RAPID COMMUNICATIONS / COMMUNICATIONS RAPIDES

A fisheries management strategy robust to ignorance: rotational harvest in the presence of indirect fishing mortality

Ransom A. Myers, Susanna D. Fuller, and Daniel G. Kehler

Abstract: We develop a simple theoretical model of yield and spawning stock biomass per recruit for the American sea scallop (*Placopecten magellanicus*), which appears to have high indirect fishing mortality when harvested with dredges, i.e., mortality caused by the act of fishing that does not result in landings. The age at and degree to which individuals are affected by the indirect mortality are unknown, and it does not appear possible to develop a robust harvest strategy with yearly harvests unless indirect fishing mortality is well quantified. We show that there could be substantial benefits to a rotational harvest strategy for sessile species with high indirect fishing mortality. First, the strategy appears to be robust to ignorance about indirect fishing mortality and results in equal or better yields than a yearly harvest across a wide range of indirect fishing mortalities. Second, under most conditions, a higher spawning stock biomass is maintained. Third, rotational management is more easily enforced, as it does not require specifying a narrow range of fishing mortality in order to maximize yield.

Résumé : Nous avons développé un modèle théorique simple pour étudier le rendement et la biomasse des géniteurs par individu recruté chez le pétoncle géant (*Placopecten magellanicus*), qui semble subir une mortalité indirecte élevée due à la pêche à la drague, i.e., une mortalité causée par la pêche qui ne résulte pas en des débarquements. L'importance de cette mortalité indirecte et l'âge des individus affectés ne sont pas connus. Néanmoins, il semble qu'on ne puisse établir une solide stratégie de récolte avec pêches annuelles sans que cette mortalité indirecte ne soit bien quantifiée. Nous démontrons qu'il pourrait y avoir d'importants bénéfices à établir une stratégie de récolte par rotation chez les espèces sessiles qui ont une mortalité indirecte élevée due à la pêche. D'abord, ce type de stratégie est applicable même lorsqu'on ne connaît pas la mortalité indirecte due à la pêche et donne des résultats semblables ou meilleurs qu'une stratégie de pêche annuelle, dans un large intervalle de mortalités indirectes. En second lieu, dans la majorité des situations, il y a maintien d'une biomasse plus élevée du stock des géniteurs. Enfin, une gestion avec rotation est plus facile à appliquer, puisqu'elle n'exige pas de fixer des limites étroites à la pêche pour maximiser le rendement.

[Traduit par la Rédaction]

Introduction

Fisheries must be managed using imperfect information about the biology and state of a stock; thus, successful management strategies must be robust in light of this lack of detailed information. We examine rotational harvest of American sea scallops (*Placopecten magellanicus*) as one such robust management strategy. The scallop fishery commonly uses dredges for harvesting, which can result in a high indirect mortality. Indirect mortality caused by fishing (e.g., discarding or damage to fish not caught in fishing gear) is one of the major problems in the management of the world's fisheries (Alverson et al. 1994). Although it is now accepted that the calculations of biological reference points, such as the maximum allowed fishing mortality rate, should include indirect fishing mortality (Chen and Gordon 1997), this is rarely done in practice.

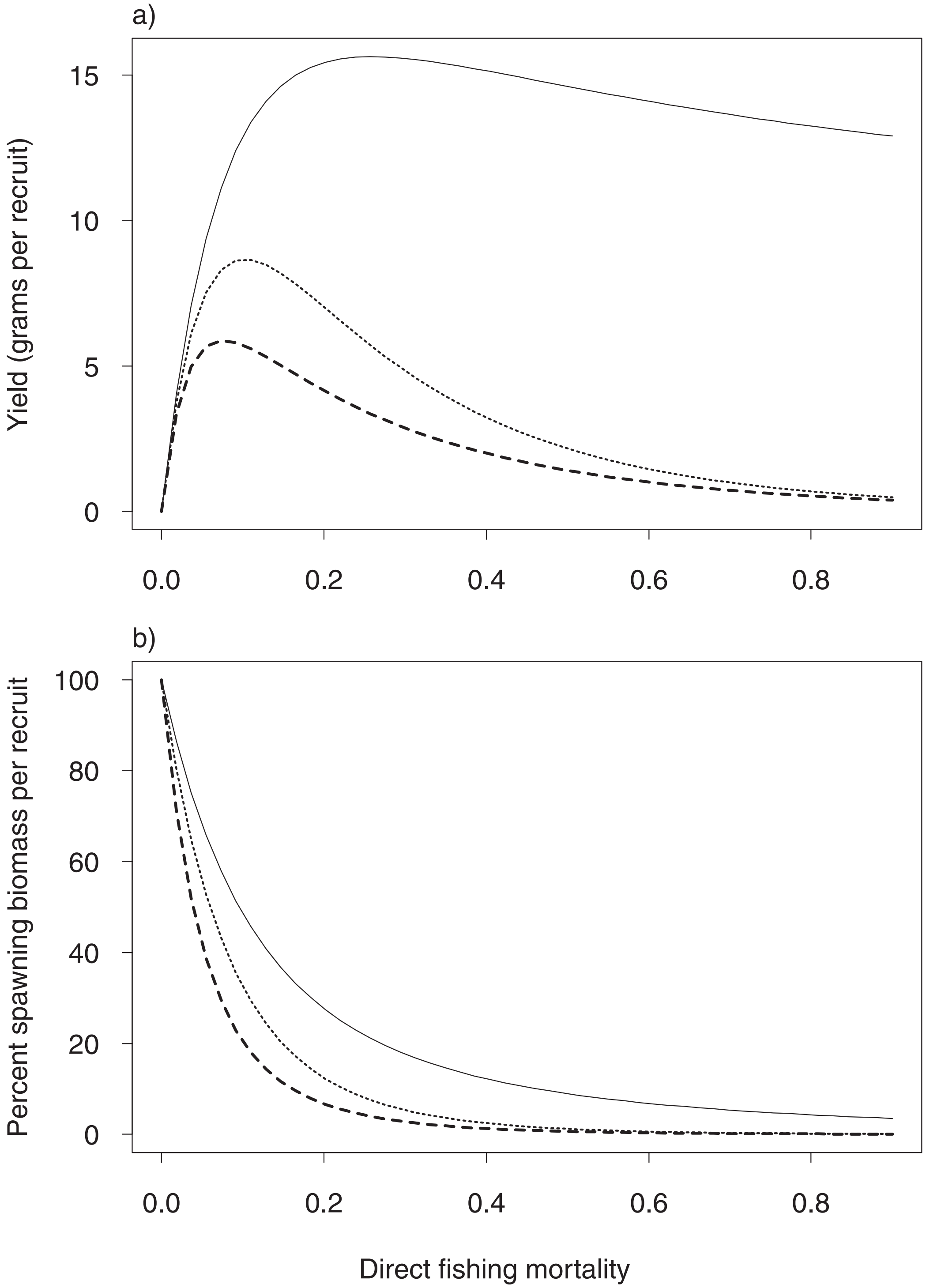
For the sea scallop, the problem of indirect fishing mortality has long been known to be a critical conservation issue (Caddy 1973). Caddy (1973) found indirect mortality rates on par with direct fishing mortality (13–17%), and a recent assessment of sea scallops (National Marine Fisheries Service 1999) estimated indirect mortality to be three times higher than the direct fishing mortality on Georges Bank. Evidence from other scallop species suggests that indirect fishing mortality may be as high as four to eight times the direct fishing mortality (Naidu 1988; McLoughlin et al. 1993).

Received August 18, 2000. Accepted December 1, 2000. Published on the NRC Research Press web site on December 20, 2000. J15928

R.A. Myers.[1] Killam Chair of Ocean Studies, Department of Biology, Dalhousie University, Halifax, NS B3H 4J1, Canada.
S.D. Fuller. Department of Biology, Dalhousie University, Halifax, NS B3H 4J1, Canada.
D.G. Kehler. Department of Mathematics and Statistics, Dalhousie University, Halifax, NS B3H 4J1, Canada.

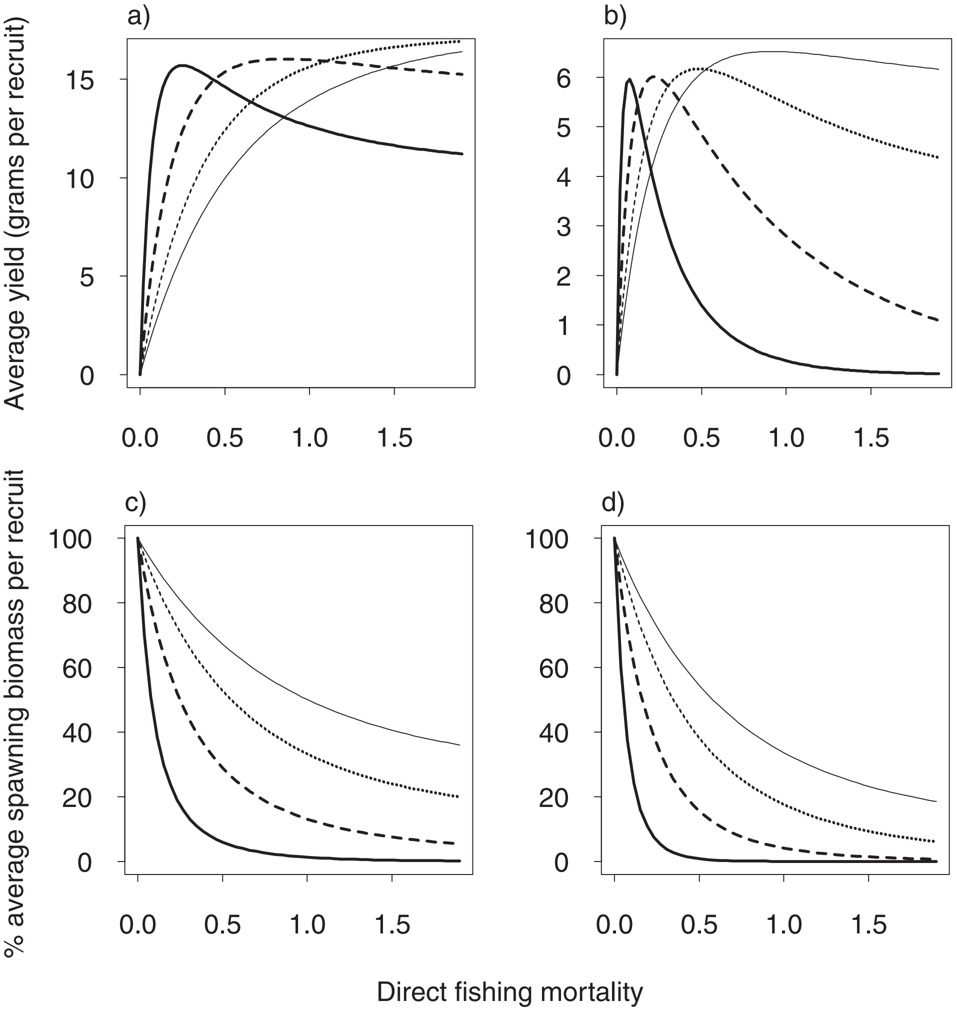
[1] Corresponding author (e-mail: ransom.myers@dal.ca).

Fig. 1. (*a*) Yield per recruit and (*b*) percentage of the maximum spawning biomass per recruit (when $F = 0$) for sea scallops at different levels of direct fishing mortality under the assumption that (*i*) there is no indirect fishing mortality (solid line), (*ii*) there is indirect fishing mortality on prerecruits only (dotted line), and (*iii*) there is indirect fishing mortality on all ages (dashed line). Indirect fishing mortality is assumed to equal the direct fishing mortality. Note that the direct fishing mortality resulting in maximum yield per recruit is much lower when indirect fishing mortality occurs (Fig. 1*a*).



In this article, we propose rotational harvesting as an alternative strategy and investigate its robustness to different levels and types of indirect fishing mortality using deterministic models. We propose rotational harvesting as an alternative strategy and investigate its robustness to different levels and types of indirect mortality using deterministic models.

Fig. 2. (*a* and *b*) Average yield per recruit and (*c* and *d*) percentage of maximum average spawning stock biomass for sea scallops harvested over a range of direct fishing mortalities for four rotational periods: harvest every year (thick solid line), once every 3 years (dashed line), once every 6 years (dotted line), and once every 9 years years (thin solid line). Results are shown under the assumption of no indirect fishing mortality (Figs. 2*a* and 2*c*) and indirect fishing mortality equal to direct fishing mortality (Figs. 2*b* and 2*d*).



Yield per recruit analysis including indirect fishing mortality

We considered a simple discrete time population dynamics model in which fishing takes place at one time of the year and natural mortality only occurs between the periods of fishing. The discrete time model will, in general, give quantitatively, but not qualitatively, different results than the standard continuous time yield per recruit model (Beverton and Holt 1957) but can easily be extended to consider a rotational harvest. The model is more appropriate when the harvest takes place yearly, over a short period, as is proposed for the reopening of portions of the groundfish closed areas of the U.S. side of Georges Bank (New England Fisheries Management Council 2000).

In our model, we divided total fishing mortality into two components: direct and indirect mortality. Direct mortality is denoted $F_y s_a$, where s_a is the selectivity of the fishing gear to a scallop of age a and F_y is the fishing mortality in year y of the "fully selected" age or ages, i.e., where $s_a = 1$. Indirect mortality is denoted $F_y i_a$, where i_a is the age-dependent selectivity of the indirect fishing mortality. To make our analyses consistent with the National Marine Fisheries Service (1999), the year was defined to start at the midpoint of the cohort year, and thus, fishing occurs at the end of this "year."

We let $N_{y,a}$ be the number of scallops of age a at the beginning of year y and m_a be the age-specific natural mortality. We assumed that both sources of fishing mortality are operating simultaneously during the fishery. The dynamics of a cohort are given by

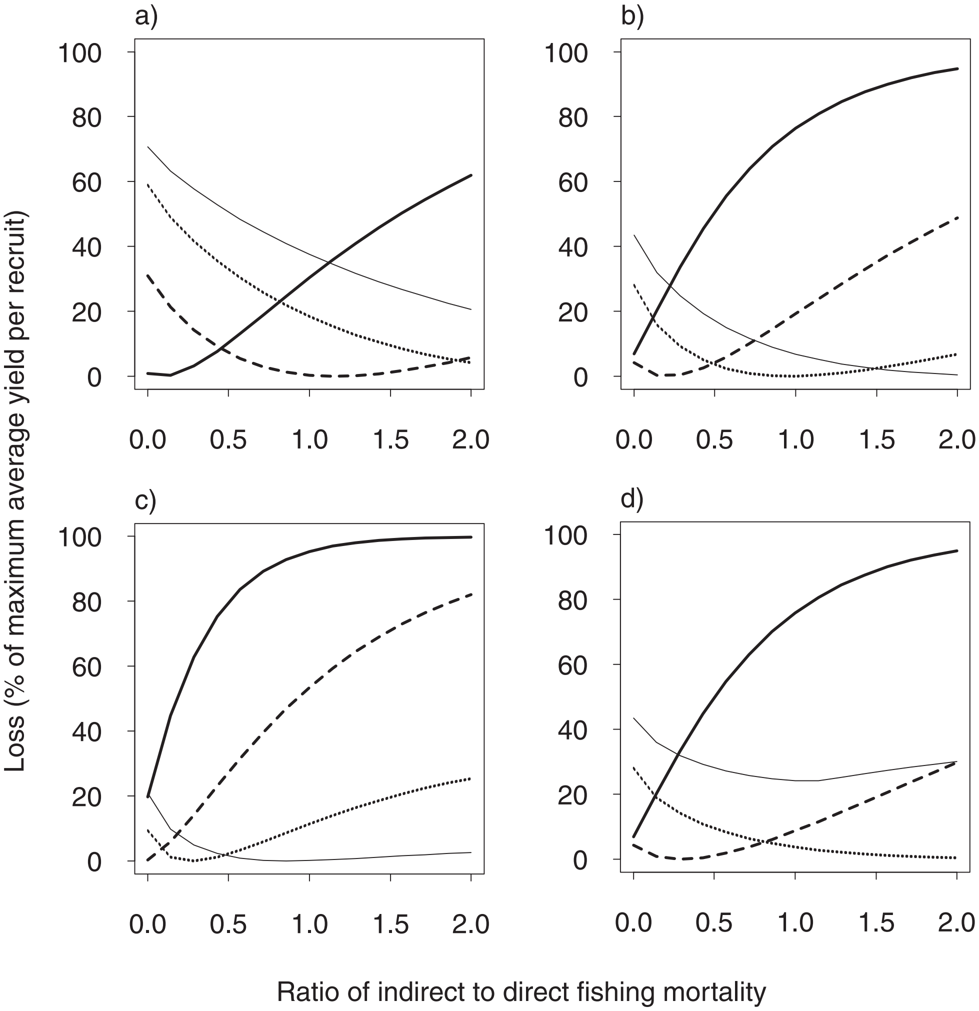
$$N_{y+1,a+1} = N_{y,a}\exp(-m_a - F_y(s_a + i_a))$$

and the catch in numbers from the cohort at age a is

$$C_{y,a} = N_{y,a}\exp(-m_a)(1-\exp(-F_y(s_a + i_a)))\left(\frac{s_a}{s_a + i_a}\right).$$

In the yield per recruit analysis, it is assumed that recruitment, $N_{y,1}$ and the selectivity at age do not vary over time. This assumption is unrealistic, as recruitment will vary with

Fig. 3. Proportional loss of maximum average yield for sea scallops as a function of the ratio of indirect to direct fishing mortality under the four assumptions for fully recruited fishing mortality and the age that indirect fishing mortality occurs at four rotational harvest periods: harvest once every 1 (thick solid line), 3 (dashed line), 6 (dotted line), and 9 years (thin solid line). The assumptions for the fully recruited fishing mortality (F) and the indirect mortality are (a) F = 0.2 and indirect fishing mortality occurs at all ages >1 at the same rate as direct fishing mortality on ages 4, (b) the same as Fig. 3a except that F = 0.5, (c) the same as Fig. 3a except that F = 1.0, and (d) F = 0.5 and indirect fishing mortality only occurs on prerecruits but at the same rate as on fully recruited scallops.



both abundance and environmental conditions, but simplifies the analysis considerably. The annual biomass yield per recruit at equilibrium, Y^*, is obtained by considering a scallop population derived from a cohort exploited over time with fishing mortality F and a selectivity of 1 (Clark 1990). This will be constant with time and is

$$Y^*(F) = \frac{1}{N_{y,1}} \sum_a w_a C_{y,a},$$

where w_a is the weight of the scallops at age a at the time of the harvest.

It is also useful to calculate the spawning stock biomass per recruit in the same manner, i.e.,

$$S(F) = \frac{1}{N_{y,1}} \sum_a N_{y,a} \phi_a w_a$$

where ϕ_a is the proportion of fish of age a that are mature. Again, this will not vary over time in our model.

We made the following additional assumptions in developing this model. Growth in weight (grams) was defined using the von Bertalanffy growth curve with parameters from the most recent assessments (National Marine Fisheries Service 1999):

$$w_a = 55.11(1 - \exp(-0.3374(a - 1.454)))^{3.0734}.$$

Spawning biomass was assumed to be proportional to the meat weight of the scallops. As per National Marine Fisheries Service (1999), scallops were considered mature at age 4, and natural mortality was assumed to be constant for all ages at a rate of 0.1 up to age 20. Senescence was assumed to begin at age 20, with natural mortality increasing by 0.1 every year after that age. Direct fishing selectivity of the commercial dredges was assumed to be 0 below age 3, 0.5 at age 3, and 1 for higher ages (National Marine Fisheries Service 1999), which makes the simplifying assumption that all scallops grow at the same rate. When we considered the effect of the age of recruitment to the fishery on yield, we assumed direct fishing selectivity to be 1 for scallops of age ≥ 4.

Two alternative patterns of indirect fishing mortality were modeled. First, indirect fishing mortality was assumed to affect all ages >1 equally and at the same rate as the fully recruited fishing mortality, i.e., $i_a = 1$ for all a, which represents an extreme situation. Second, it may only be the smaller, weaker scallops that are affected by indirect fishing mortality, and thus, we assumed that for the prerecruits ($a < 4$), $i_a = 1$, and for older scallops ($a \geq 4$), $i_a = 0$.

We began by comparing the pattern of yield given different direct fishing mortalities and age of recruitment to the fishery. The typical pattern of maximum yield at infinite mortality and a high age of recruitment (Beverton and Holt 1957) does not emerge. Instead, yield is maximized at a lower age of recruitment (≈4) and a relatively low direct fishing mortality (0.08). Ignoring indirect fishing mortality results in estimates of fishing mortality that give the maximum yield per recruit that are suboptimal (Fig. 1*a*).

The fishing mortality that results in the maximum sustainable yield is smallest when indirect fishing occurs on all ages (0.07), intermediate when indirect fishing mortality occurs only on prerecruits (0.09), and greatest with no indirect fishing mortality (0.22) (Fig. 1*a*). We also compared the spawning biomass per recruit for the three levels of indirect fishing mortality with the percentage of the spawning biomass per recruit with no fishing (Fig. 1*b*). Incorporating indirect fishing mortality results in even lower levels of spawning biomass, particularly at low levels of direct fishing mortality. We have shown using a simple model that ignoring indirect fishing mortality results in setting "optimal" fishing mortalities that are much too high.

Rotational harvest strategy

We investigated a model where fishing is rotated among p subdivisions of the fishing ground, and each subdivision is harvested every p years. The calculation of yield and spawning biomass per recruit is not straightforward for the rotational harvest, since the yield per recruit depends upon the age at which a scallop is first subjected to periodic harvesting. In other words, a scallop first harvested at age 4 and harvested every p years will have a different yield than a scallop first harvested at age 5 and harvested every subsequent p years. Thus, for a rotational harvest of p years, we need to average over the p different possible yields per recruit. Since recruitment was assumed to be constant over time, the same number of recruits will have accumulated in subdivision p over p years as in the entire fishing ground in a year. If the average yield per recruit remains the same between the rotational and nonrotational harvest schemes, then total yield (which is of greater interest) will also remain the same.

We assessed the rotational strategy in terms of average yield and spawning biomass per recruit at different fishing mortalities for four different rotational periods: 1, 3, 6, and 9 years (Fig. 2). In all cases, the rotational strategy resulted in at least as high an average yield per recruit as the nonrotational strategy, provided the fishing mortality was sufficiently high. The rotational strategy maintains a considerably larger stock biomass, thus reducing the risk of stock collapse. The larger yield per recruit obtained under rotational management results from allowing scallops to reach the ages where the ratio of somatic growth to loss by natural mortality is highest. If indirect fishing mortality only occurs on prerecruits, then there is a greater advantage in yield per recruit for a longer rotational management scheme (not shown). From a management perspective, the rotational system is appealing because it is not necessary to control fishing mortalities very precisely when $p > 5$, since near-optimal yields are achieved across a wide range of fishing mortalities. The above plots suggest that a rotational period close to 6 years, with a fishing mortality of around 0.5, would result in a close to maximum average yield per recruit and would maintain spawning biomass per recruit at acceptable levels, i.e., above 20% of the spawning stock biomass.

We examined the consequences of a nonrotational harvesting strategy by calculating the loss in yield per recruit under different assumptions about indirect fishing mortality. We defined the percent loss of fishing at a fully recruited fishing mortality of F at a rotational period p as

$$L_p(F) = 100 \times \frac{Y_p(F)}{\max\limits_{F,\,p}(Y_p(F))}.$$

We calculated the loss in yield per recruit for four rotational periods, 1, 3, 6, and 9 years, and three direct fishing mortalities. To determine the impact of different indirect fishing mortalities, we allowed the ratio of indirect mortality to direct fishing mortality to vary between 0 and 2 (Fig. 3).

There is a large loss under the nonrotational management regime under all assumptions of indirect mortality except when the ratio of indirect to direct fishing mortality is very small and direct fishing mortality is kept very low, around 0.2. However, the direct fishing mortality has been very much larger than 0.5 in the areas open to fishing on Georges Bank for the last 20 years (National Marine Fisheries Service 1999). If $F = 0.5$ and the rotational period is between 3 and 6 years (Figs. 3*b* and 3*d*), there is relatively little loss under most levels of indirect fishing mortality.

Discussion

Controlling the age of recruitment to the fishery has been often considered a robust approach to fishery management (Myers and Mertz 1998). In our analysis, we show that indirect fishing mortality can greatly affect the optimal fishing strategy and that a rotational harvest strategy may be a reasonable approach to use when the form and magnitude of indirect fishing mortality are uncertain. We have shown, theoretically, that the primary benefits of a rotational strategy, relative to a nonrotational strategy, are that it (*i*) provides equal or greater yield across most levels of indirect fishing mortality, (*ii*) may be more easily enforced, and (*iii*) maintains a higher spawner biomass.

In the nonrotational plan, the range of fishing mortalities resulting in maximum yield per recruit is very narrow. Fisheries managers in the past have found it very difficult to achieve such precise control. This problem has led to overfishing on Georges Bank and other regions (Walters and Maguire 1996). In contrast, the range of fishing mortality resulting in maximum yield per recruit for the rotational strategy is very broad. Enforcement of the rotational plan is simpler than that of the nonrotational plan, as it is easier to completely restrict access to an area than to enforce a fishing limit on each individual boat, particularly if all fishing vessels are required to have electronic location beacons (as scallop vessels are on the U.S. side of Georges Bank). An important conservation benefit of many rotational management strategies is the increase in spawning biomass resulting from a rotational closure. This has been noted in previous studies (e.g., Sluczanowski 1984), but the effect is much larger in fisheries with large indirect mortality, such as scallops harvested with dredges.

As the total amount of dredging can be reduced as a result of rotational harvesting, the impact of scallop dredging on other species can be reduced. However, the fishing intensity in the harvested areas may be still be quite high (0.5–1.0), and we need to insure that this does not compromise the scallop stock or other components of the ecosystem (e.g., groundfish).

There are some obvious disadvantages if very long rotational periods are used, e.g., the somatic growth of sea scallops may decrease because of crowding. As well, very long rotational periods would require the harvested area to be divided into many more areas for the rotational management, which would increase the complexity of enforcement. For these reasons, the period for rotation should probably be <7 years. Rotational management must be considered carefully in a multispecies fishery, as intense scallop fishing can have an impact on groundfish species and structure-forming epifaunal species.

Although the rotational harvest is very appealing theoretically, it remains to be seen whether it can be succesfully implemented. One of the key simplifying assumptions of our analysis is that fishing grounds, which are undoubtedly heterogeneous, can be divided into areas of relatively equal productivity. Monitoring is essential to determine if and how productivity varies over space and time.

An ideal situation for the implementation of a rotational harvest currently exists on the U.S. side of Georges Bank, as there are three sections that have been closed since 1994 to groundfish and scallop harvesting. Proposals to open these areas do not presently include a rotational plan, which is unfortunate, as such a plan could be easily implemented (New England Fisheries Management Council 2000). The implementation of a rotational strategy could also contribute to the ability of scientists to evaluate the effects of fishing through an experimental approach.

References

Alverson, D.L., Freeberg, M.H., Murawski, S.A., and Pope, J.G. 1994. A global assessment of fisheries bycatch and discards. FAO Fish. Tech. Pap. 339.

Beverton, R.J., and Holt, S.J. 1957. On the dynamics of exploited fish populations. Fish. Invest. Ser. II Mar. Fish. G.B. Minist. Agric. Fish. Food, **19**: 533.

Caddy, J.F. 1973. Underwater observations on tracks of dredges and trawls and some effects of dredging on a scallop ground. Can. J. Fish. Aquat. Sci. **30**: 173–180.

Chen, Y., and Gordon, G.N.G. 1997. Assessing discarding at sea using a length-structured yield-per-recruit model. Fish. Res. **30**: 43–55.

Clark, C.W. 1990. Mathematical bioeconomics. 2nd ed. Wiley-Interscience, New York.

McLoughlin, R., Zacharin, W., Cartwright, I., Gwyther, D., Probestl, M., and Sterling, D. 1993. New harvesters for the scallop industry in south east Australia. Aust. Fish. **52**: 12–14.

Myers, R.A., and Mertz, G. 1998. The limits of exploitation: a precautionary approach. Ecol. Appl. **8**(Suppl. 1): S165–S169.

Naidu, K.S. 1988. Estimating mortality rates in the Iceland scallop, *Chlamys islandica* (O.F. Mueller). J. Shellfish Res. **7**: 61–71.

National Marine Fisheries Service. 1999. Twenty-ninth northeast regional stock assessment workshop. NEFSC Ref. Doc. 99/14.

New England Fisheries Management Council. 2000. Framework Adjustment 13 to the Atlantic Sea Scallop Fishery Management Plan with options for the Framework Adjustment 34 to the Northeast Multispecies Fishery Management Plan. New England Fisheries Management Council, Saugus, Mass.

Sluczanowski, P.R. 1984. A management oriented model of an abalone fishery whose substocks are subject to pulse fishing. Can. J. Fish. Aquat. Sci. **41**: 1008–1014.

Walters, C., and Maguire, J.J. 1996. Lessons for stock assessment from the Northern cod collapse. Rev. Fish Biol. Fish. **6**: 125–137.