ICES Journal of
Marine Science

ICES Journal of Marine Science (2012), 69(6), 1038–1044. doi:10.1093/icesjms/fss064

Managing harvest risk with catch-pooling cooperatives

Suresh Andrew Sethi[1‡*], Michael Dalton[2], and Ray Hilborn[1]

[1]*School of Aquatic and Fishery Sciences, University of Washington, PO Box 355020, Seattle WA 98195, USA*
[2]*NOAA Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle, WA 98115, USA*

**Corresponding Author: tel: +1 907 786 3655; fax: +1 907 786 3848; e-mail:sasethi@gmail.com*
‡Present address: US Fish and Wildlife Service, 1011 E. Tudor Road, Anchorage, AK 99503, USA

Sethi, S. A., Dalton, M., and Hilborn, R. 2012. Managing harvest risk with catch-pooling cooperatives – ICES Journal of Marine Science, 69: 1038–1044.

Received 7 November 2011; accepted 27 March 2012; advance access publication 7 May 2012.

Catch-pooling cooperatives are a strategy for fishers to manage variability which can be organized independently of a central management agency. We examined the statistical properties of equal-share catch-pooling cooperatives, and tested their potential to mitigate risk using data from two Bering Sea crab fisheries prior to rationalization. The results suggest that small cooperatives of crabbers could have reduced vessel-level catch risk by as much as 40% in the red king crab fishery, but would have been ineffective in the snow crab fishery. Analytical examination of catch variances under cooperatives explains the discrepancy between the two fisheries and demonstrates that variability reduction depends on the degree of correlation amongst participants' catches. In the best-case scenario, catch-pooling cooperatives can diversify away all season to season variation resulting from individuals' luck and skill, leaving only variation in fishery-wide harvest.

Keywords: Bering Sea crab, catch variability, commercial fisheries, cooperatives, portfolio, risk management.

Introduction

Alaskan fisheries operate in some of the most productive fishing grounds in the world, yet large swings in catches and stock abundances are commonplace. Both fishers and management agencies employ strategies to cope with high variability in commercial fisheries, or to manage risks of harvest or stock collapse (e.g. Salas and Gaertner, 2004; Sethi, 2010). In this article, we used a combination of simulation analyses and analytical derivations to explore the potential of catch-pooling cooperatives to reduce harvest risk for participants in competitive fisheries (i.e. participants do not have individual rights to a portion of the total allowable harvest), using the notoriously variable Bering Sea red king (*Paralithodes camtschaticus*) and snow (*Chionoecetes opilio*) crab fisheries as demonstrations.

From their advent, Bering Sea crab fisheries have seen huge booms and busts, with peaks in the late 1970s for red king crab and early 1990s for snow crab, followed by abundance crashes (Figure 1). Eventually, these fisheries would see a major transformation as managers responded by changing regulation of the fishery to an individual-based quota system, or 'rationalization' (Fina, 2005; Fina et al., 2010). In the competitive era prior to rationalization, however, too much catching power in the fleet and a lack of secure property rights to harvest led to a race for fish where participants' landings varied widely year to year. For example, in the 2004 Bering Sea red king crab fishery, the year prior to rationalization, 251 vessels landed the entire season's catch of 6410 mt in just 3 d (Bowers *et al.*, 2008). In these pre-rationalization derby fisheries, a mechanical failure on the crabbing grounds could ruin a fisherman's season.

One strategy to manage the high risk levels experienced in competitive commercial fisheries is to form catch-pooling cooperatives, where multiple fishers pool their landings and then redistribute proceeds from the harvest pool at the end of a season according to pre-determined allocation rules such as an equal share for all participants. The idea is simple: reduce catch variability by spreading the risk (of a bad season) across multiple individuals. A poor season for some fishers in the cooperative could be offset by better results from other cooperative members. Such arrangements are known to be used in highly variable herring fisheries in Alaska, and anecdotal evidence suggests some vessels in the pre-rationalization Bering Sea red king crab fishery formed catch-pooling cooperatives in the portion of the vessels' catches allocated to crew members in order to mitigate catch risk (Alaska Fisheries Science Center staff pers. comm. June 2011). This arrangement was believed to allow some boats in a group to gamble and fish areas of greater uncertainty, potentially leading to a high-risk but high-reward outcome, while other vessels in the group remained on more familiar crab grounds.

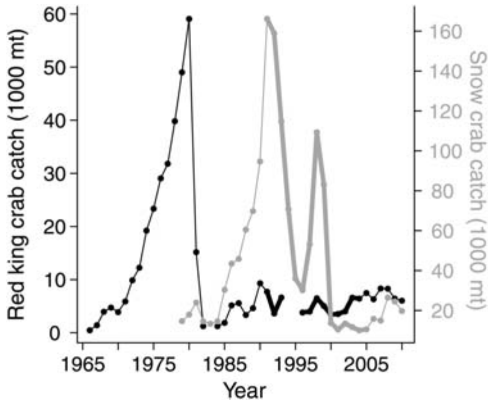

Figure 1. Total harvest in the Bering Sea red king crab fishery 1966–2010 (black lines, left axis) and snow crab fishery 1979–2010 (grey lines, right axis). The study periods used for cooperative simulations are indicated by thick lines. The red king crab fishery was closed in 1983, 1994, and 1995. Data are from Bowers *et al.* (2008) and Alaska Commercial Fisheries Entry Commission (2011).

Although the use of catch-pooling cooperatives to mitigate risk in Bering Sea crab fisheries prior to rationalization was limited, the king and snow crab fisheries are good case studies to examine the potential effectiveness of catch-pooling cooperatives in highly variable competitive fisheries because vessel-level data are available with which to simulate artificial cooperatives (see below).

Different types of fishery cooperatives are established to satisfy different objectives (e.g. Haight *et al.*, 2007). For example, harvesters may form marketing cooperatives to negotiate prices with processors or distributors (Kitts and Edwards, 2003). In this analysis, we focus specifically on catch-pooling cooperatives with a goal of mitigating individual-level catch risk, i.e. the chance that an individual fisher has a poor season harvest. We test the performance of equal-share catch-pooling cooperatives in highly variable competitive fisheries by conducting a retrospective analysis simulating artificial cooperatives in the pre-rationalization Bering Sea crab fisheries. Catch risk is quantified using two measures from investment theory, semi-deviation and conditional value-at-risk (CVaR), which characterize the magnitude of typical bad and extremely bad outcomes, respectively (expanded explanations are provided below; also see Sethi *et al.*, 2012). In addition, we explore the statistical properties of cooperatives which can lead to risk reduction by deriving formulae for season to season catch variance for individuals under a range of scenarios. The results indicate that catch-pooling cooperatives can substantially reduce risk, but success depends on the degree of correlation amongst fishers' catches. The analyses in this article are motivated under a set of simplifying assumptions about the behaviour of fishers in cooperatives, allowing us to focus on the statistical properties of catch-pooling cooperatives that lead to variability reduction; however, we do not propose an explicit theory for the decisions that lead to cooperative formation.

Material and methods

Data

Data used in simulations are individual vessel landings for the Bristol Bay red king crab and Eastern Bering Sea snow crab pot fisheries collected by the Alaska Department of Fish and Game and maintained in the Alaska Fisheries Information Network. These data are protected by confidentiality constraints to preserve vessels' anonymity. In these analyses we do not present results that identify specific vessels. Detailed descriptions of the fisheries are contained in the North Pacific Fisheries Management Council report (PTBSAI, 2010). For the purposes of these simulations, we consider a vessel to represent an individual fisher.

Risk measure calculation

We characterized the risk of a bad season outcome over an individual's catch time-series using semi-deviation and 25% CVaR. These measures focus on downside, or 'bad', outcomes for the return of an asset (e.g. a below-average return). In a fishery context, the term 'asset' represents a fisher's opportunity to participate in a fishery, and the 'return' their time-series of annual catch. A brief discussion of semi-deviation and CVaR measures is provided here; detailed examinations of the application of these metrics to fisheries data are provided in Sethi *et al.* (2012) and Sethi and Dalton (2012).

Semi-deviation (Markowitz, 1959; Porter, 1974) characterizes risk by estimating the typical bad outcome expected from the return of an asset relative to a minimum acceptable return (MAR). Let R be a random variable for asset return, r an individual draw from R, and r_n a sample of n draws from R. In this analysis, r_n is an individual's catch time-series. The sample-based formula for semi-deviation is:

$$\delta(r_n, MAR) = \sqrt{\frac{1}{n}\sum_{r_i < MAR}(r_i - MAR)^2} \quad (1)$$

for $i = 1,2,\ldots,n$ where n is the total number of returns considered and not only those $< MAR$. We set MAR to the mean return so that semi-deviation characterizes the typical loss relative to mean performance.

CVaR characterizes risk by estimating the magnitude of extreme bad events (Andersson *et al.*, 2001; Rockafellar and Uryasev, 2002). It is the expected outcome conditional on being in the α% worst case scenarios for asset return:

$$\phi(R, \alpha) = E[R|F(r) < \alpha] = \frac{1}{\alpha}\int_{r < F^{-1}(\alpha)} rf(r)dr \quad (2)$$

where F is the cumulative probability and F^{-1} the inverse cumulative probability function for the distribution describing the return behaviour of the asset. Smaller α values characterize more extreme bad outcomes, but also require estimation of increasingly smaller tail probabilities. Choosing a balance between the degree of extreme and difficulties with estimating small tail probabilities, we use 25% CVaR in these analyses, such that the risk measure can be interpreted as the magnitude of a bad event expected in one in four fishing seasons. To estimate 25% CVaR, we used a resampling routine to generate an artificial dataset from sample data ($n = 10$ 000, sampling independently with replacement from a time-series of catches) and computed empirical quantiles and lower tail expectations corresponding to Equation (2):

$$\hat{\phi}(R, \alpha) = \frac{1}{\tilde{n}} \sum_{r_i^* < q(\alpha)} r_i^* \tag{3}$$

for $i = 1,2, \ldots, \tilde{n}$ where r_i* denotes the resample data, $q(\alpha)$is the α% empirical quantile for the resampled data, and $\tilde{n}$ is the total number of resampled data that satisfy the condition $r_i* < q(\alpha)$.

To calculate risk measures, we use time-series of catches from the earliest year for which individual-level data were available through to the year preceding the change to individual fishing quota management: 1991–2004 for the red king crab fishery and 1991–2005 for the snow crab fishery. Both fisheries were managed as competitive limited-access fisheries over the study period; total allowable harvest and entry were restricted, but participants had no guarantee of a portion of the catch. The red king crab fishery was closed in 1994 and 1995 due to concerns over low population abundance. We chose to exclude these years from risk calculations because closures affected all fishers similarly, and because semi-deviation and CVaR risk measures are more stable without zero-return years (Sethi and Dalton, 2012).

Both semi-deviation and 25% CVaR risk measures are standardized to the long-term mean of a catch time-series and scaled such that a more positive number indicates higher risk. For example, a semi-deviation measure of 0.35 indicates that the typical loss year results in a return that is 35% less than the long-term mean (or a return that is only 65% of the long-term mean). A 25% CVaR measure of 0.45 indicates that in one in four seasons you expect a return that is 45% less than the long-term mean. Although the time-series employed in this analysis are relatively short, simulation analyses in Sethi and Dalton (2012) using data modelled after Alaskan commercial fishery landings show that these measures provide unbiased estimates of 'true' risk at sample sizes of the order of >10 data points.

Cooperative simulations

An equal-share catch-pooling cooperative is defined as a group of individual fishers who pool their season landings and then allocate an equal share of the catch pool to each participant at the end of season. We examined the potential for such arrangements to reduce catch risk by simulating artificial cooperatives. To generate an artificial cooperative, a group of individuals was selected without replacement from the set of fishers in the individual-level datasets, and their catch time-series were combined. Thus simulations represent a retrospective analysis examining the effectiveness of a sample of hypothetical cooperatives that could have been formed in the Bering Sea crab fisheries over the study period. In order to construct cooperatives in which participants did not drop out (by leaving the fishery temporarily or permanently) and in which every member fished each year, we constrained the study population to consist only of full-participation vessels: 119 vessels participated a full 12 years during 1991–2004 (excluding closure years of 1994 and 1995) in the red king crab fishery and 96 vessels participated a full 15 years during 1991–2005 in the snow crab fishery. We made the simplifying assumption that fishers would have behaved the same in or out of a simulated cooperative, fishing equally as hard in either scenario. This may not be an appropriate assumption for all real-world cooperatives; however, anecdotal evidence from known catch-pooling cooperatives with a goal of mitigating harvest risk in Alaskan fisheries suggests that participants fish equally hard in cooperatives as independently (the authors' personal experience with Alaskan purse seine herring and salmon fisheries).

For each group size ranging from two to 20 participants, we generated 1250 different artificial cooperatives. Catch risk was calculated for a single participant in each artificial cooperative using time-series of one share of the catch pool. For comparison, we also computed individual risk information for the set of full-participation fishers outside any cooperatives, i.e. fishing alone. Simulations were carried out using the R statistical programming environment (R Development Core Team, 2010).

Analytical examination of catch variances

The statistical properties of catch-pooling cooperatives which can lead to a reduction in variability and therefore catch risk are examined by deriving expressions for catch variance for an individual fisherman under different regulatory and cooperative scenarios. Key results are summarized in the Results section; derivations are presented in the online Supplementary material.

Results

Statistical properties of catch-pooling cooperatives

To examine the statistical properties of catch-pooling cooperatives that can lead to risk reduction, consider the equation for the catch variance expected by an individual fisher in a cooperative in a fishery where participants compete against each other for a share of the total harvest, such as regulated open-access fisheries or, as in the case of the Bering Sea crab fisheries during the study period, limited-entry fisheries. We label this general category of management as 'competitive' to distinguish it from individual-based quota management where participants are guaranteed a portion of the total harvest. Catch variance incorporates deviations both above and below the mean, in contrast to the downside risk measures presented above; however, variance is analytically tractable to examine and, because downside catch risk measures are correlated with catch variance, still provides insight into potential risk-reduction benefits from cooperatives.

For what follows, H is a random variable for the total fishery harvest in a season, with $E[H] = \mu_H$ and $Var(H) = \sigma_H^2$. W_i is a random variable for the proportion of the total harvest that fisher i captures in a season, with $E[W_i] = \mu_{W_i}$and $Var(W_i) = \sigma_{W_i}^2$. In this formulation, a fisher's proportion of the total catch is a random quantity season to season, in contrast to an individual-based quota management scheme where this proportion would be a fixed percentage of total harvest. To simplify the problem and facilitate comparison of catch variability across different management and cooperative scenarios, we assume here that all individuals in the pool of potential cooperative participants have the same expected catch and variance, $E[W_1] = E[W_2] = \ldots = E[W_i] = \mu_W$ and $Var(W_1) = Var(W_2) = \ldots = Var(W_i) = \sigma_W^2$ for $i = 1, 2, \ldots, N$ individuals; however, fishers can have different pairwise covariation amongst their catches [these assumptions are used to generate Equations (4)–(6) and Table 1; the online Supplementary material presents derivations and catch variance equations which do not rely on fisher homogeneity assumptions]. That is, on average, all potential participants in a cooperative have the same expected catch and the same level of variation in catches season to season. Furthermore, assume that H and W_i are independent such that $Cov(H, W_i) = 0$. Under these assumptions,

Table 1. Relative catch variance for an individual fisher in an equal-share catch-pooling cooperative across a range of cooperative sizes and mean pairwise catch correlations amongst participants modelled after the pre-rationalization red king and snow crab fisheries[a].

Red king crab		**Mean pairwise catch correlation**									
		−1.00	**−0.50**	**−0.33**	**−0.25**	**−0.20**	**0.00**	**0.20**	**0.40**	**0.80**	**1.00**
Participants	$K=2$	**0.34**	0.50	0.56	0.58	0.60	0.67	0.73	0.80	0.93	1.00
	3		**0.34**	0.41	0.45	0.47	0.56	0.65	0.73	0.91	1.00
	4			**0.34**	0.38	0.40	0.50	0.60	0.70	0.90	1.00
	5				**0.34**	0.36	0.47	0.57	0.68	0.89	1.00
	6					**0.34**	0.45	0.56	0.67	0.89	1.00
Snow crab		**Mean pairwise catch correlation**									
		−1.00	**−0.50**	**−0.33**	**−0.25**	**−0.20**	**0.00**	**0.20**	**0.40**	**0.80**	**1.00**
Participants	$K=2$	**0.83**	0.87	0.89	0.90	0.90	0.92	0.93	0.95	0.98	1.00
	3		**0.83**	0.85	0.86	0.87	0.89	0.91	0.93	0.98	1.00
	4			**0.83**	0.84	0.85	0.87	0.90	0.92	0.97	1.00
	5				**0.83**	0.84	0.87	0.89	0.92	0.97	1.00
	6					**0.83**	0.86	0.89	0.92	0.97	1.00

[a]Based on Equations (4)–(6) generated under the assumptions outlined in the text. Under these assumptions, individual fishers have the same expected catch whether they operate alone or in an equal-share cooperative under a competitive fishery, or in a quota-based fishery (see derivations in the Supplementary material). Calculations use empirical estimates for equation parameters as follows. Red king crab: $\mu_H = 4.6\text{E} + 6$ (kg), $\sigma_H^2 = 2.1\text{E} + 12$, $\mu_W = 8.4\text{E} - 3$, and $\sigma_W^2 = 11.6\text{E} - 6$; snow crab: $\mu_H = 49.5\text{E} + 6$ (kg), $\sigma_H^2 = 1.9\text{E} - 15$, $\mu_W = 10.4\text{E} - 3$, and $\sigma_W^2 = 9.0\text{E} - 6$ (μ_W and σ_W^2 are mean values across the fleet). Catch variances are relative to the individual fishing alone under a competitive fishery ($Var_{i,C}$), the highest expected catch variance among all scenarios considered in these analyses. Minimum mean pairwise correlations are truncated at the lower bounds possible for K-participant cooperatives. Note, relative variances for the 'optimally' diversified portfolio (numbers in bold; where mean pairwise correlation amongst cooperative participants is equal to the theoretical lower bound possible) are equal to those under individual-based quota management.

the catch variance for an individual fisher in a K-participant equal-share cooperative under a competitive fishery, Var_{i,C_K}, is:

$$Var_{i,C_K} = \mu_W^2\sigma_H^2 + \left(\mu_H^2 + \sigma_H^2\right)\frac{\sigma_W^2}{K}(1 + (K-1)\bar{\rho}_{Wij}) \quad (4)$$

where $\bar{\rho}_{Wij}$ is the mean of the pairwise correlations amongst fisher's catches in the cooperative generated from pairs (represented by the 'ij' subscript) of individuals' catch time-series.

The diversification effect is encapsulated in the $\bar{\rho}_{Wij}$ term, where the less positive the correlation amongst participants' catches, the smaller the individual cooperative participant's resulting catch variance. It can be shown that the lower bound for the mean of pairwise correlations from a set of K random variables as defined under the assumptions listed above is $-\frac{1}{(K-1)}$ (Supplementary material). A cooperative whose participants have mean pairwise correlation equal to this lower bound indicates the largest variance-reducing diversification effect possible for a K-participant equal-share cooperative, or an 'optimally diversified' portfolio. Plugging this value for $\bar{\rho}_{Wij}$ in Equation (4), the variance for an individual in the optimally diversified cooperative, Var_{i,C_K*}, reduces to:

$$Var_{i,C_K*} = \mu_W^2\sigma_H^2 \quad (5)$$

Under the assumptions that a participant's quota in a rationalization programme is allocated based upon past fishing history (the typical rationalization implementation policy) such that individual i's quota is $E[W_i] = \mu_W$ and quotas do not get redistributed amongst seasons, this quantity is actually the same as a fisher under an individual-based quota fishery, $Var_{i,IQ}$, where the proportion of total harvest an individual receives each year is a fixed quantity and no longer a random variable (Supplementary material). That is to say, in the best-case scenario, an equal-share catch cooperative in a competitive fishery can diversify away all the season to season variation in the proportion of the total harvest an individual fisher captures, though catch is still subject to variation in total fishery-wide harvest.

Finally, to bookend the potential for catch cooperatives to reduce catch variability in a competitive fishery, consider the case where cooperative participants' catches are perfectly positively correlated: $\bar{\rho}_{Wij} = 1.0$. In this scenario, there is no diversification effect and the expected catch variance for a participant turns out to be the same as that of an individual fishing alone under a competitive fishery, $Var_{i,C}$ (Supplementary material):

$$Var_{i,C} = \mu_W^2\sigma_H^2 + \sigma_W^2\left(\mu_H^2 + \sigma_H^2\right) \quad (6)$$

Thus, depending on the 'quality' of the cooperative in terms of the correlation amongst participants' catches, equal-share catch-pooling cooperatives in a competitive fishery have the potential to reduce catch variability to be equivalent to individual-based quota management, where fishers only experience variation in the total fishery-wide harvest and not in the proportion of total harvest they take in any one season, or can be ineffective and provide no diversification benefit whatsoever, in which case they experience the same catch variance as fishing alone:

$$Var_{i,IQ} \leq Var_{i,C_K} \leq Var_{i,C}$$

Simulated cooperatives in the Bering Sea crab fisheries

Prior to rationalization, there was substantial risk-reduction benefit to forming catch-pooling cooperatives in the competitive red king crab fishery. Simulation results indicate that cooperatives could reduce risk with as few as two participants, and both semi-deviation and 25% CVaR could be reduced by as much as 40% with sufficiently large cooperatives (~5 or more participants; Figure 2a). The marginal risk-reduction benefit by including another participant in the cooperative is high initially, but generally drops off after six-participant cooperatives (Figure 2b).

In sharp contrast to the red king crab fishery, the snow crab fishery shows very little risk-reduction benefit to forming a cooperative (Figure 3). This occurs because the interseason variance in total fishery-wide harvest over the data series is high (Figure 1) and dominates the variance amongst fishers' shares of the total catch. Furthermore, individuals' catches in the snow crab fishery are highly positively correlated (Figure 4), attenuating the benefits of diversification through cooperatives. Heuristically, forming a cooperative with highly positively correlated catches is analogous to forming a stock portfolio with securities that are highly positively correlated—such as investing only in banks.

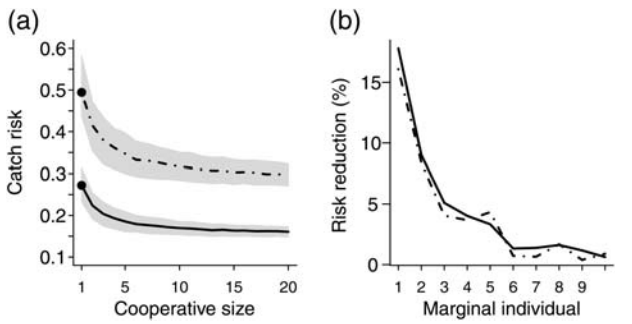

Figure 2. Catch risk information for simulated cooperatives in the Bering Sea red king crab fishery prior to rationalization (1991–2004, excluding closure years of 1994 and 1995). (a) The 25–75% quantile regions (shaded areas) and median risk for semi-deviation (solid line) or 25% conditional value-at-risk (dashed line) across 1250 randomly generated cooperatives. Filled circles indicate the median risk across the study population ($n = 119$) without cooperative participation. (b)The marginal risk-reduction benefit (percentage decrease in the median risk measure across simulated cooperatives, relative to the no-cooperative median risk level) as additional participants are included in a cooperative; '1' indicates the first marginal cooperative participant, indicating a cooperative with two individuals.

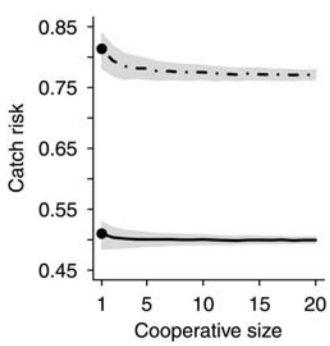

Figure 3. Catch risk information for simulated cooperatives in the Bering Sea snow crab fishery prior to rationalization (1991–2005). Shaded areas are 25–75% quantile regions and lines are median risk for semi-deviation (solid line) or 25% conditional value-at-risk (dashed line) across 1250 randomly generated cooperatives. Filled circles indicate the median risk across the study population ($n = 96$) without cooperative participation.

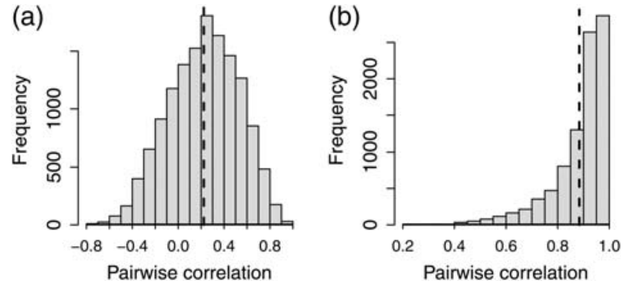

Figure 4. Histograms of pairwise correlations for catch time-series of full-participation individuals in the Bearing Sea red king fishery (a; 1991–2004, excluding closure years of 1994 and 1995) and snow crab fishery (b; 1991–2005). Vertical dashed lines indicate mean values across all possible pair combinations: red king crab = 0.22, snow crab = 0.88.

Table 1 shows the expected catch variance for an individual in the pre-rationalization red king and snow crab fisheries in a K-participant equal-share cooperative over a range of mean pairwise catch correlations relative to the catch variance for an individual operating alone under a competitive fishery [Equations (4)–(6)]. These calculations illustrate why catch-pooling cooperatives can lead to risk reduction in fisheries such as the red king crab fishery, but would not have been expected to perform well in the snow crab fishery over the study period. The variation in the total harvest in the snow crab fishery over the study period is large [Figure 1; total harvest coefficient of variation $(CV) = 85\%$], and thus even the theoretical variation expected under an individual-based quota fishery (or optimally diversified catch cooperative in a competitive fishery) is still high. This can be seen by the contribution of season to season variation in total harvest, σ_H^2, in Equations (4)–(6). This, coupled with the fact that fishers' catches are highly positively correlated in the snow crab fishery (Figure 4; mean pairwise correlation amongst fishers' catches over the study period = 0.88), indicates that any gains to be had through diversification are unobtainable because cooperatives would have high positive correlation amongst participants' catches; regardless of cooperative size, as $\bar{\rho}_{Wij}$ goes towards 1.0 (perfect positive correlation amongst participants' catches), catch variance of a cooperative participant, Var_{i,C_K} from Equation (4), approaches catch variance for an individual fishing alone, $Var_{i,C}$ from Equation (6) (Supplementary material). On the other hand, year to year total harvest variance over the study period is less in the red king crab fishery (Figure 1; total harvest $CV = 27.4\%$) and fishers' catches are less positively correlated (Figure 4; mean pairwise catch correlation = 0.22); an equal-share catch-pooling cooperative with five participants and pairwise catch correlation of 0.2 would capture ~65% of the potential variance reduction (calculated relative to the 'minimum' catch variance level expected under individual-based quota management, from Table 1: (1−0.57)/(1−0.34) = 65.2%.

Discussion

These simulation results suggest that catch-pooling cooperatives can be an effective tool for fishers to manage catch risk under a range of scenarios. We examined a simple equal-share allocation rule within cooperatives, but unequal catch allocation is still expected to result in lower year over year catch variability for cooperative participants [cf. Equation (S.6) and derivations in the

Supplementary material]. We also repeated cooperative simulations with an allocation scheme that provided a 10% bonus to the highest-catch participant and found similar risk-reduction results (Supplementary material, Figure S1).

With highly variable fisheries such as the pre-rationalization Bering Sea crab fisheries, most of the risk-reduction potential to be had from catch-pooling cooperatives can be realized with a small number of participants, of the order of 4–6 individuals. This property is important, because problems of moral hazard (i.e. behaving differently under a cooperative than when operating alone because individuals do not bear the full responsibility for their actions) and shirking (not working as hard in a team as individuals might alone) may be obstacles to the success and longevity of cooperatives. For example, cooperatives which share fuel costs can reduce the incentive to economize and avoid high fuel-consumption fishing behaviour such as running at high speeds. Smaller cooperatives may lead to easier monitoring of participants' actions and provide better control over moral hazard or shirking problems (Jones, 1984; Kraak, 2011, and references therein). Bonuses for high-catch participants to incentivize hard work may also help to address these problems, as could penalties for poor performance such as dropping members after a series of poor performances.

Derivations of individuals' catch variance demonstrate the statistical properties under which catch-pooling cooperatives can mitigate risk. Under the assumptions outlined above, we showed that, all else being equal, an optimally diversified cooperative where participants' catches are least positively correlated can result in catch variability in a competitive fishery that is equivalent to that under individual-based quota management. While optimally diversified cooperatives are probably not feasible due to a lack of information available on the covariation amongst individuals' catches and that some fleets' catches may be too highly positively correlated, the fact that suboptimal cooperatives could capture a substantial proportion of the catch risk-reduction benefits (e.g. as in the case of the Bering Sea red king crab fishery) enjoyed by individual-based quota fisheries is a noteworthy prospect.

Ultimately the decision to form a cooperative and the determination of whether or not a fisher is better off by joining a cooperative is a consideration of net benefit—including expected catch. We do not consider an explicit theory for the decisions leading to the formation of a cooperative or optimal behaviour once in a cooperative, instead simplifying analyses by assuming that participants in a cooperative have similar expected catches and variances, which allowed us to focus on the portfolio properties leading to risk reduction; effectively, we fix the 'return' component of a risk–return trade-off decision and imply that fishers in a cooperative are better off if they observe any reduction in risk. While a formal theory of cooperative formation is beyond the scope of this paper, we argue that the assumptions we use are not unreasonable. The above assumptions imply that only fishers with similar skill and luck form a cooperative. It is likely that groups of fishers with similar mean catch and variance exist in most commercial fishing fleets. For example, 83% of the red king crab vessels considered in the simulation study had five or more fishermen in the fleet with a mean catch within 5% of their own (73% for snow crab), and 55% had $\geq$10 fishermen with a mean catch within 5% of their own (50% for snow crab). Similarly, 72% of the red king crab vessels had five or more fishermen with a standard deviation of catch within 5% of their own (84% for snow crab), and 45% had $\geq$10 fishermen with a standard deviation of catch within 5% of their own (40% for snow crab).

Sustained pressure on ocean ecosystems, coupled with globalized seafood markets, sets the stage for continued challenges for commercial fisheries (Garcia and Rosenberg, 2010). Many countries' regulatory agencies are responding with updated strategies such as individual-based quota management; however, successful top-down management requires substantial financial and institutional resources. Our results demonstrate that catch cooperatives provide a tool for fishers in competitive fisheries to control their harvest risk that could be organized independently of regulatory management agencies. Furthermore, catch-pooling cooperatives can lead to income smoothing for participants in competitive fisheries, allowing fishermen to allocate resources more efficiently, for example by investing in cost-reducing fishing technology (e.g. Warren, 2011), as well as preventing hardships associated with income shocks such as loan defaults. Harvest or revenue insurance has also been proposed as a strategy to smooth income in wild capture fisheries by spreading the risk of a bad season across a group (Mumford *et al.*, 2009). Under an insurance policy, fishers trade uncertain, potentially large losses, for certain, but small losses, in the form of insurance premiums. In the event that a participant has a bad season as judged relative to an agreed upon benchmark, they receive a payout from the insurance pool to augment their revenues. Catch-pooling cooperatives to manage harvest or revenue risk also function by spreading risk across a group, but they may avoid some of the obstacles that prevent the successful implementation of insurance programmes in wild capture fisheries that include difficulty in setting appropriate payout triggers, difficulty in monitoring for moral hazard problems where participants change their behaviour in order to receive insurance payouts, and substantial administrative costs (Herrmann *et al.*, 2004; Mumford *et al.*, 2009). Catch-pooling cooperatives can operate without the need for premium payments or payout triggers, and, if small in size, are less susceptible to moral hazard problems that arise due to the difficulty in monitoring the actions of a large group of individuals.

Fishers typically guard information about their operations, such that the extent to which informal landings cooperatives to reduce catch risk are employed is largely unknown. At least within the Alaskan commercial fisheries familiar to the authors, it is likely that there are opportunities where catch-pooling cooperatives could successfully reduce risk, but they are not employed. This raises several future research questions as to the reason cooperatives are not used more widely. (i) Do time or financial costs in maintaining a cooperative outweigh the risk-mitigation benefits? (ii) Is there utility to operating alone that outweighs the risk-mitigation benefits of cooperatives? Perhaps fishers are willing to accept high season to season catch variability for the opportunity to achieve the rare exceptional season, or, put another way, fishers may exhibit risk-seeking behaviour, weighting a previous exceptional year more than they do a symmetric previous disastrous year. (iii) Is there a lack of information available to fishers regarding the potential benefits of using cooperatives? While management agencies do not need to be directly involved in informal catch cooperatives, they could address the latter concern by providing resources to aid fishers in forming landings-pooling cooperatives to manage catch risk, such as information on the business management of cooperatives (e.g. Haight *et al.*, 2007), or fishery-specific information on the potential risk-reduction benefits of cooperatives by conducting risk analyses as demonstrated in this article.

Supplementary material

Supplementary material is available at the *ICESJMS* online version of the manuscript and consists of the following: catch variance derivations and Figure S1, which shows cooperative simulation results under a 10% bonus allocation scheme.

Acknowledgements

SAS was supported by a National Science Foundation Graduate Research Fellowship, the Moore Foundation-funded UW Alaska Salmon Program, and the Alaska Fisheries Science Center. RH was supported by National Science Foundation award 1041570. We thank two anonymous reviewers and S.B.M. Kraak for comments which improved this manuscript. We thank B. Garber-Yonts for discussions regarding crab fisheries. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the US Government.

References

Alaska Commercial Fisheries Entry Commission (CFEC). 2011. Fishery statistics—participation and earnings. http://www.cfec.state.ak.us/fishery_statistics/earnings.htm (last accessed 27 July 2011).

Andersson, F., Mausser, H., Rosen, D., and Uryasev, S. 2001. Credit risk optimization with conditional value-at-risk criterion. Mathematical Programming Series B, 89: 273–291.

Bowers, F.R., Schwenzfeier, M., Milani, K., Salmon, M., Herring, K., Shaishnikoff, J., Russ, E., *et al.* 2008. Annual Management Report for the Commercial and Subsistence Shellfish Fisheries of the Aleutian Islands, Bering Sea, and Westward Region's Shellfish Observer Program. Alaska Department of Fish and Game Report no. 08-73.

Fina, M. 2005. Rationalization of the Bering Sea and Aleutian Islands crab fisheries. Marine Policy, 29: 311–322.

Fina, M., Evans, D., McCracken, J., Heltzel, J., Merrill, G., Fey, M., and Schug, D. 2010. Five-year Review of the Crab Rationalization Management Program for the Bering Sea and Aleutian Islands Crab Fisheries. North Pacific Fisheries Management Council Report v. December 2010.

Garcia, S.M., and Rosenberg, A.A. 2010. Food security and marine capture fisheries: characteristics, trends, drivers and future perspectives. Philosophical Transactions of the Royal Society B: Biological Sciences, 365: 2869–2880.

Haight, G., Crow, A., and Geier, H. 2007. Developing Cooperatives for the Alaska Seafood Industry. Alaska Sea Grant Marine Advisory Bulletin no. 61.

Herrmann, M., Greenberg, J., Hamel, C., and Geier, H. 2004. Extending federal crop insurance programs to commercial fisheries: the case of Bristol Bay, Alaska, sockeye salmon. North American Journal of Fisheries Management, 24: 352–366.

Jones, G.R. 1984. Task visibility, free riding and shirking: explaining the effects of technology on employee performance. Academy of Management Review, 9: 684–695.

Kraak, S.B.M. 2011. Exploring the 'public goods game' model to overcome the Tragedy of the Commons in fisheries management. Fish and Fisheries, 12: 18–33.

Kitts, A.W., and Edwards, S.F. 2003. Cooperatives in US fisheries: realizing the potential of the Fishermen's Collective Marketing Act. Marine Policy, 27: 357–366.

Markowitz, H. 1959. Portfolio Selection: Efficient Diversification of Investments. Wiley, New York. 344 pp.

Mumford, J.D., Leach, A.W., Levontin, P., and Kell, L.T. 2009. Insurance mechanisms to mediate economic risks in marine fisheries. ICES Journal of Marine Science, 66: 950–959.

Plan team for the King and Tanner Crab fisheries of the Bering Sea and Aleutian Islands (PTBSAI). 2010. Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. North Pacific Fishery Management Council report v. May 2010.

Porter, R.B. 1974. Semivariance and stochastic dominance: a comparison. The American Economic Review, 64: 200–204.

R Development Core Team. 2010. R: A language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.

Rockafellar, R.T., and Uryasev, S. 2002. Conditional value-at-risk for general loss distributions. Journal of Banking and Finance, 26:1443–1471.

Salas, S., and Gaertner, D. 2004. The behavioural dynamics of fishers: management implications. Fish and Fisheries, 5: 153–167.

Sethi, S.A. (2010) Risk management for fisheries. Fish and Fisheries, 11: 341–365.

Sethi, S.A., and Dalton, M. 2012. Risk measures for natural resource management: description, simulation testing and R code with fisheries examples. Journal of Fish and Wildlife Management, in press.

Sethi, S.A., Hilborn, R., and Dalton, M. 2012. Quantitative risk measures applied to Alaskan commercial fisheries. Canadian Journal of Fisheries and Aquatic Sciences, 69: 487–498.

Warren, B. 2011. Bering crab quotas prove their worth. Pacific Fishing, December Issue: 8–11.

Handling editor: Sarah Kraak