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Sharing the Northeast Atlantic mackerel

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The sharing of the Northeast Atlantic mackerel (*Scomber scombrus*) stock is analysed as a game between four parties: the European Union, Norway, the Faroe Islands, and Iceland. Consideration is given to how the outcome depends on the nature of the stock's migrations. Two types of migrations are considered: (i) density-dependent, where the mackerel migrates into the Icelandic economic zone only if it exceeds 3.5 million t, and (ii) stochastic migrations, where the said migrations are stochastic. It is determined that the Faroe Islands would never accept a cooperative solution wherein they can only fish with the globally optimal fishing mortality within their own zone. This is also true for Iceland when the migrations into her zone are stochastic, but not if they are density-dependent. In the latter case, the other players have incentives to retaliate to Icelandic overfishing by fishing harder, which greatly reduces the number of years when mackerel are available in the Icelandic zone. It is assumed that the objective is maximization of the catch volume over a time-horizon of 50 years.

Keywords: Atlantic mackerel, fishery management, game theory.

Introduction

In the 1980s, Norway and the European Union (EU) began co-operative management of Atlantic mackerel (*Scomber scombrus*) by setting an overall catch quota and dividing it among themselves. Later, the Faroe Islands came to participate in this arrangement. Mackerel, however, is also accessible outside the exclusive economic zones of these three countries, bringing it under the mandate of the North East Atlantic Fisheries Commission (NEAFC), of which the three are members. (Because of its Common Fisheries Policy, it is appropriate and convenient to refer to the European Union as a country in this context.) Therefore, NEAFC allocates a certain quota of mackerel to its members, primarily Russia, that fish mackerel outside the economic zones.

In 2008, the mackerel stock began to migrate into the Icelandic economic zone. Iceland had not previously fished mackerel in any significant amounts, but began doing so when it showed up in her waters. Iceland was not satisfied with the quota offered by the traditional partners (Norway, the EU, and the Faroe Islands) and unilaterally set a quota for herself, taking about 20% of the total catch in 2008, while the other parties adhered to their allotted quotas. Soon after, the Faroese withdrew from the cooperative arrangement, finding their quota allocation unacceptably low, compared with what the Icelanders were taking. Despite several attempts, the parties had not managed to reach a comprehensive agreement by mid-2012 (a bilateral agreement between the EU and Norway was concluded in March of that year).

Clearly, the major stumbling block hindering agreement on the mackerel is the migration of the stock into the Icelandic zone and the resultant Icelandic fishery. If an agreement is to be reached, the Icelanders and the Faroese will have to be offered quotas that they find acceptable. For an acceptable offer to come forward, it will also have to be in the interest of the major players, Norway and the EU. The criterion of acceptability is that each player will have to gain, or at least not lose, compared with what happens in the absence of cooperation. That everyone will gain from co-operation is not a foregone conclusion. It should also be noted that it may not be sufficient to offer one player a share in the overall quota equal to the share of the stock in his economic zone. This is sometimes called the zonal attachment principle. It has an intuitive fairness appeal, but is not always viable when we consider the strategic options of those who share a fish stock. On the zonal attachment principle and its credibility, see Engesæter (1993), Hamre (1993), and Hannesson (2006, 2007). In general, as will be shown below, the quota shares which would be viable in a cooperative solution depend critically on the nature of the fish migrations.

What, then, is the nature of the migrations of the mackerel between different economic zones? Unfortunately, there are no long time-series available on the catches of mackerel taken in the various economic zones and on the high seas; all that is available are series broken down by ICES statistical areas. Figure 1 shows the catches of mackerel broken down by relevant statistical areas, and Figure 2 shows the national economic zones and the ICES statistical areas, the latter being rectangles named with Roman numerals. We see that the catches of mackerel in Division Va, which largely overlaps with the Icelandic economic zone, are a recent phenomenon. In 2010, the share of catches taken in Subarea II, which covers parts of the Icelandic, Faroese, and Norwegian economic zones, as well as the high seas area in the Norwegian Sea,

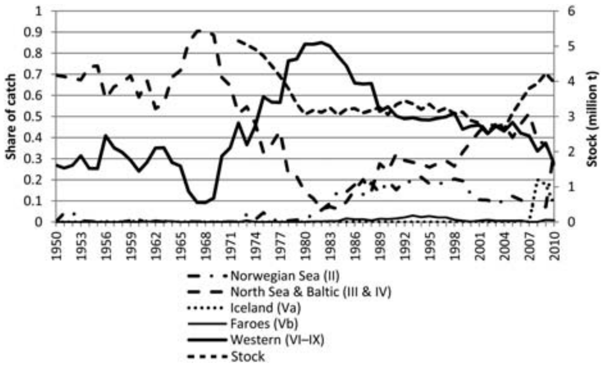

Figure 1. Catches of mackerel 1950–2010 divided into ICES areas, and size of the mackerel stock 1972–2010 as estimated by ICES (2011).

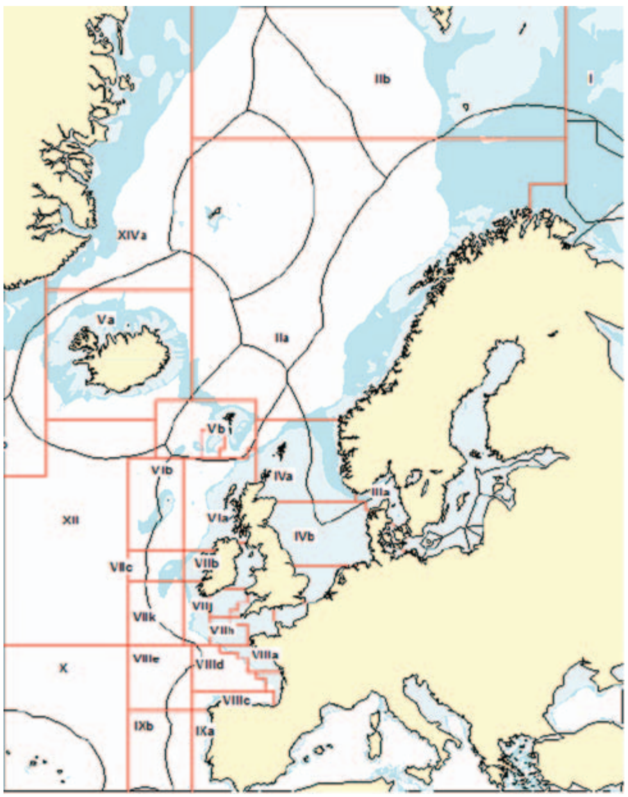

Figure 2. ICES statistical areas (rectangles with Roman numerals) and exclusive economic zones in the Northeast Atlantic (ICES, 2011, reproduced with permission).

increased to unprecedented levels, while the share taken in Division Va declined.

Figure 1 also shows the estimated size of the mackerel stock (total stock biomass, according to ICES (2011), Table 2.6.9). From 1980 to 2006, it varied between 2.5 and 3.4 million t, but after 2004, it grew from 2.7 million t to about 4 million t in 2009–2010. It was during this last phase that the migration into the Icelandic zone began. It is very tempting, therefore, to hypothesize that this migration depends on the size of the stock, with the stock spilling over into the Icelandic zone when it exceeds a certain size. This would be consistent with the idea that a larger stock migrates farther and wider in search of food or for other reasons. For density-dependent distribution of fish stocks, see MacCall (1990). Against this it may be argued that the stock exceeded 4 million t in the 1970s, without there being any mackerel fishery in the Icelandic zone. At that time, however, there was a separate mackerel stock in the North Sea, which collapsed under heavy fishing pressure (Iversen, 2002), The mackerel now being caught in the North Sea is "western mackerel", which spawns west of the British Isles and even further south and migrates into the North Sea in summer (Iversen, 2002). An alternative hypothesis is that the mackerel migrations are random, directed by oceanographic conditions that vary randomly, sending the stock into the Icelandic zone under exceptional conditions. Yet another hypothesis is that we are seeing a permanent change in the migratory pattern, generated by a permanent change in oceanographic conditions. Interestingly, Iversen (2002), in his thorough review of mackerel migrations over 100 years, makes no mention of the mackerel ever migrating into the waters around Iceland. This suggests that the said migration of the mackerel into Icelandic waters is a recent phenomenon, whatever its causes.

These three hypotheses have very different implications for the kind of agreement we are likely to obtain, if any, on the mackerel stock. In what follows, we shall focus on the two hypotheses that the mackerel migrations into the Icelandic zone are random vs. dependent on stock abundance, but we will, nevertheless, comment briefly on the third hypothesis that there has been a permanent shift in the distribution of the mackerel stock. We shall analyse this with the traditional tools of game theory; that is, we investigate what the different players will do when each acts unilaterally and takes the actions of others as given, looking for a solution where the players' assumptions about what the others will do are mutually consistent. The latter is a benchmark for the cooperative solution; if cooperation is to be achieved, each player must gain, or not lose, compared with what he would obtain in the absence of cooperation. We will not be concerned with how the players divide the gains from cooperation, only with whether it is feasible or not, and what the minimum quota allocations would have to be in order to attain cooperation. In this investigation, we ignore the mackerel fishery on the high seas, which largely involves Russian vessels, and concentrate on the interaction between the four coastal states: the EU, Norway, the Faroe Islands, and Iceland.

The analysis below is done on data for the Northeast Atlantic mackerel stock and with the current dispute on its management in mind. Nevertheless, we suspect that this situation is not without parallels in other contexts. There have, in fact, been disputes on fish-sharing arrangements elsewhere due to changed migratory habits of the fish involved. Several years ago, such a dispute developed between Canada and the United States about Pacific salmon fisheries, and was ultimately resolved with a new treaty with side payments (Miller and Munro, 2004). Therefore, the modelling approach taken here could be of interest for other fisheries where a similar situation has occurred or could develop.

Material and methods

The yield model

We shall use an age-structured model of the mackerel fishery. This is a traditional Beverton–Holt (1957) model, where the catch of fish (Y) in year t is given by

$$Y_t = \sum_{i=1}^{12} \frac{s_i F_t}{M + s_i F_t} w_i N_{i,t} \left(1 - e^{-(M+s_i F_t)}\right) \tag{1}$$

where i is the age of the fish (age group 12 includes fish 12 years and older), F_t is fishing mortality in year t, s_i is gear selectivity, M is natural mortality, and $N_{i,t}$ is the number of fish of age i at the beginning of year t. This last number is determined by the number of fish in the age group when it was recruited to the stock and the mortality it has been exposed to since then. Recruitment (number of fish of age 1) is determined by a recruitment function and random variations, to be further discussed below. The parameters of the yield equation (1) have been set on the basis of the 2011 report of the ICES Working Group on Widely Distributed Stocks (ICES, 2011). The Working Group uses a constant natural mortality $M = 0.15$ for all age groups and years. Likewise, it has used the same selectivity pattern since 1999 (ICES, 2011, Table 2.6.13), shown in Table 1. The initial stock was set as estimated for 2001 (ICES, 2011, Table 2.6.11), a fairly typical year before the recent upsurge in stock abundance.

The weight at age (w_i) has varied over time. The report distinguishes between weight at age in the catch and in the stock. We shall use a w_i-function based on weight at age in the stock. Using the weight in the stock and not the weight in the catch does not affect the relative payoff for the different nations that fish for mackerel, which is the focus of the analysis; it would simply change all payoffs proportionately according to how the weight in the catch differs from the weight in the stock. Whether or not weight at age is density-dependent could be important in the case where the migrations of the stock depend on its abundance. If fish growth is density-dependent, the gain in weight in a particular year, or the weight at age in that year, or both, should be negatively correlated with the size of the year class (number of fish) or with the size of the entire stock. The former would be the case if each age group "goes its own way", as it were, and competes for food with individuals in the same age group, and the latter would pertain if the stock migrates as a whole and all the fish in the stock are competing for the same food supply.

Table 1. Selectivity (s), weight at age (w) and fraction mature used in the yield model (Equation 1).

Age	*w*	*s*	Maturity
1	0.08631	0.065	0.07
2	0.16541	0.197	0.59
3	0.237301	0.47	0.88
4	0.301981	0.766	0.97
5	0.359451	1	0.97
6	0.409712	1.247	0.99
7	0.452762	1.308	1
8	0.488603	1.353	1
9	0.517234	1.429	1
10	0.538654	1.663	1
11	0.552865	1.5	1
12	0.559866	1.5	1

To investigate this, the following four sets of linear regressions were run (data on numbers were taken from Table 2.6.11 and weight at age from Table 2.6.3, both in ICES, 2011):

$$w_{i,t} \text{ on } N_{i,t} \text{ and } w_{i,t} \text{ on } \sum_j N_{j,t}$$
$$\frac{w_{i+1,t+1} - w_{i,t}}{w_{i,t}} \text{ on } N_i \text{ and } \frac{w_{i+1,t+1} - w_{i,t}}{w_{i,t}} \text{ on } \sum_j N_{j,t}$$

The results are shown in Table 2. The strongest evidence for density-dependent growth is given by the results with the total number of fish in the stock as an independent variable. For weight-at-age, all regression coefficients except one are negative, but only the results for 3-, 5-, and 6-year-old fish are significant at the 5% level (the result for 4-year-old fish is significant at the 10% level). For the rate of growth, all but two regression coefficients are negative, but only the result for 4-year-old fish is significant at the 5% level (the results for 5- and 7-year-old fish are significant at the 10% level). There is, thus, some, albeit weak, indication that individual fish growth is density-dependent. A referee has pointed out that one reason for the low statistical significance could be that stock size and weight-at-age are estimates and not true values. Attempts to build in density-dependence and to simulate the observed time-pattern of weight-at-age were unsuccessful, however, and we proceed by regarding individual growth as independent of stock size. It may be added that taking density-dependent growth into account would probably not have much affect on the results to be presented; the largest weight-at-age of any given age group is about 10% greater than the smallest weight.

Figure 3 shows the weight-at-age for ten year classes of mackerel, the youngest being the one for which we have data for all 12 years of age (this is the 1998 year class, which was 12 years old in 2010). The growth over the lifespan up to age 12 seems adequately described by a quadratic equation, as follows:

$$w_h = ah - bh^2 \tag{2}$$

where w_h is the weight of h-year-old fish and a and b are parameters, with $a = 0.089915$ and $b = 0.003605$ giving the best fit. The resulting growth curve is shown as a solid line in Figure 3 and the resulting numbers in Table 1.

Recruitment and stock variability

The variations in the mackerel stock are largely driven by variations in recruitment. In the case where migrations are related to stock abundance, these variations lead to occasional migrations of the stock into the Icelandic zone. Figure 4 shows a scatter diagram of observed recruitment (1-year-olds) vs. size of the spawning stock two years before (from Tables 2.6.9 and 2.6.11 in ICES 2011). For the purposes of this paper, we define recruitment as the number of 1-year-old fish at the beginning of the year. The Working Group on Widely Distributed Stocks (ICES, 2011) defines recruitment as 0-year-old fish, but they are not included in the stock abundance. 1-year-olds at the beginning of the year were spawned by the spawning stock at the beginning of the year two years earlier, with spawning taking place in late winter and early spring. There is no correlation between spawning stock and

Table 2. Results of a linear regression of weight at age and gain in weight on the number (N) in the year class ($N \times 10^{-9}$) and the number in the stock ($N \times 10^{-9}$).

	Number in year class		Number in stock	
Age	***w***	**d*w*/*w***	***w***	**d*w*/*w***
1	−0.0013 (0.598 1)	−0.0005 (0.993 7)	−0.0009 (0.111 8)	0.0243 (0.260 5)
2	−0.0037 (0.124 0)	−0.0102 (0.721 8)	−0.0003 (0.243 4)	−0.0159 (0.171 0)
3	−0.0078** (0.005 2)	0.0127 (0.510 8)	−0.0026* (0.040 8)	−0.0006 (0.920 9)
4	0.0083* (0.012 7)	−0.0290* (0.019 4)	−0.0021 (0.091 3)	−0.0124** (0.003 9)
5	0.0053 (0.287 9)	−0.0135 (0.415 4)	−0.0038* (0.011 9)	−0.0072 (0.099 5)
6	0.0062 (0.437 3)	0.0046 (0.814 3)	−0.0045* (0.022 3)	0.0036 (0.352 2)
7	0.0096 (0.282 2)	0.0017 (0.953 2)	−0.0006 (0.717 8)	−0.0067 (0.052 1)
8	0.0094 (0.557 8)	−0.0741 (0.334 9)	−0.0016 (0.352 8)	−0.0044 (0.433 2)
9	−0.0170 (0.645 2)	−0.0173 (0.883 3)	−0.0013 (0.613 9)	−0.0080 (0.144 0)
10	−0.0399 (0.383 9)	−2.8029 (0.995 3)	−0.0020 (0.371 4)	10.0614 (0.413 8)
11	−1.5054 (0.995 0)	−0.5492 (0.070 7)	5.0614 (0.413 7)	−0.0058 (0.674 2)
12	−0.0670 (0.158 0)	–	−0.0009 (0.688 8)	–

Numbers show regression coefficients and numbers in parenthesis p-values. * (**, ***) denotes significance at the 5 (1, 0.1) % level.

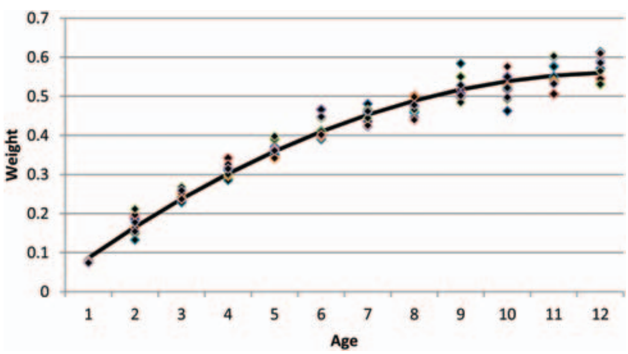

Figure 3. Weight-at-age for 1989–1998 year classes.

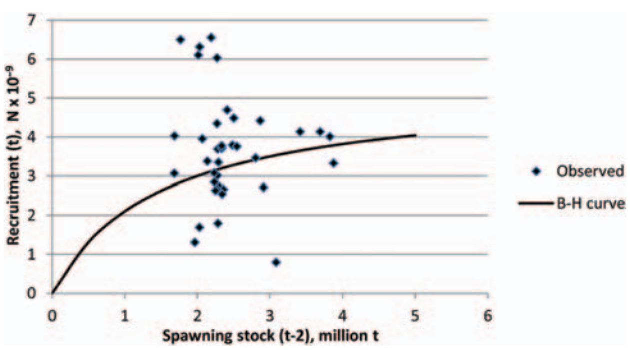

Figure 4. Recruitment of Northeast Atlantic mackerel (1-year-olds) as estimated by ICES (2011), and a Beverton–Holt recruitment function.

recruitment. The purpose of the recruitment function shown in Figure 4 will be explained shortly.

The four coastal states have, in principle, agreed on a target fishing mortality of 0.22 as an average for age groups 4–8; the dispute is over the proportion of the total permitted catch each should be allowed to take. With the selectivity pattern used in modelling the fishery (Table 1), this corresponds to a fishing mortality of $F = 0.194$ for the age group with selectivity equal to 1 (age 5; see Table 1). This target fishing mortality is based on elaborate simulations of the mackerel stock, with different specifications of the stock–recruitment relationship, with the objective of keeping low the risk of the spawning stock falling below a critical level (see ICES, 2008). To establish a benchmark that takes these concerns into account, we use a Beverton–Holt stock–recruitment function which results in a catch-maximizing fishing mortality of $F = 0.194$ for 5-year-old fish in a stationary model (one with no fluctuations in recruitment). The Beverton–Holt recruitment function is

$$R = \frac{aS}{1 + S/K} \qquad (3)$$

where R is recruitment, S is spawning stock, and α and K are parameters. The catch-maximizing fishing mortality is particularly sensitive to α; the value $\alpha = 3.5$ implies a catch-maximizing $F = 0.194$ for 5-year-old fish. The annual catch and the spawning stock are affected by K. We wish to emulate the results of ICES (2008), which obtained an annual catch of 620 000–640 000 t and a spawning stock of 2.9–3.0 million t with $F = 0.194$ ($F = 0.22$ on average for fish aged 4–8 years). Our model either underpredicts the annual catch or overpredicts the size of the spawning stock; we settled for $K = 1.5$, which in a stationary model results in an annual catch of 551 000 t and a spawning stock of 3.38 million t. Using weight in the catch, which is about 10% higher than weight in the stock, would raise the annual catch to about 600 000 t.

The differences between actual recruitment and the curve in Figure 4 are compared to a normal distribution in Figure 5. These differences roughly follow the normal pattern, but their mean is well above zero. A skewness-kurtosis test fails to reject the hypothesis of a normal distribution of the differences, while this is soundly rejected for differences in logarithms. Since our model overpredicts the spawning stock, we set the mean at zero, but keep the standard deviation when simulating the annual recruitment. Table 3 shows the outcome from 100 simulations over a time-horizon of 50 years, with the initial stock set equal to what it is in the stationary model with the catch-maximizing F-value. The spawning stock is roughly in line with the results in ICES (2008), but the annual catch is lower. The size of the spawning stock is calculated using the maturity ratios in ICES (2011), Table 2.6.5, shown in Table 1 here. In some simulations,

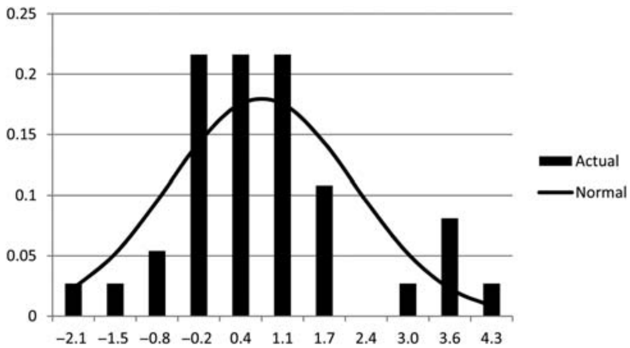

Figure 5. Distribution of differences between estimated recruitment (ICES, 2011) and the recruitment curve in Figure 4 compared with the normal distribution.

Table 3. Results from 100 simulations with variable recruitment.

	Optimal *F* (age 5)	Catch/year (t)	Spawning stock (million t)
Average	0.2335	549 315	2.92
Maximum	0.2650	633 476	4.33
Minimum	0.1710	389 222	1.24

recruitment failure happens; that is, the stochastic element in the recruitment function produces a negative recruitment, which, of course, cannot happen in reality and is, therefore, rounded off to zero. Because the spawning stock consists of several year classes, it never falls below 1.24 million t.

The objective function

In economic modelling of fishery management, it is frequently assumed that the objective is maximization of economic rent. This is useful for setting a benchmark for the economics of fishery management, but cases where governments follow such policies probably are not many and would rarely involve shared stocks. For the Northeast Atlantic mackerel specifically, it has already been noted that the governments involved have, in principle, agreed to a fishing mortality of $F = 0.194$ for 5-year-old fish, while, in practice, they have failed to agree on the implied catch quota and its distribution. As also noted, the said fishing mortality target was based on extensive simulations of the fishery, with the objective of minimizing the risk of the spawning stock falling below a certain critical level. The purpose of the recruitment function derived above is to mimic this objective; with this recruitment function, the fishing mortality of $F = 0.194$ for 5-year-old fish maximizes the catch per year from a stationary population. It may be noted that the simulations reported in Table 3, on average, produce a somewhat higher fishing mortality. This is due to the 50-year time-horizon; any shortening of the time-horizon tends to raise the fishing mortality that maximizes the catch per year within that horizon, compared with an infinite horizon. This effect is not very marked here, however, because the stock consists of many year classes, and it is also affected by the random element in recruitment; it may be noted that the minimum F-value produced in the simulations reported in Table 3 is, in fact, slightly below the optimal F-value in a stationary model.

We shall, however, take this objective of maximizing the fish catch within a 50-year time-horizon farther than that and assume that this is what the individual countries try to do when they act unilaterally or in coalitions of less than all four. There is no indication that any of the countries involved is trying to maximize the present value of fishing rents, while the fight over shares of the annual quota and the setting of unilateral quotas indicates that each is trying to maximize its annual fish catch.

Hence, the objective function for each country i is

$$V_i = \sum_{t=1}^{T} Y_{i,t}\left(v_{i,t}, F_i, F_{j\neq i}, u_{t-\tau}\right),\ \tau = 2, \ldots, 13. \qquad (4)$$

where $v_{i,t}$ is the share of the stock appearing in the zone of country i at the beginning of year t, and u is a random variable determining the deviation each year from the recruitment function Equation (3). There are 12 year classes in the model (Equation 1), and the size of each year class depends on the recruitment conditions two years before it was recruited (age 1) and the mortality every year after that, but it is assumed that fishing mortality is held constant over time. As already noted, we set $T = 50$. The objective function is maximized with respect to F_i.

The cooperative solution implies maximization of the sum of all values of V_i with respect to all values of F_i equal. F^o denotes the value of F producing the global maximum, and $V_i^o$the payoff to each country in the cooperative solution. The latter is the average annual catch resulting from applying F^o within each country's zone.

We then consider solutions where one or more countries act on their own. We do this in two steps. First, we maximize the payoff for each non-cooperating country, given that all other countries apply F^o:

$$\underset{F_j}{\text{Maximize}}\ V_i\left(F_i; v_{i,t}, F^o_{j\neq i}, u_{t-\tau}\right)\ t = 1, \ldots, T,\ \tau = 2, \ldots, 13 \qquad (4')$$

Denote the resulting solution by V_i^n, with n denoting non-retaliation. The remaining cooperating countries could retaliate to this, as follows:

$$\underset{F_j}{\text{Maximize}} \sum_{j\neq i} V_j\left(F_j; v_{j,t}, \bar{F}_i, u_{t-\tau}\right)\ t = 1, \ldots, T,\ \tau = 2, \ldots, 13. \qquad (4'')$$

where $\bar{F}_i$is the F the cooperating countries (j) assume that the non-cooperating country (i) applies. We look for a consistent retaliatory solution V_i^r,V_j^rsuch that $\bar{F}_i$maximizes (4') and $F^o_{j\neq i}$in (4') is replaced by $\bar{F}_{j\neq i}$ which maximizes (4"). Retaliation will be a credible (loss-minimizing) strategy for the j-countries if $V_j^r > V_j^n$, and non-cooperation will be a profitable strategy for country i if $V_i^r > V_i^o$. The extension of these definitions to the cases where more than one country does not cooperate is straightforward.

Results

Migrations dependent on stock abundance

We begin with the case where the migrations of the stock are related to its size. As noted above, the stock appears to spill over into the Icelandic zone when it is large. The Icelandic catches began in earnest (and peaked at 20% of the total) in 2008, when the stock was 4 million t. In the two subsequent years, the stock remained above this level, but the Icelandic catches declined somewhat (Figure 6). There certainly are not sufficient data to estimate how the migration into the Icelandic zone depends on stock size, but the following relationship is not unreasonable, given the recent experience:

$$v_I = \max\left[0, k\left(X - \bar{X}\right)\right] \qquad (5)$$

where v_I is the share of the stock in the Icelandic zone, $\bar{X}$ is the level beyond which it begins to spill over into the Icelandic zone, and k is a parameter. We set $\bar{X} = 3.5$ million t and $k = 0.1$, implying that 5% of the stock will be in the Icelandic zone when the stock is 4 million t and 15% if it were 5 million.

For the Faroese zone, we assume a constant share of 3%. The remaining share is split between Norway and the EU, with 65% going to the EU and 35% going to Norway. This is broadly consistent with the shares of the mackerel catches in the past, as shown in Figure 6; except for the years after 2007, the EU has taken about 60% of the mackerel catches since the early 1990s, Norway has taken slightly less than 30%, and the Faroe Islands about 3%. Russia has usually taken less than 10%, but we do not include the Russian fishery in this analysis.

A reality check can be provided by comparing results from simulations with the recent catches and stock assessments. Table 4 shows results from 100 simulations over a 50-year time-horizon, an initial stock as estimated for 2001, and the average

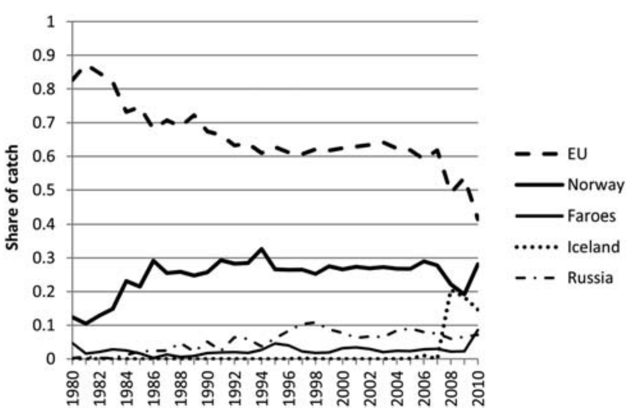

Figure 6. Shares of catches of Northeast Atlantic mackerel 1980–2010. Source: ICES Fish Catch Database.

fishing mortality as estimated for 2001–2010 ($F = 0.334$ for fish 4–8 years old; estimates from ICES, 2011). The combined average catch of Norway and the EU is about the same as in 2001–2010, while the Faroese catch is about a quarter lower. The average Icelandic catch is much lower, but the highest Icelandic catch in any single year is about the same as in 2008–2010 after the Icelandic fishery began in earnest. The reason for the low Icelandic average is that, with such high fishing mortality, the stock seldom exceeds 3.5 million t in the simulations, the level where it begins to migrate into the Icelandic zone. The frequency of its visits to the Icelandic zone does not appear unrealistic; about 5 years on average and at most 23, but in some simulations, it does not show up there at all. As pointed out by a referee, the parameters $\bar{X}$ and k are obviously not known with much precision, but the important question is whether the migrations into the Icelandic zone are density-dependent. If this is true, $\bar{X}$ could not be higher than 3.8, as the Icelandic catches began when the stock exceeded this level in 2008–2010. The parameter k could well be higher than assumed here. Both would weaken the Icelandic position; a higher $\bar{X}$ would make it easier for the others to shut Iceland out of the fishery, and a higher k (greater spillover into the Icelandic zone) would make it more profitable for them to do so, cf. the subsequent discussion.

Table 5 shows the outcomes of various strategies chosen by the four countries for one draw of the random variables influencing recruitment. These outcomes are typical (see Table 6). The strategy ENFI is full cooperation; here, the fishing mortality (5-year-old fish) is set so that the total catch per year is maximized. Each country is assumed to fish in its own economic zone. To achieve cooperation, it might, however, be necessary to allow some countries to catch more fish than they can take in their own zone with the agreed fishing mortality. As will be shown below, this is indeed the case.

Consider now whether any single country would have an incentive to refuse to cooperate. Suppose Iceland does so and fishes as hard as she can in her own zone (the strategy ENF;I). This would imply maximum fishing mortality, which we set arbitrarily at 2. This is fishing mortality for 5-year-old fish, which, with the selectivity pattern in Table 1, implies an average fishing mortality of 2.27 for fish 4–8 years old. This implies that only about 9% of the fish are left at the end of the year [exp(−0.15−2.2696)]. The payoff numbers show the gains vs. losses if the other countries stick to the globally optimal solution; Iceland gains and the other three (ENF) lose. We also see that the aggregate losses are smaller than the gain by Iceland, so the other three would be better off tolerating Iceland's unilateral action than by giving her an additional quota to entice her to stick to the cooperative solution; Iceland would demand a greater additional quota (more than

Table 4. Average, maximum, and minimum stock, spawning stock (SSB), and annual catch of the four players from 100 simulations over 50 years with $F = 0.334$ for fish 4–8 years old, and actual averages 2001–2010.

	Catches (t)						
	EU	Norway	Faroes	Iceland	Stock (million t)	SSB (million t)	Years in Iceland's zone
Average	316 041	170 176	15 098	1 951	2.8	2.3	5
Maximum	494 014	266 008	25 443	101 776	4.8	3.9	23
Minimum	80 607	43 403	3 835	0	0.7	0.6	0
Average 2001–2010	337 079	153 617	20 409	35 525	3.3	2.3	–

Migrations into the Icelandic economic zone density-dependent.

Table 5. Outcomes of different fishing strategies for one drawing of the random variable governing recruitment, with a 50-year time-horizon.

Strategy	F	Catch per year				Gains compared with cooperation								
		EU	Norway	Faroes	Iceland	Iceland	ENF	Faroes	ENI	Norway	EFI	EU	NFI	EN
ENFI	$F = 0.2503$	345.9	186.3	17.1	20.8	–	–	–	–	–	–	–	–	–
ENF;I	$F_I = 2, F_o = 0.2503$	335.2	180.5	16.3	46.9	26.1	−17.3	–	–	–	–	–	–	–
rENF;I	$F_I = 2\ F_o = 0.3250$	347.6	187.2	16.7	13.7	−7.0	2.1	–	–	–	–	–	–	–
ENI;F	$F_F = 2, F_o = 0.2503$	319.7	172.2	63.4	11.6	–	–	46.3	−49.5	–	–	–	–	–
rENI;F	$F_I = 2, F_o = 0.2768$	323.3	174.1	59.0	7.1	–	–	41.9	−48.4	–	–	–	–	–
EFI;N	$F_N = 1.4378, F_o = 0.2503$	159.1	322.0	7.6	0	21.7	–	45.3	–	135.7	−217.1	–	–	–
rEFI;N	$F_N = 2, F_o = 0.9065$	163.0	146.4	7.8	0	−0.2	–	34.7	–	−39.8	−213.1	–	–	–
NFI;E	$F_E = 0.5591, F_o = 0.2503$	408.4	112.2	9.9	0.1	–	–	–	–	–	–	62.5	−101.9	–
rNFI;E	$F_E = 1.212, F_o = 1.16$	159.2	117.4	10.4	0	–	–	–	–	–	–	−186.7	−96.4	–
EN;I,F	$F_I = F_F = 2, F_E = F_N = 0.2503$	313.8	169.0	61.9	28.9	8.1	–	44.8	–	–	–	–	–	−49.4
rEN;I,F	$F_I = F_F = 2, F_E = F_N = 0.3298$	322.9	173.9	51.3	6.9	–	–	–	–	–	–	–	–	−35.4
E;N,F,I	$F_N = 1.463, F_I = F_F = 2, F_E = 0.2503$	144.6	297.5	30.9	0	–	–	–	–	123.7	–	−178.4	–	–
rE;N,F,I	$F_N = 2, F_I = F_F = 2, F_E = 1.212$	159.2	117.4	10.4	0	–	–	–	–	−56.5	–	−163.7	–	–

26.1) than the maximum the other three would be willing to concede (17.3).

But, sitting idly by is not the best response by the three to the unilateral action by Iceland. The strategy rENF;I (r for retaliation) shows the results when the three choose the fishing mortality that would maximize their total catch per year, given that Iceland applies $F = 2$ in her own zone. We see that the three actually come out better than when all four cooperate, while Iceland loses. The reason is that with more aggressive fishing, the mackerel appears less frequently in the Icelandic zone and in smaller quantities. This happens in the majority of cases, and in all simulations, the loss suffered by the three is less if they retaliate than if they do not. Iceland always loses if the three retaliate. Hence, the threat of retaliation is credible and would suffice to deter Iceland from not cooperating.

The situation is the opposite if the Faroe Islands refuse to cooperate and apply the maximum fishing mortality of 2 in their zone. The Faroese gain is handsome if the other three continue to apply the globally optimal fishing mortality, but always smaller than the combined losses of the other three (strategy ENI;F). This is also true if the other three retaliate (strategy rENI;F) and go for the fishing mortality which maximizes their combined catches with a given fishing mortality of 2 in the Faroese zone. Hence, the three would do better if they gave an additional quota to the Faroese to entice them to cooperate. This is the outcome in all simulations. The conclusion, therefore, is that the Faroese would refuse to cooperate, unless given an extra quota over and above what they could catch in their own zone.

Why this difference between the Faroese and Icelandic situations? Both are marginal players. The difference lies in the stock-dependent migrations into the Icelandic zone. If we compare strategies rENF;I and rENI;F, we see that the retaliatory fishing mortality applied against Iceland is higher than the one applied against the Faroes. The reason is that a higher fishing mortality means less fish migrating into the Icelandic zone. In the cooperative solution, the mackerel would be in the Icelandic zone in 26 out of 50 years. With retaliation against Iceland, this is reduced to 9 years. The Faroese case illustrates well the general case that a small player can have bargaining power out of proportion to his size, provided that aggressive threat strategies applied by him do not undermine his position. The latter is the case for Iceland when the migrations depend on stock abundance.

Would the remaining players have an incentive not to cooperate? In strategies EFI;N and rEFI;N, Norway goes her own way and chooses a fishing mortality in her zone that maximizes her average catch, and in strategy rEFI;N, the others retaliate. Note that in the retaliation strategy, we consider the whole sequence of retaliation to retaliation until neither party has any incentive to change his fishing mortality (this was not an issue with the Faroes and Iceland, which chose the maximum fishing mortality when breaking away from cooperation). The results in Table 5 show that retaliation imposes losses on Norway compared with what she gets under cooperation. This is also a credible threat, because the other three (EU, Faeroes, and Iceland) minimize their losses by applying the retaliation strategy. But this kind of solution does not occur in all simulations. In 10% of the simulations, Norway gains even under retaliation, and in 30% of the simulations, the other three, in fact, lose more from retaliation than they would do if they abstained. This may sound improbable, but the reason is that Norway retaliates against retaliation until there is no incentive for either party to change the fishing mortality. But the threat

Table 6. Outcome of various strategies (percent of 30 simulations) when migrations into the Icelandic zone are stock-dependent vs. random.

Strategy		Stock-dependent migrations (%)	Random migrations (%)
ENF;I	Gain I > Loss ENF	57	10
rENF;I	Retaliation profitable	100	100
	Iceland loses after retaliation	97	0
	EU, N, and F better off after retaliation than with full cooperation	53	0
rENI;F	Retaliation profitable	100	100
	Faroe Islands lose after retaliation	0	0
rEFI;N	Retaliation profitable	70	53
	Norway loses after retaliation	90	80
rNFI;E	Retaliation profitable	70	43
	EU loses after retaliation	100	100
rEN;F,I	Retaliation profitable	100	100
	Faroe Islands lose after retaliation	0	0
	Iceland loses after retaliation	70	0
rE;N,F,I	Retaliation profitable	60	90
	Norway loses after retaliation	97	100

of loss from non-cooperation seems more likely than the opposite for Norway, and so is the credibility of retaliation by the other three. Hence, it is more likely than not that Norway would stay in a coalition with the other three.

Would non-cooperation by the EU be profitable? In the strategies NFI;E and rNFI;E, the EU acts unilaterally, and in strategy rNFI;E, the other three retaliate (and the EU retaliates against their retaliations, and so on). As was the case for Norway, the EU loses with retaliation, compared with what happens with cooperation. This is the case in all simulations. The other three lose less under retaliation than without it, so this is a credible threat; this happens in 70% of the simulations. The threat of a loss for the EU from not cooperating must, therefore, be considered likely, so the EU would most probably be best served by sticking to cooperation.

So far, the conclusion is that neither Norway nor the EU is likely to be well served by unilaterally breaking away from cooperation, whereas this would be a rewarding strategy for the Faroe Islands, unless given extra quotas to stick to it. Would Norway have an incentive to break away from cooperation with the EU, given that the Faroe Islands have done so? This happens in strategies E;N,F,I and rE;N,F,I; in the latter, the EU retaliates (Iceland is considered as not cooperating, but this makes no difference since there are no fish in her zone anyway under these strategies). Retaliation by the EU would turn Norway's gains from acting unilaterally to losses and is also a credible threat, as retaliation would reduce the loss for the EU. This is the typical outcome; the EU reduces its loss by retaliation in 60% of all cases, and Norway suffers a loss after retaliation in 97% of all cases. Note that the loss is measured relative to the outcome of the EU–Norway coalition (strategy rEN;F,I). Therefore, it seems more likely than not that cooperation between the EU and Norway would survive. An additional argument supporting this cooperation is that retaliation by the EU is a very destructive strategy. In some years, the stock would be extremely small, only a few thousand tonnes in some simulations. While extinction of even a small stock is ruled out in our model, it is entirely unknown whether such a small stock could survive in the real world.

There are a few more strategic constellations that are possible, but which are not reported in detail, as they do not change the conclusions already drawn. If Iceland and the Faroe Islands form a coalition against the EU and Norway, the outcome would be the same as with each of the former acting on its own; both Iceland and the Faroe Islands would fish with the maximum $F = 2$, leading to the same outcome as the strategy rEN;F,I. The EU could form a coalition with the Faroe Islands or Iceland, with Norway forming a coalition with the other minor player, or Norway and the other minor player could each act unilaterally. The outcome with retaliation is similar or identical to what happens when Norway, Iceland, and the Faroe Islands act unilaterally and the EU retaliates (rE;N,F,I).

Random migrations

Consider now the case when the migrations into the Icelandic zone are purely random. We model this in the following way. Each year, there is a probability p that the mackerel will migrate into the Icelandic zone. If it does, a share v_I of the stock will be there, irrespective of its abundance. We set $p = 0.25$ and $v_I = 0.15$. With this specification, 15% of the stock would be expected to appear in the Icelandic zone in 12–13 years out 50, but 100 simulations produce as few as 3 years and as many as 21.

The results from one drawing of the random variables governing recruitment and migrations are shown in Table 7. These are typical (see Table 6). The main difference from the previous case is that the random migrations into the Icelandic zone turn Iceland into a player like the Faroe Islands, a small player with disproportionate bargaining power. The strategy ENFI is the globally optimal solution; the one that maximizes the average total catch over a 50-year time-horizon.

In strategy ENF;I, Iceland refuses to cooperate and fishes with the maximum F of 2. If the other three continue cooperating, Iceland gains 45.9, but the others lose more, 49.9. They would reduce their loss if they retaliated (strategy rENF;I), but they would still lose more than Iceland gains and would thus be better off if they gave Iceland a large enough extra quota to entice her into cooperating; Iceland would demand at least 41.9, but the other three can afford to pay up to 48.7. This is the typical outcome; in 90% of all cases, the other three lose more than Iceland gains, and they always do so if they retaliate. Iceland is always better off than with full cooperation, even with retaliation by the other three. The contrast with the density-dependent migrations is stark; in that case, we found that

Table 7. Outcomes of different fishing strategies for one drawing of the random variables governing recruitment and migrations, with a 50-year time-horizon.

		Catch per year				Gains compared with cooperation								
Strategy	**F**	**EU**	**Norway**	**Faroes**	**Iceland**	**Iceland**	**ENF**	**Faroes**	**ENI**	**Norway**	**EFI**	**EU**	**NFI**	**EN**
ENFI	$F = 0.2345$	324.7	174.8	15.9	15.8	–	–	–	–	–	–	–	–	–
ENF;I	$F_I = 2, F_o = 0.2345$	293.4	158.0	14.4	61.7	45.9	−49.6	–	–	–	–	–	–	–
rENF;I	$F_I = 2, F_o = 0.2565$	293.9	158.3	14.4	57.8	41.9	−48.7	–	–	–	–	–	–	–
ENI;F	$F_F = 2, F_o = 0.2345$	293.7	158.1	61.5	14.3	–	–	45.5	−49.1	–	–	–	–	–
rENI:F	$F_I = 2, F_o = 0.2557$	294.2	158.4	57.7	14.3	–		41.8	−48.3	–	–	–	–	–
EFI;N	$F_N = 1.25, F_o = 0.2345$	151.5	285.7	7.4	7.2	–	–	–	–	110.9	−190.3	–	–	–
rEFI;N	$F_N = 2.0, F_o = 0.5234$	142.9	135.7	7.0	6.4	–	–	–	–	−39.1	−200.0	–	–	–
NFI;E	$F_E = 0.5063, F_o = 0.2345$	371.7	104.6	9.5	9.3	–	–	–	–	–	–	47.1	−83.1	–
rNFI;E	$F_E = 1.36, F_o = 2.0$	137.0	93.2	8.5	7.6	–	–	–	–	–	–	−187.6	−97.3	–
EN;I,F	$F_E = F_N = 0.2345, F_o = F_I = 2.0$	265.6	143.0	56.3	56.5	42.2	–	41.8	–	–	–	–	–	−90.8
rEN;I,F	$F_E = F_N = 0.2781, F_o = F_I = 2.0$	267.5	144.1	49.8	49.8	35.5	–	35.4	–	–	–	–	–	87.8
E;N,F,I	$F_N = 1.52, F_I = F_F = 2, F_E = 0.2344$	110.5	245.3	25.7	25.2	–	–	–		101.3	–	−157.1	–	–
rE;N,F,I	$F_N = F_I = F_F = F_E = 2.0$	137.0	93.2	8.5	7.6	–	–	–	–	−50.8	–	−130.5	–	–

Iceland would always lose from acting unilaterally, because it would be in the interest of the others to retaliate so that the stock would be small enough to seldom, if ever, migrate into the Icelandic zone. Random migrations imply that Iceland is a small player comparable with the Faroes, even if a small share of the stock is always available in the Faroese zone, but not always in the Icelandic zone, with Iceland also having a "small player advantage"; that is, having greater bargaining power than her share of the stock would indicate.

In strategies ENI;F and rENI;F, the Faroe Islands abandon cooperation, and in the latter, the other three retaliate. The outcome is similar to the Icelandic deviation; the three always lose more than the Faroese gain and would thus be able to entice them to cooperate by offering extra quotas. In all cases, the three would minimize their loss by retaliating against the Faroese, but even so, the Faroese would come out better than under full cooperation. Hence, if full cooperation is to be preserved, both Iceland and the Faroe Islands would have to be offered larger fish quotas than they could take within their economic zones with the globally optimal fishing mortality.

In strategies EFI;N and rEFI;N, Norway acts unilaterally, and in the latter, the other three retaliate. The retaliation increases the loss of the three in about a half of all cases, so it is unclear whether the three would choose to retaliate. If they do, Norway would lose from acting unilaterally; this happens in 80% of all cases, but it is unclear whether the threat of possible retaliation is strong enough to deter her from not cooperating.

In strategies NFI;E and rNFI;E, the EU acts unilaterally, and in the latter, the other three retaliate. The result is similar to what happens with Norway acting unilaterally; the other three would lose more from retaliation than otherwise. This happens in 67% of all cases. Obviously, the coalition of EU, the Faroes, and Iceland tolerating non-cooperation by Norway and the coalition of the Faroes, Iceland, and Norway tolerating non-cooperation by the EU cannot happen simultaneously.

So far, the conclusion is that both Iceland and the Faroes would prefer to act unilaterally, unless being given extra quotas to make cooperation attractive. We have also found that it would be in the interest of the two big players, the EU and Norway, to compensate them for cooperating, if one of them did not cooperate. What if neither did? In strategies EN;F,I and rEN;F,I, both Iceland and the Faeroes act unilaterally, and in strategy rEN;F,I, Norway and the EU retaliate. The Faroes and Iceland together gain less from not cooperating than the other two lose in the absence of retaliation; note that the gains for the Faroes and Iceland respectively are measured relative to the outcome of the coalition with the other three (rENI;F and rENF;I). Norway and the EU would lose less if they retaliated, but their losses would still be greater than the gains by Iceland and the Faroes, so there is scope to offer the latter two extra quotas that would entice them to cooperate. This happens in all simulations.

But would the Norway–EU coalition itself break down? In strategies E;N,F,I and rE;N,F,I, Norway abandons cooperation and acts unilaterally, like Iceland and the Faroes, and in the latter strategy, the EU does likewise. Norway would gain if the EU did not retaliate, but the EU reduces its losses by retaliating and turns Norway's gain into a loss (note that the gains for the two are measured relative to the coalition rEN;F;I). This is the typical outcome; the EU reduces its loss by retaliating in 90% of all simulations. The conclusion thus is that the Norway–EU coalition is likely to be robust against defection by Iceland and the

Faroes, and that they have incentives to provide extra quotas for the latter two to entice them to cooperate.

Discussion

Two main results from the above analysis bear emphasizing. First, the outcome of bargaining over quota from a migratory stock such as the mackerel depends critically on the nature of the migrations. If the migrations of the stock into a minor party's zone depend on stock abundance, as the case seems to be for the migrations of the mackerel into the Icelandic zone, the bargaining position of the minor player is weak. By choosing a high enough fishing mortality, the major players can reduce or altogether prevent the migrations of the stock into the minor player's zone and thus shut him out of the fishery. For the parameters used in this analysis, this is precisely the outcome for Iceland.

If, on the other hand, the migrations are purely random, the minor player into whose zone the fish occasionally find their way can have a strong bargaining position, just like a minor player to whose zone a small share of the stock always migrates. This is well illustrated by the position of the Faroe Islands and Iceland with respect to the mackerel in case its migrations into the Icelandic zone are purely random. This brings up the second result worth emphasizing; a small player can have a greater bargaining strength than the share of the stock in his zone would indicate. National fish quotas set on the basis of the share of the stock in each national economic zone (the so-called zonal attachment principle) are not necessarily sufficient to entice the small players to cooperate; they typically require more, because they gain by acting unilaterally, and it is not in the major players' interest to annihilate these gains by fishing more intensively. The reason why the small player has a disproportionate bargaining strength is that the gains from leaving any fish behind mainly accrue to the major player and only slightly to the minor player. Furthermore, since the major player has a stronger conservation motive, the minor player knows that he can benefit from the major player's conservation efforts.

To this must be added that these results depend critically on the assumptions about the migrations of the fish, more precisely that the fish stock grows and breeds as a unit and redistributes itself between the different economic zones before the fishing season begins. This simplified description appears to apply to the mackerel; in the beginning of each year, the stock is mainly fished on the spawning grounds west of the British Isles, France, and Spain. It then moves north into the Norwegian Sea, the North Sea, and south of Iceland; in summer, the fishery is mainly in these areas. In autumn, the fishery is concentrated around and west of the Shetland Islands, when the stock is migrating back to its spawning grounds (see Figure 2.3.2 in ICES, 2011). Then, the cycle begins anew.

It is also worthwhile to point out that the total absence of cooperation could be extremely destructive, reducing the stock to near extinction. This is not caused by short-sightedness; in the above model, we have set the discount rate at zero, which is as far-sighted as one can be, and maximized the catch per year over a 50-year time-horizon. Rather, it comes about through a destructive competition for a resource essentially given by nature. Such deleterious outcomes are in no one's interest, except as responses to the ravages by others, and could act as incentives promoting cooperation, at least among those with most at stake. In both of the migration cases above, we found the cooperation between the EU and Norway to be fairly robust. As already stated, in order to get the Faroe Islands and Iceland to accept the cooperative solution, the big players would have to offer them larger catch quotas than the latter two could catch within their zone with the fishing mortality that maximizes the overall catch. The small players would have to be offered an additional quota of at least the difference between what they get when the big players cooperate against them (strategy rEN;F,I) and full cooperation in the absence of such "side payments" (ENFI). Assuming that the big players get away with this minimum, their gain, expressed with reference to what they get when they cooperate and retaliate against the small players, is only 2.5% with stock-dependent migrations, but 6.3% with the random migrations (averages over all simulations). The reason why the first number is smaller is that with stock-dependent migrations, Iceland is a truly marginal player and can be shut out from the fishery by a moderate fishing mortality.

A further reason why the big players might want to secure the full cooperation of the small players is that with a lower fishing mortality, the spawning stock would be greater. To prevent recruitment failure, it is considered important to prevent the spawning stock from falling below some minimum, which fortunately perhaps we do not know. The minimum spawning stock in the simulations is 1.16 million t under full cooperation (1.42 with random migrations), but 0.72 when the big two retaliate against the small players (0.71 with random migrations). The minimum spawning stock in any single year in the period 1972–2010 was 1.68 million t (ICES, 2011), so this could be a concern.

Finally, what about the possibility that the migration of the mackerel into the Icelandic zone has become a permanent feature, due to a lasting change in the oceanographic conditions around Iceland? This would turn Iceland into a player with a permanent, but probably small, share of the mackerel stock in her zone. She would become a player similar to the Faroe Islands, which we have assumed always get a 3% share of the stock in their zone. The outcome under this scenario is likely to be similar to what we obtained above for the case of random migrations, as the outcomes for Iceland and the Faroe Islands were strikingly similar in that case.

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References

Beverton, R. J. H., and Holt, S. J. 1957. On the Dynamics of Exploited Fish Populations. Ministry of Agriculture, Fisheries and Food, Fishery Investigations, London, OSeries II, XIX. 533 pp.

Engesæter, S. 1993. Scientific input to international fish agreements. International challenges. The Fridtjof Nansen Institute Journal, 13: 85–106.

Hamre, J. 1993. A Model of Estimating Biological Attachment of Fish Stocks to Exclusive Economic Zones. ICES Document CM 1993/D: 43.

Hannesson, R. 2006. Individual rationality and the "zonal attachment" principle: three stock migration models. Environmental and Resource Economics, 34: 229–245.

Hannesson, R. 2007. Incentive compatibility of fish-sharing agreements. *In* Advances in Fisheries Economics. Festschrift in Honour of Professor Gordon R. Munro, pp. 196–206. Ed. by

F. Asche, D. Gordon, R. Arnason, and U. R. Sumaila. Blackwell, Oxford. 320 pp.

ICES. 2008. European Commission (EC) request on evaluation of management plan for NEA mackerel. *In* Report of the ICES Advisory Committee, 2008. ICES Advice, Book 9: 43–61. 345 pp.

ICES. 2011. Report of the Working Group on Widely Distributed Stocks (WGWIDE). ICES Document CM 2011/ACOM: 15. 642 pp.

Iversen, S. A. 2002. Changes in the perception of the migration pattern of Northeast Atlantic mackerel during the last 100 years. ICES Marine Science Symposia, 215: 382–390.

MacCall, A. D. 1990. Dynamic Geography of Marine Fish Populations. University of Washinton Press, Seattle.

Miller, K. A., and Munro, G. R. 2004. Climate and cooperation: a new perspective on the management of shared fish stocks. Marine Resource Economics, 9: 367–393.

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