45	124.32
17	0.16	17.58	5.11	305.00	123.79
18	0.16	17.62	5.04	305.35	123.78
19	0.17	17.65	4.96	306.65	124.38
20	0.17	17.66	4.86	308.89	125.61

Period	FMAX	YMAX	Y_DIS_MAX	B_MAX	BFISH_MAX
1	0.00%	0.00%	0.00%	0.00%	0.00%
2	0.01%	-0.03%	-0.02%	0.03%	0.04%
3	0.11%	-0.04%	-0.03%	0.05%	0.06%
4	0.32%	-0.05%	-0.02%	0.07%	0.07%
5	0.63%	-0.05%	0.01%	0.09%	0.07%
6	1.05%	-0.03%	0.06%	0.10%	0.07%
7	1.55%	-0.01%	0.14%	0.12%	0.06%
8	2.15%	0.02%	0.30%	0.15%	0.07%
9	2.95%	0.07%	0.61%	0.12%	-0.02%
10	3.91%	0.12%	1.10%	0.05%	-0.17%
11	5.08%	0.21%	1.73%	-0.04%	-0.37%
12	6.58%	0.33%	2.34%	-0.26%	-0.78%
13	8.46%	0.51%	2.76%	-0.59%	-1.37%
14	10.68%	0.72%	2.85%	-0.96%	-2.07%
15	13.20%	0.97%	2.54%	-1.32%	-2.77%
16	16.05%	1.23%	1.82%	-1.64%	-3.43%
17	19.03%	1.49%	0.73%	-1.78%	-3.84%
18	22.00%	1.71%	-0.68%	-1.67%	-3.85%
19	24.86%	1.88%	-2.37%	-1.25%	-3.39%
20	27.57%	1.97%	-4.26%	-0.53%	-2.43%

Table 3. Results of Rotational Yield per Recruit Package (ROTYPR) Simulations of Arctic Surfclam under rotation periods of one to 20 years, fishing at $F_{0.1}$ assuming input parameters of Table 1; top panel: estimates of parameters (indicated in column heading); bottom panel: percent change in parameter compared to one – year rotation; Y0.1 (yield at $F_{0.1}$); Y_DIS_0.1 (discounted yield at $F_{0.1}$); B_0.1 (total biomass at $F_{0.1}$); BFISH_MAX (fishable biomass at $F_{0.1}$).

Period	**$F_{0.1}$**	**Y0.1**	**Y_DIS_0.1**	**B_0.1**	**BFISH_0.1**
1	0.08	16.08	3.34	437.16	211.70
2	0.08	16.07	3.34	437.27	211.78
3	0.08	16.07	3.34	437.45	211.90
4	0.08	16.06	3.34	437.72	212.06
5	0.08	16.06	3.33	438.05	212.27
6	0.08	16.05	3.33	438.46	212.53
7	0.08	16.05	3.33	438.96	212.85
8	0.08	16.04	3.32	439.55	213.22
9	0.08	16.03	3.31	440.21	213.64
10	0.08	16.03	3.31	440.94	214.10
11	0.08	16.02	3.30	441.73	214.60
12	0.08	16.02	3.30	442.54	215.10
13	0.08	16.01	3.29	443.38	215.62
14	0.08	16.02	3.28	444.30	216.17
15	0.08	16.02	3.28	445.26	216.74
16	0.08	16.06	3.28	444.59	216.16
17	0.08	16.06	3.27	445.85	216.91
18	0.08	16.05	3.25	447.38	217.83
19	0.08	16.05	3.23	449.23	218.98
20	0.08	16.03	3.20	451.40	220.37

Period	**$F_{0.1}$**	**Y0.1**	**Y_DIS_0.1**	**B_0.1**	**BFISH_0.1**
1	0.00%	0.00%	0.00%	0.00%	0.00%
2	-0.02%	-0.03%	-0.04%	0.03%	0.03%
3	-0.04%	-0.06%	-0.10%	0.07%	0.09%
4	-0.03%	-0.09%	-0.18%	0.13%	0.17%
5	-0.02%	-0.12%	-0.28%	0.20%	0.27%
6	0.01%	-0.16%	-0.39%	0.30%	0.39%
7	0.05%	-0.19%	-0.53%	0.41%	0.54%
8	0.09%	-0.23%	-0.69%	0.55%	0.72%
9	0.16%	-0.27%	-0.86%	0.70%	0.91%
10	0.23%	-0.31%	-1.04%	0.86%	1.13%
11	0.32%	-0.35%	-1.22%	1.05%	1.37%
12	0.45%	-0.38%	-1.40%	1.23%	1.61%
13	0.62%	-0.39%	-1.58%	1.42%	1.85%
14	0.80%	-0.38%	-1.79%	1.63%	2.11%
15	1.03%	-0.37%	-2.03%	1.85%	2.38%
16	2.12%	-0.13%	-1.90%	1.70%	2.10%
17	2.37%	-0.12%	-2.29%	1.99%	2.46%
18	2.58%	-0.14%	-2.80%	2.34%	2.90%
19	2.74%	-0.20%	-3.43%	2.76%	3.44%
20	2.83%	-0.32%	-4.19%	3.26%	4.09%

Table 4. Results of Rotational Yield per Recruit Package (ROTYPR) Simulations of Arctic Surfclam under rotation periods of one to 20 years, fishing at $F_{0.33M}$ assuming input parameters of Table 1; top panel: estimates of parameters (indicated in column heading); bottom panel: percent change in parameter compared to one – year rotation; Y33M (yield at $F_{0.33M}$); Y_DIS_33M (discounted yield at $F_{0.33M}$); B33M (total biomass at F0.33M); BFISH_33M (fishable biomass at $F_{0.33M}$).

Period	F33M	Y33M	Y_DIS_33M	B_33M	BFISH_33M
1	0.03	9.82	1.59	655.15	369.50
2	0.03	9.82	1.59	655.16	369.51
3	0.03	9.81	1.59	655.20	369.53
4	0.03	9.81	1.59	655.26	369.58
5	0.03	9.81	1.59	655.34	369.63
6	0.03	9.81	1.59	655.45	369.71
7	0.03	9.80	1.59	655.58	369.80
8	0.03	9.80	1.59	655.73	369.91
9	0.03	9.79	1.59	655.91	370.03
10	0.03	9.79	1.59	656.11	370.17
11	0.03	9.78	1.58	656.33	370.33
12	0.03	9.77	1.58	656.58	370.50
13	0.03	9.77	1.58	656.84	370.69
14	0.03	9.76	1.58	657.14	370.89
15	0.03	9.75	1.57	657.46	371.11
16	0.03	9.75	1.57	657.80	371.35
17	0.03	9.74	1.57	658.18	371.60
18	0.03	9.73	1.56	658.59	371.88
19	0.03	9.72	1.56	659.04	372.19
20	0.03	9.71	1.55	659.52	372.53

Period	F33M	Y33M	Y_DIS_33M	B_33M	BFISH_33M
1	0.00%	0.00%	0.00%	0.00%	0.00%
2	0.00%	-0.01%	-0.01%	0.00%	0.00%
3	0.00%	-0.03%	-0.04%	0.01%	0.01%
4	0.00%	-0.05%	-0.08%	0.02%	0.02%
5	0.00%	-0.08%	-0.13%	0.03%	0.04%
6	0.00%	-0.11%	-0.19%	0.05%	0.06%
7	0.00%	-0.15%	-0.26%	0.07%	0.08%
8	0.00%	-0.19%	-0.35%	0.09%	0.11%
9	0.00%	-0.24%	-0.45%	0.12%	0.14%
10	0.00%	-0.30%	-0.56%	0.15%	0.18%
11	0.00%	-0.35%	-0.68%	0.18%	0.22%
12	0.00%	-0.42%	-0.80%	0.22%	0.27%
13	0.00%	-0.49%	-0.94%	0.26%	0.32%
14	0.00%	-0.55%	-1.09%	0.30%	0.38%
15	0.00%	-0.63%	-1.26%	0.35%	0.44%
16	0.00%	-0.71%	-1.45%	0.40%	0.50%
17	0.00%	-0.79%	-1.67%	0.46%	0.57%
18	0.00%	-0.87%	-1.92%	0.52%	0.65%
19	0.00%	-0.97%	-2.20%	0.59%	0.73%
20	0.00%	-1.09%	-2.53%	0.67%	0.82%