Sharing a Fish Stock with Density-dependent Distribution and Unit Harvest Costs[§]

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Abstract

We study cooperative and competitive solutions for managing a fish stock that has stock-size dependent distribution, using Norwegian spring-spawning herring (*Clupea harengus*) as a case study. Three players in our game can be asymmetric in stock ownership, efficiency (cost of harvesting) and stock concentration profile. The special feature of Norwegian spring-spawning herring is that it comes under sole ownership of Norway when stock is sufficiently low. In some important ways, our model is more realistic than earlier game-theoretic harvesting models: catch function in our model is density-dependent, implying unit harvest cost is no longer a constant; we use a reference fishing mortality as the control parameter that determines annual catch quotas, making fishing effort a dynamic variable that reflects changes in stock biomass. We find that the likelihood of a stable grand coalition increases with the degree of asymmetry in the players' efficiency levels. When Norway, the player with the largest stock share and inherently the highest fish density in her zone, is the least efficient player, she is not guaranteed to receive the largest shares of grand cooperation benefits. Low initial stock level increases Norwegian share of the grand coalition benefits. In the present of dynamic stock distribution, it is not the interest of any players to drive stock down below the biomass level in which Norway becomes the sole owner.

Keywords: cooperative game, Shapley value for partition function games, dynamic stock distribution, international resource management

JEL classification code: C71, Q22, Q57

1 Introduction

Trans-boundary fishery resources challenge effective fishery management. The challenge becomes even greater if distribution of the targeted fish stocks vary in space and time, or more dramatically, migration patterns change. Several commercial fish stocks have shown considerable shifts in their distribution. For example, Pacific salmon in Alaska increased sharply in abundance from mid 1970s, whereas salmon stocks along the U.S. west coast and in southern British Columbia showed strong declines; the situation was completely reversed compared to the 1960s and early 1970s (Mantua et al. 1997). Norwegian spring-spawning herring (NSSH) has undergone profound distributional shifts since 1950s: during years of the high stock abundance, NSSH stock can occupy five exclusive economic zones (EEZ) as well as international waters, but when the stock abundance was low, the stock was confined to the Norwegian EEZ (Dragesund et al. 1997). Finally, Atlantic mackerel, which used to visit Icelandic waters only occasionally, has in recent years become so abundant that it supports a sizeable Icelandic commercial fishery (ICES 2010). The underlying reasons for such distributional changes are likely multifaceted, although climatic changes are often in the spotlight (Toresen and Østvedt, 2000; Perry et al. 2005). Climatic shifts can trigger changes in ocean temperature and circulation patterns, which can have significant impact on the dynamics of marine fish populations (Miller and Munro 2004).

Overlooking distributional shifts can lead to distorted fisheries management decisions (Hannesson 2007; Johnson and Welch 2010). Most of trans-boundary fisheries agreements are based on the "zonal attachment" principle, that is, a country's share of total quota is proportional to the share of the total stock in its EEZ. Clearly, fish neither know about nor would respect these boundaries. The displacement of fish from one zone to another can then threaten the stability of existing fishing agreements, and further, it may incentivize uncoordinated fishing practices that potentially harm the biological stocks and economic outcomes. Pacific salmon moving from Canada to Alaska triggered breakdown of a cooperative harvest agreement (Miller and Munro 2004); Scottish fishermen called for "mackerel war" against the new entrant, Iceland, who together with the Faroe Islands unilaterally set large catch quotas in their own waters; in the case of NSSH, competitive open access fisheries during 1950s–1960s coupled with climate-driven low recruitment eventually led to the collapse of NSSH stock (Dragesund et al. 1997).

Game theory has been widely used to tackle research questions in international fishery management (Bailey et al. 2010), including several applications to herring fisheries (Lindroos and Kaitala 2000; Lindroos 2004; Bjørndal et al. 2004; Hannesson 2006). However, studies addressing the implications of dynamic stock distribution on the trans-boundary fishery decisions are few. One line of research addressed the implications in terms of strategic interactions of non-cooperative players and the risk of stock depletion (Golubtsov and McKelvey 2007; Hannesson 2007; Liu and Heino 2011). Another branch of literature concerns implications on the stability of a cooperative arrangement and the resilience of fishery agreements. Arnason et al.(2000) studied equilibrium strategies for various competitive and cooperative situations in a stylized model of five exploiters. They modelled herring migration as a stochastic process, but the dynamic stock distribution was not the focus of their study. Hannesson (2006) studied the question in a two players' game using a biomass dynamic model for NSSH, including density-dependent migration, but his model is based on steady-state equilibrium only. Ekerhovd (2010) used an age-structured model to study the impacts of distributional shift for managing the blue whiting fishery. He assumed two scenarios: one with a more westerly stock distribution in which Russia is not a coastal state, and the other one where blue whiting spreads further east (as has been happened in recent years; Heino et al. 2008) such that Russia becomes a coastal state. He found that inclusion of Russia as a coastal state increases the likelihood of a stable coastal state agreement.

The key question in this paper is the stability of a grand coalition (co-operation among all the players) and the benefit sharing within the stable grand coalition when stock distribution is dynamic. We have chosen to use Norwegian spring-spawning herring (NSSH) fishery as the example. As already mentioned, the distribution of NSSH is highly dynamic, and the stock becomes under sole ownership at low stock abundance. Intriguingly, co-operative management of herring has not always been stable: the coastal states agreement (i.e., the grand coalition in the game parlance) was suspended during 2003–2006, primarily because Norwegian fishermen were not satisfied with the share they received, given that the stock spends critical stages of its life cycle near the Norwegian coast (Sissener and Bjørndal 2005).

We address our research question using a three-player game for Norwegian spring-spawning herring. We include Norway and Russia as independent players and group the remaining players, Iceland, the Faroe Islands, and EU (hereafter referred to as IFE), as the

third one. It is important to treat Norway as an independent player (some earlier studies have merged Norway and Russia), given the unique strategic position Norway has in the game. Merging IFE countries helps to limit the complexity of the game. We use an age-structure model where the stock distribution is dependent on spawning stock biomass. The players in our model are asymmetric; in particular, Norway could monopolize the stock. Unlike earlier studies, we consider unit harvest cost dependent on the stock size and the stock elasticity of harvest. The benefit sharing is studied according to the Shapley value generalized for partition function games. As a robustness check, we also consider an alternative sharing rule.

2 The model set-up

Our bio-economic model is built upon three-player's cooperative game framework in an age-structured model. Model parameters and variables are summarized in the Appendix.

2.1 Spatial distribution rule

Norwegian coast is the only spawning area for NSSH, and also the main habitat for juvenile herring. After spawning, adult herring may remain in Norwegian waters migrate further away for foraging. In our setting, players are only allowed to harvest in their own exclusive economic zones (EEZ)—even under full cooperation case—and the harvest takes place after stock is redistributed. In the end of a fishing season (one year), NSSH from different zones merge again in the Norwegian EEZ, before a new spawning season starts. The NSSH is also partly accessible in the the international waters; our model has ignored this component.

To model the dynamic stock distribution, we assume a spatial distribution rule specified by Patterson (1998). According to this rule, the share of total stock abundance (θ) received by each player is a piece-wise linear function of total spawning stock biomass (B^{SS}), which is jointly determined by each player's fishing policy ex-ante:

$$\theta_{j,t} = \begin{cases} \frac{d_{j,1950}+d_{j,1959}+d_{j,1983}}{3} & \text{if } B_t^{SS} > B_{high}^{SS} \\ \phi\frac{d_{j,1950}+d_{j,1959}+d_{j,1983}}{3} + (1-\phi)d_{j,1972} & \text{if } B_{low}^{SS} \leq B_t^{SS} \leq B_{high}^{SS} \\ d_{j,1972} & \text{if } B_t^{SS} < B_{low}^{SS}, \end{cases} \tag{1}$$

where $d_{j,t}$ denotes empirically observed stock share in zone j in year t, an average over

all age classes, and $\phi = \frac{B_t^{SS} - B_{low}^{SS}}{B_{high}^{SS} - B_{low}^{SS}}$. $t = 1972$ represents a year when Norway was the sole owner of NSSH fishery, whereas the other years represent years when the stock had a broad, trans-boundary distribution. $B_{high}^{SS} = 5.0Mt$ and $B_{low}^{SS} = 2.5Mt$ are the two biomass thresholds; alternative values are considered in section 4.3.

The above formulation indicates two sources of dynamism in the stock distribution: 1) the distribution is the function of the spawning stock biomass, here characterized as an endogenous force, and 2) the distributional rule might be driven by exogenous factors such climate warming, giving potentially rise to new stock distribution patterns.

2.2 Non-linear density effects

The main features of our bio-economic model are similar to earlier game theoretical herring papers. An important distinction is that we consider a non-linear relationship between stock density and stock abundance. For example, we formulate zone specific density ρ as follows:

$$\rho_j = h\left(\frac{N_j}{\theta_j K}\right)^{\alpha_j}, 0 \leq \alpha_j \leq 1, \tag{2}$$

where N_j is stock abundance in fishing zone j, normalized with respect to $\theta_j K$, the environmental carrying capacity in zone j. The 'global' environmental carrying capacity K corresponds to the population dynamical equilibrium in absence of fishing. Scaling parameter h can be interpreted as the stock density when $N = K$.

α, stock elasticity of harvest, has special interpretation in our model. It depends on the behaviour of the targeted fish as wellas the ability of fishermen to find the fish. Typically α has a value between 0 and 1. $\alpha = 0$ represents an extreme schooling species and where fishermen can find even the last fish school with ease. $\alpha = 1$ represents a non-schooling fish which is uniformly distributed, or that the encounters between fishable schools and fishermen are random.

Given that NSSH is known to be a schooling species and that the herring stock is fairly accessible in Norwegian zone even in years of very low overall abundance (e.g., year 1972), we assume $\alpha = 0$ for Norwegian zone; in contrast, α is set to $\frac{1}{2}$[1] in other two zones because distribution of NSSH is less predictable further away from the Norwegian coast, fishermen thus having more difficulty in locating the schools. When two countries

[1]This particular value is chosen because it represents an intermediate stock elasticity of harvest and because the catch expression for $\alpha = \frac{1}{2}$ is relatively simple.

have the same α, equation (2) suggests that fishermen in different fishing zones experience same density in the beginning of a fishing season. However, situation changes during the season if they apply different harvest policies.

2.3 Stock dynamics and harvest function

The assumption of non-linearity between stock density and abundance has a series of implications, one of which is that we can no longer treat catchability as a constant, except for the special case $\alpha = 1$. Steinshamn (2011) has derived stock dynamic and harvest model based on such non-linear relationship. Our model is an extension of his model, with one important change: we allow fishermen to fish until the last fish of the fishable stock is taken. In Steinshamn's model, fishermen stop fishing when the first age class in the fishable stock gets exhausted, even if other age classes are still present.

We specify stock dynamics as follows:

$$\begin{aligned} N_{i+1,j,t+1} &= \left\{ \left[N_{i,j,t}^{1-\alpha_j} + \frac{s_i h_i E_{j,t}}{M_i \theta_{j,t}^{\alpha_j} K_i^{\alpha_j}} \right] e^{-M_i(1-\alpha_j)\tau_{i,j,t}} - \frac{s_i h_i E_{j,t}}{M_i \theta_{j,t}^{\alpha_j} K_i^{\alpha_j}} \right\}^{\frac{1}{1-\alpha_j}}, \\ & 0 \leq \alpha_j < 1, i \in [0, 1, \ldots, 15], \end{aligned} \tag{3}$$

where $N_{i,j,t}$ indicates zone-specific stock abundance, and i, j, t are indexes for age, zone and time, respectively. Effort $E_{j,t}$ is assumed to be constant within a season t and zone j. M is age-specific natural mortality. s is a knife-edge selectivity parameter defined such that only fish $i \geq 2$ years of age are fully fishable ($s = 1$) and fish $i < 2$ are fully protected ($s = 0$). $\tau_{i,j,t}$ denotes the length of a fishing season, which ends when abundance at age i becomes zero or the maximum season length is reached:

$$\tau_{i,j,t} = \min \left[1, \frac{1}{M_i(1-\alpha_j)} \log \left(1 + \frac{M_i \theta_{j,t}^{\alpha_j} K_i^{\alpha_j} {N_{i,j,t}}^{1-\alpha_j}}{s_i h_i E_{j,t}} \right) \right] \tag{4}$$

NSSH in our model distributes in multiple EEZs and its spawning only occurs in one of the zones. In a new season, the total stock abundance is simply a sum of unharvested fish over all zones: $N_{i+1,t+1} = \sum_{j=1}^{j=3} N_{i+1,j,t+1}, i \in [0, 1, ..., 15]$. The abundance of newly spawned recruits follows the Beverton-Holt stock-recruitment model:

$$\begin{aligned} B_t^{SS} &= \sum_{i=0}^{16} O_i W_i^S N_{i,t}, \\ N_{0,t} &= \frac{\beta B_t^{SS}}{1 + \frac{B_t^{SS}}{\gamma}}, \end{aligned} \tag{5}$$

where B_t^{SS} is total spawning stock biomass at time t, O_i is maturity ogive (proportion of maturity individuals) at age i, W_i^S is the (stock) weight at age i, and $N_{0,t}$ is the total stock abundance at age 0. The respective values for parameter β and γ are: 78.4 1/kg and 3044.867 million kg, taken from Patterson (1998). Further, we assume that NSSH at age 2 years and younger do not spawn, only ages 6 or older are considered as fully mature ages.

The seasonal harvest is obtained through integrating instantaneous catch rate over the effective fishing season, $C = \int_0^{\tau_{i,j,t}} s\rho(t)Edt$. For specific values of stock elasticity α, explicit harvest functions can be derived (Steinshamn 2011):

$$C_{i,j,t} = \begin{cases} s_i h_i E_{j,t} \tau_{i,j,t} & \alpha = 0 \\ \frac{2 s_i h_i E_{j,t} \sqrt{N_{j,t}}}{M_i (\theta_{j,t} K_i)^{\alpha}} (1 - e^{-\frac{M_i \tau_{i,j,t}}{2}}) + (\frac{s_i h_i E_{j,t}}{M_i (\theta_{j,t} K_i)^{\alpha}})^2 (2 - 2e^{-\frac{M_i \tau_{i,j,t}}{2}} - M_i \tau_{i,j,t}) & \alpha = \frac{1}{2} \end{cases} \tag{6}$$

An important insight from the harvest equation is that when $\alpha = 0$, the marginal yield of effort is constant, independent of stock size, whereas when $\alpha = \frac{1}{2}$, the marginal yield of effort depends on instantaneous stock biomass in an EEZ (the lower the biomass level, the less catch a player can get from additional unit of effort). Further, marginal yield of effort reduces with increases of α.

2.4 Decision rule

The control variable in our decision model is reference fishing mortality F^{ref}. F^{ref} is zone-specific management target and we assume that it remains constant over the entire decision horizon (here 40 years). It is common in real fisheries management to express harvest policies in terms of a fixed target fishing mortality (Hilborn and Walters 1992).

We consider a NSSH management model with two decision layers. First, fishery managers in each country choose their policy, F_j^{ref}. Based on the chosen policies and the fishable stock abundance[2] in each zone, $N_{j,t}^{tot}$, the managers derive catch quota $C_{j,t}^{tot}$,

$$C_{j,t}^{tot} = (1 - e^{-F_j^{ref}}) N_{j,t}^{tot}, \tag{7}$$

which is season and zone-specific but age-unspecific. The fishermen in each country then collectively 'decide' the total effort $E_{j,t}$ which yields total catch that satisfies the quota for the season. We assume effort rate is constant within the season. Because the population's

[2]Total fishable stock abundance, $N_{j,t}^{tot}$, is a sum over all age classes with positive selectivity, i.e., $s_i > 0$

age structure is not fixed, total effort cannot be derived directly from the catch quota; instead, it is necessary to solve it iteratively from equation:

$$C_{j,t}^{tot} = \sum_i C_{i,j,t}(E_{j,t}). \tag{8}$$

Notice that we have assumed equality in the equation (8) above. This implies that fishermen are forced to fish, even if cash flow is negative in some years. We have made this assumption in order to avoid a situation in which a manager chooses an unsustainable F^{ref}, such that the stock is diminished early on and fishing ceases when it is no longer profitable. In other words, we force the fisheries managers to adopt a long-term perspective in their fishing policies.

Our formulation is different from typical fishery economic models where fishing effort is used as control variable (fishing effort is costly and easy to convert into a monetary value). However, sustainability of fishing is usually emphasized in fisheries management, and it is customary to express management targets in terms of maximum allowable fishing mortality. While the solutions we are aiming at are open-loop game equilibria—the control variables F_t^{ref} are constant over the decision horizon—the seasonal effort E_t will vary over the time with the biological stock. Allowing effort to be dynamic is important for the research question of our interest, emphasizing the effect of dynamic stock distribution.

Finally, our economic decision is a constrained optimization problem. The objective is to choose the reference fishing mortality so as to maximize net present value. For the grand coalition, the problem can be specified as follows:

$$\begin{aligned} NPV &= \max_{F_j^{ref}} \sum_j \sum_t \frac{\overbrace{p_0 \sum_{i=0}^{16} W_i^C C_{i,j,t}(E_{j,t}) - c_j E_{j,t} \tau_{j,t}^e}^{\text{Seasonal profit}}}{(1+r)^{t-1}} \\ &\quad \text{subject to eqs. (3), (5) and (8)} \end{aligned} \tag{9}$$

where $p_0 = 1.3$ NOK/kg, an exogenous price similar to the value used in earlier studies. W^C is age-specific catch weight, c is player/zone specific cost per unit effort, a constant, and $\tau_{j,t}^e = \max(\tau_{i,j,t})$ is the season length, determined by the age class that sustains fishing longest[3]. Equation (3) and (5) are biological production functions. Effort rate $E_{j,t}$ is derived by applying root finding technique in equation (6).

[3]Steinshamn (2011) assumed $\tau_{j,t}^e = \min(\tau_{i,j,t})$.

3 Partition function game and sharing rules

3.1 Game theoretic model

Three players in our coalition game are asymmetric. They are differentiated by stock ownership (θ), cost per unit effort (c), and stock elasticity (α), reflecting different local stock densities experienced by fishermen. In the paper, we interpret c in terms of economic efficiency: a low c value corresponds to high efficiency, or vice versa.

Our three-player's coalition game belongs to the class of partition function games (P-game) according to Thrall and Lucas (1963). P-game is based on assumption of transferable utility, or transferable side payments in a risk neutral world. A P-game can be split into two stages: a player chooses a membership in the first stage and a respective action in the second stage. The optimal actions are computed in backward order. We assume a simultaneous move "open-membership" game (Yi and Shin 2000), where a player is free to join or leave a coalition. Different coalitions adopt Nash strategies in a competitive game. The optimal coalition structure is self-enforcing.

We compute optimal solutions for each player under all possible coalition strategies numerically using a gradient ascent algorithm. Gradient ascent in a single player maximization is a standard first-order optimization algorithm: given an initial search point, step size, and tolerance, the search path follows the steepest ascent to a maximum after a finite number of iterations. The exact procedure followed here depends on the coalition structure. In the singleton case where all players maximize their own NPV (subject to the other players' strategies), the gradient ascent is in a player's own NPV, with step sizes being proportional to the gradients of each player. For partial coalitions, for example when players 2 and 3 are in the same coalition and player 1 remains singleton, the optimal policy is found with simultaneous gradient ascent in player 2 and 3's joint NPV, and in the single-player's NPV function of player 1. For grand coalition, the gradient ascent is in joint NPV function of all players. We overcome the problem local maxima by considering several initial conditions. Method of simultaneous gradient ascent is commonly used in evolutionary game theory (Brown and Vincent 1987, Dieckmann and Law 1996).

3.2 Stability conditions

Prior to definition of coalition stability, we first introduce some basic notation. Our coalition game consists of a set of all players $\mathcal{N} = \{1, ..., n\}$ with $n = 3$. A coalition S is a subset of $\mathcal{N}$, a partition P is a set of disjoint coalitions which covers the whole set of players, and $\mathcal{P}$ is a set of all partitions, i.e. $S \subseteq \mathcal{N}$, $S \in P, P \in \mathcal{P}$. A coalition S being a part of a partition P is called an embedded coalition and denoted by $(S; P)$. For convenience, we define $S_{-j} \stackrel{\text{def}}{=} S \backslash \{j\}$, similarly, $P_{-S} \stackrel{\text{def}}{=} P \backslash \{S\}$.

We distinguish two functions in a partition function game: partition function π, which associates a real number to every embedded coalition, e.g., $\pi(S; P)$ denotes the aggregate payoff of coalition S whose value also depends on how the rest of the players are organized; valuation function v, which specifies how the above aggregate payoff distributed among members of the same coalition. For $\forall j \in S$, $v_j(S; P)$ denotes share of coalition payoffs j receives that depends on which sharing rule we deploy. The two functions satisfy following relationship: $\sum_{j \in S} v_j(S; P) = \pi(S; P)$, and $v_j(S; P) = \pi(S; P)$ if S is a singleton.

Following D'Aspremont et al. (1983), we define stability conditions in forms of partition function and valuation function. A coalition S is considered stable with respect to valuation function v if and only if:

$$\text{internal stability (IS)}: \quad v_j(S; P) \geq v_j(j; \{j \cup S_{-j} \cup P_{-S}\}), \forall j \in S, \tag{10}$$

$$\text{external stability (ES)}: \quad v_{j'}(j'; \{j' \cup S \cup P_{-(S+j')}\}) \geq v_{j'}(S_{+j'}; P), \forall j' \notin S. \tag{11}$$

That is, a coalition S is stable if no insider is interested in leaving the coalition to form a singleton coalition, nor any outsider wants to join the coalition.

Eyckmans and Finus (2004) define a stability condition termed potential internal stability (PIS) that only links to partition function. Formally, a coalition is considered PIS if and only if:

$$\pi(S; P) \geq \sum_{j \in S} \pi(j; \{j \cup S_{-j} \cup P_{-S}\}). \tag{12}$$

That is, a coalition is PIS if the aggregated payoff to the coalition is no less than the sum of free-rider payoffs of its members. It is easy to see that PIS is simply the sum of IS condition in (10) over all $j \in S$. PIS is a necessary condition, but not sufficient condition for IS to hold. If PIS holds for a coalition, it implies there exist some sharing rules which make the coalition internally stable (Pintasilgo et al. 2010). For grand coalition, PIS alone is sufficient to determine whether or not a grand coalition stable, since there is no

player, or only empty set, outside the grand coalition, ES is always satisfied; if PIS does not hold for grand coalition, meaning grand coalition cannot be stable, then a player j has to stay outside N_{-j} coalition, the ES condition for N_{-j} is met automatically. By checking against PIS condition, we can tell whether coalition N_{-j} is potentially stable. Note we do not need to introduce any sharing rule in order to discuss the stability of the grand coalition or a partial coalition.

Two forces shape the stability of a coalition: positive externality and superadditivity. The former implies the remaining player gains from her fellows forming coalition. Thus, positive externality encourages to deviate from a large coalition. In contrast, superadditivity implies the aggregated payoffs of all players involving in forming larger coalition increases (Eyckmans and Finus 2004). Positive externality gives incentive to deviate, and super-additivity increases incentive to merge, the stability of a coalition then depends on the relative force of the two.

3.3 Sharing rules

Sharing rules closely link to the valuation function. We consider two different sharing rules in this paper: "externality-free" Shapley value that is generalized for partition function game (Pham Do and Nordes 2007; De Clippel and Serrano 2008); the other one termed "almost ideal sharing scheme" by Eyckmans and Finus (2004).

The classic Shapley value (Shapley 1953) assumes that players in game enter coalition one by one in a random order and that the player receives her share of benefits that is an average of the sum of all her marginal contributions resulting from different orders of arrival. Note that classic Shapley value is associated with characteristic function where a coalition payoff is independent of how the rest of players in game are organized (Greenberg 1994). In the literature extending the Shapley value for partition function games, an important contribution is the "average approach" (Macho-Stadler et al. 2008). In line with classic Shapley value, this approach allocates the benefits based on player's marginal contributions. Since the payoff by coalition S also depends on how coalition strategy of other players in a partition P, and P that contains S is not unique. Macho-Stadler et al. proposed to take a weighted average of the payoffs generated by all possible partitions where S embedded.

A drawback is that the "average approach" does not produce a unique solution, due

to unspecified weight parameter. Pham Do and Nordes (2007) took an extreme stand and gave full weight to a partition where players outside of coalition S remain singletons. De Clippel and Serrano (2008) justify this treatment by proposing a two-step process: in the first step, player j leaves the coalition S and remains alone; in the second step, j joins coalition from P_{-S}. They argue that only the first step is the intrinsic marginal contribution, and the externality which arises from merging coalition in the second step is an external effect, hence should not be captured. Using this "externality-free" Shapley value (hereafter termed as Shapley value) as the main solution concept, we can specify the sharing rule of our three-player's partition function game as follows:

$$\begin{aligned}\varphi_{j=x}^{Shap} &= \frac{\pi(x;\{x,y,z\})}{3} + \frac{\pi(xy;\{xy,z\}) - \pi(y;\{x,y,z\})}{6} \\ &+ \frac{\pi(xz;\{xz,y\}) - \pi(z;\{x,y,z\})}{6} + \frac{\pi(xyz;\{xyz\}) - \pi(yz;\{yz,x\})}{3} \end{aligned} \quad (13)$$

where x, y and z are the players.

The other sharing rule, "almost ideal sharing scheme" (AISS), ascertains that players in coalition at least receive their free-riding payoff, formally: ${\varphi_j}^{AISS} = v_j(j;\{j \cup S_{-j} \cup P_{-S}\}) + \lambda_j(S)\Delta(S)$ where λ_j is a weight parameter. This can only be achieved if the surplus $\Delta(S)$ is non-negative (coalition payoff less the sum of free-rider payoffs), or $\Delta(S) \stackrel{\text{def}}{=} \pi_{j\in S}(S;P) - \sum_{j\in S} v_j(j;\{j \cup S_{-i} \cup P_{-S}\})$ is non-negative. Because the weight parameter, λ_j, can be any value between 0 and 1, AISS does not give a unique solution. Hence, we follow Kronbak and Lindroos' definition (2007) and let the surplus be evenly distributed among players after each of them have secured their free-rider payoffs (i.e., let $\lambda_j = \frac{1}{3}$ for all players).

4 Results

We first study the stability of grand coalition regarding the degree of asymmetry among players. Then we investigate the benefit distribution and the associated system dynamics in cases when the grand coalition is stable and players are heterogeneous. In the sensitivity analysis, we test how Shapley values respond to the initial stock size and critical biomass levels. This gives insights to two interesting questions, whether Norway shall receive as many benefit shares as her stock ownership would suggest, and whether Norway shall use her strategic advantage to keep the stock so low that she becomes the sole owner?

Table 1: Heterogeneity and grand coalition stability: $r = 5\%, p_0 = 1.3\text{NOK}/kg, B_0^{SS} = 5.58Mt$, $j \in \{\text{Nor}, \text{Rus}, \text{IFE}\}$. Stability criteria: + PIS/ES are satisfied, − not satisfied.

a) Example 1:	$\alpha_j = [0,0,0], c_j = [2,2,2]$ NOK/e.							
	$F^{ref}(yr^{-1})$			NPV (10^9 NOK)			Stability	
Coalition	Nor	Rus	IFE	Nor	Rus	IFE	PIS	ES
Singleton	0.115	0.253	0.173	4.81	2.50	3.08	+	+
{Nor Rus, IFE}	0.095	0.095	0.225	5.34	1.77	5.24	–	+
{Nor IFE, Rus}	0.085	0.282	0.096	5.39	4.38	3.09	+	+
{Nor, Rus IFE}	0.126	0.134	0.134	6.56	2.27	3.51	+	+
Grand (**unstable**)	0.083	0.084	0.084	7.66	2.64	4.07	–	+
b) Example 2:	$\alpha_j = [0,0,0], c_j = [2,2.8,2.4]$ NOK/e.							
Singleton	0.124	0.113	0.137	6.79	0.86	2.60	+	+
{Nor Rus, IFE}	0.139	0	0.151	8.49	0	3.44	+	–
{Nor IFE, Rus}	0.135	0.164	0.005	9.77	2.02	0.22	+	–
{Nor, Rus IFE}	0.139	0.011	0.147	8.34	0.17	3.30	+	–
Grand (**stable**)	0.152	0	0.011	13.43	0	0.58	+	+

4.1 Cost asymmetry and stability of the grand coalition

In this section, we exam the role of asymmetry in shaping the stability of the grand coalition—in the sense of potential internal stability (PIS). Recall that players exhibit asymmetry in three dimensions: stock ownership, cost per unit effort and stock elasticity. To begin with, we study the case in which players are only differentiated by their stock ownership, represented by the point (1,1) in Figure 1 where all three players have same cost per unit effort $c = 2.0$ and their harvest costs are all independent of stock size ($\alpha = 0$). Note that the ownership is dynamic, but Norway always owns the largest stock share, followed by IFE countries, and then Russia. The minimum stock Norway owns is 54%, and maximum stock IFE and Russia own are respectively 28% and 18%.

Table 1a summarizes the results for the example of heterogeneous stock ownership: in a singleton game, the largest stock owner Norway applies the lowest harvest rate of $F^{ref} = 0.115$, and the smallest stock owner, Russia, is the heaviest harvester with $F^{ref} = 0.253$. This reiterates a familiar phenomenon, namely that in competitive games

the major owner has more conservation incentive than the minor owner(s), a result often seen in fishery games (e.g., Hannesson 2007). Another feature is that players in the same coalition adopt similar harvest policies, mostly due to the same cost per unit effort we have assumed. Notice that the most aggressive harvest policy a player adopts is not in a fully competitive singleton game, but when she is playing against a two-player coalition. This free-riding proves the game in this example is a game of positive externality. We can further verify that the game is also superadditive since free-rider joining to grand coalition does not reduce the aggregated payoff of the merging player. Because grand coalition does not satisfy PIS (Table 1a), this implies that the effect of positive externality exceeds the superadditive effect. Intuition is as follows: when players are in a coalition, they harvest more responsibly than they would do in non-cooperative game; this creates positive externalities in form of more stock spill-over to the zone of the free-rider in the following period. If the free-rider is also a minor owner, she gains more from positive stock spill-over because the proportion of total stock migrates into her zone may also increase. According to equation (8), this means the free-rider can raise her catch quota and catch more fish. When $\alpha = 0$, the seasonal profit is proportional to the catch. The positive externalities are then fully monetized.

In the next case, we allow heterogeneity both in stock ownership and cost per unit effort c, keeping everything else unchanged. Table 1b is an example of this case where we assume Norway be the most efficient(lowest c) and Russia be the least efficient(highest c). One important contrast to the previous example is that the most efficient player is now also the dominant player in any non-trivial coalition. Whenever Russia is in the same coalition as Norway, it becomes optimal for her not to engage in harvest. We notice the grand coalition becomes stable in this example. This suggests that asymmetric costs make joining grand coalition more beneficial than being a free-rider, at least in this particular example. To test whether the result also holds in a more general setting, we fix cost per unit effort for Norway at $c = 2$ and run the model with different combination of c for the other two players. The results (Figure 1) show that when $\alpha = 0$ in all zones, grand coalition is unstable in a roughly circular area centered around point (1,1), which corresponds to homogeneous players in terms of cost per unit effort. The further a point deviates from (1,1), the more likely the grand coalition becomes stable. This proves our hypothesis that the degree of cost asymmetry improves the stability of the grand coalition. Our interpretation is that in the presence of heterogeneous cost, harvest decision can be

made in a more cost-effective way, resulting in increased payoff to the grand coalition. On the other hand, a higher c means less profit from a given catch, hence inefficient players will have less incentive to free ride.

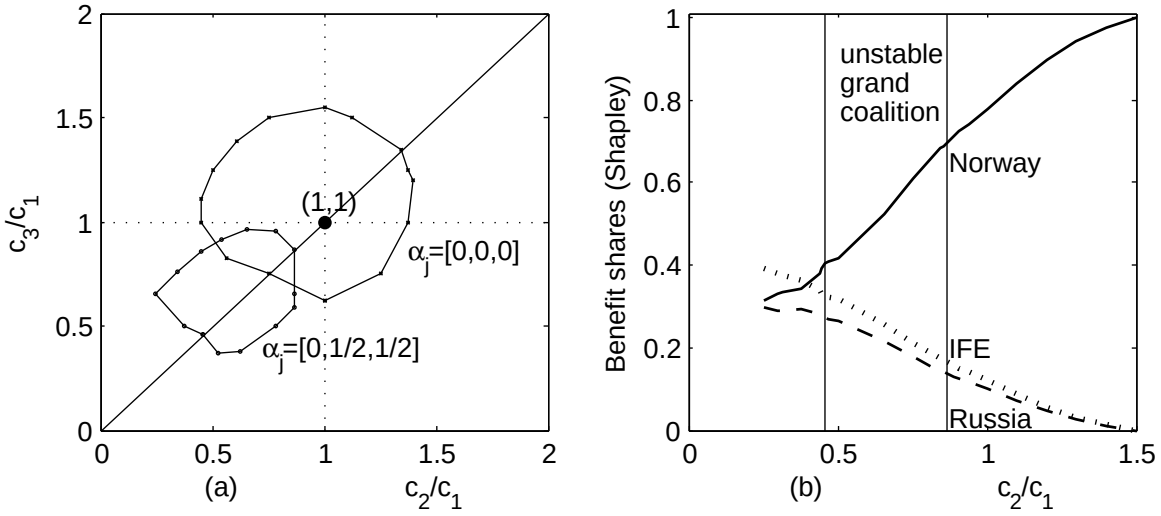

Figure 1: Influence of asymmetries on stability of the grand coalition. c_2/c_1 is the ratio of cost of unit effort between Russia and Norway, and c_3/c_1 cost ratio between IFE and Norway. (a) Boundary of stable grand coalitions: a grand coalition is unstable inside the circular area but stable outside. (b) Change in benefit allocation by moving along the 45° diagonal on plot (a), for $\alpha = [0, \frac{1}{2}, \frac{1}{2}]$ only. We assume $c_1 = 2.0$, $B_0^{SS} = 5.86Mt$ in both panels.

The aforementioned result still holds if we add the third dimension of asymmetry, asymmetry in stock elasticity α. In this case, we set parameter $\alpha = \frac{1}{2}$ both for Russia and IFE countries, and keep $\alpha = 0$ for Norway. Comparing with the case with homogeneous α's, we observe that the area of unstable grand coalition tends to shrink and the instability occurs in the area where both minor players have higher efficiency level, see Figure 1a marked as $\alpha = [0, \frac{1}{2}, \frac{1}{2}]$. This result is intuitive: when α increases from 0 to $\frac{1}{2}$ for Russia and IFE countries, harvest costs become stock-dependent and more effort is needed to catch same amount of fish, and the more so the smaller the stock becomes. Two strategies may apply to avert this situation: a) manager to revise down fishing mortality to balance free-rider's loss due to increased effort expenses. One consequence is that the free-rider cannot or can only partially enjoy the aforementioned positive stock spill-over in her zone; b) fisherman to make unit effort cheaper, that is to overcome disadvantage of fishing in a

low density stock by improving economic efficiency(a low c). By this way, the free-riding incentive can still remain. Therefore, we observe that unstable grand coalition coincides with the area in which Norway is the least efficient player (highest c).

If the grand coalition were not stable as the example showed in Table 1a, which coalition will become the equilibrium coalition structure? Since the singleton is stable by definition, hence it is always an equilibrium structure (Pintassilgo etal. 2010). Our simulations show that singleton cannot be the optimal coalition structure, because Pareto efficiency cannot be satisfied. Among three partial coalitions, some or all of them can be the optimal coalition structures, depending on the model configuration. For the example shown in Table 1, partial coalition formed by Norway and IFE is unstable, because PIS condition cannot be satisfied, meaning Norway and Russia are worse off from forming a coalition. The situation for other two partial coalitions is the opposite, hence both of them can be the optimal coalition.

4.2 Sharing benefits

We will now focus on cases when the grand coalition is stable. We are particularly interested in benefit allocation when Norway's unique position and inherent advantage are fully realized. Table 2 provides a such example where Norway, in addition to being the largest stock owner, is the only player whose harvest costs are independent of stock size, that is $\alpha = 0$ for Norway and $\alpha = \frac{1}{2}$ for the other two players. But the two minor players can compensate for their disadvantage by reducing their cost of fishing, namely cost per unit effort c. The respective benefits shares received by Norway, IFE and Russia are 38%, 34% and 28% according to Shapley value, and 37%, 30% and 33% according to the Almost Ideal Sharing Scheme (AISS) with equal weights. The result suggests that, in this particular example, none of the two benefit sharing rules can give Norway an allocation of shares in excess of or in proportion to her shares of stock ownership which is $\geq 54\%$ of the total stock.

Figure 2 illustrates the model dynamics associated with the example in Table 2. Since sharing benefits among the grand coalition members is also depends on the partition functions of other coalition structures, it is helpful to compare dynamics of different embedded coalitions. As expected, the grand coalition leads to the highest spawning stock biomass (SSB) and singleton the lowest (Figure 2a). For any coalition, its total SSB

Table 2: Benefits allocation: $\alpha_j = [0, \frac{1}{2}, \frac{1}{2}]$, $c_j = [2, 0.875, 0.875]$ NOK/e, $j \in \{\text{Nor}, \text{Rus}, \text{IFE}\}$. $r = 5\%$, $p_0 = 1.3$ NOK/kg, $B_0^{SS} = 5.58Mt$.

Coalition	$F^{ref}(yr^{-1})$			NPV (10^9 NOK)		
structure	Nor	Rus	IFE	Nor	Rus	IFE
Singleton	0.143	0.318	0.233	5.21	2.67	3.39
{Nor Rus, IFE}	0.077	0.378	0.285	3.94	4.31	5.66
{Nor IFE, Rus}	0.048	0.409	0.318	2.85	4.95	6.70
{Nor, Rus IFE}	0.127	0.173	0.173	6.28	3.31	5.13
Grand (**stable**)	0.008	0.221	0.221	0.87	6.83	10.59
Sharing rule	Benefit (10^9 NOK)			Benefit share (%)		
Shapley	6.98	5.15	6.16	38%	28%	34%
AISS	6.75	5.41	6.13	37%	30%	33%

converges to an equilibrium state after some fluctuations. Our model is deterministic and this volatility is due to the age structure that makes equilibration of the biological model slow.

We observed two features during the stock transition: first, the total SSB levels are among the lowest in the transition years, but the total abundance of the fishable stock still increases due to some transient effects (not shown in the figure); second, Norway has higher stock shares due to lower total SSB levels, except the grand coalition case in which stock distribution is uniform in time for each player (Figure 2c). These features, together with assumption of heterogeneity in stock elasticity, i.e. $\alpha_j = [0, \frac{1}{2}, \frac{1}{2}]$, enable Norway to earn extra Shapley dividends during the two stock 'dips'. Because Norway has higher fishable stock in her zone due to simultaneous increases of stock shares and total fishable stock, Norway thus has her seasonal yields and profits increased in the initial transition years. The two minor players, however, face double "belows": on one hand, both of them have to reduce their yields due to lower fishable stock in their zones and that brings in less income; on the other hand, the marginal effort of yield increases with the decreases of fishable stock in their zones, resulting in higher costs. A lower cost per unit effort can help the two minor owners to reduce costs but does no help to improve their incomes. Seasonal effort dynamics (Figure 2b) follow the development of yields described

above. For the two minor owners, they also adjust efforts against stock size in their zones. As stock stabilizes, the difference in player's seasonal Shapley values also becomes stable (Figure 2d).

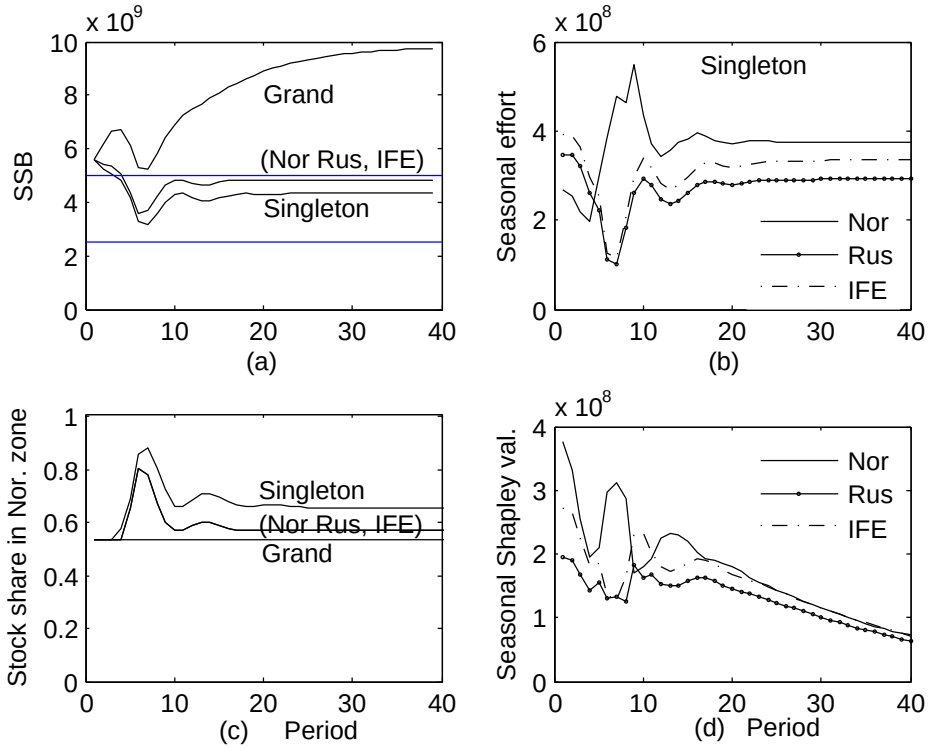

Figure 2: Model dynamics in terms of (a) spawning stock biomass, (b) fishing effort, (c) proportion of the stock in Norwegian zone, and (d) seasonal Shapley value. Two horizontal lines in (a) indicate two critical biomass levels; seasonal Shapley value in (d) is after discounting. Parameter values: $\alpha_j = [0, \frac{1}{2}, \frac{1}{2}]$, $c_j = [2, 0.875, 0.875]$, $j \in \{\text{Nor}, \text{Rus}, \text{IFE}\}$; $B_0^{SS} = 5.58Mt$.

We will further investigate to what extent a lower cost per unit effort can help the two minor players to offset their costs in face of inherent disadvantages. Figure 1b illustrates how the benefit shares received by each country vary with the ratio c_2/c_1, assuming IFE and Russia has the same cost per unit effort, i.e., $c_2 = c_3$. It shows that the benefit shares for Norway, using Shapley value, sway from approximately 31% to 100%, depending on her relative efficiency level in terms of c. If Norway's efficiency level were far below that of her competitors' (e.g., $c_2/c_1 \lessapprox 0.4$), her shares can even go below what IFE countries, the second largest owner, obtain. The finding confirms that neither the largest stock ownership, nor the inherently high fish density in Norwegian zone, can guarantee Norway

to receive the largest share of grand cooperation benefits. However, IFE countries always receive a higher benefit share than Russia. This proves that the size of stock ownership can finally take the lead if everything else is the same. But this result is not robust to the alternative sharing rule, AISS.

4.3 Sensitivity

We choose to focus sensitivity test on three key parameters: the initial stock biomass, the low critical biomass level and the discount rate.

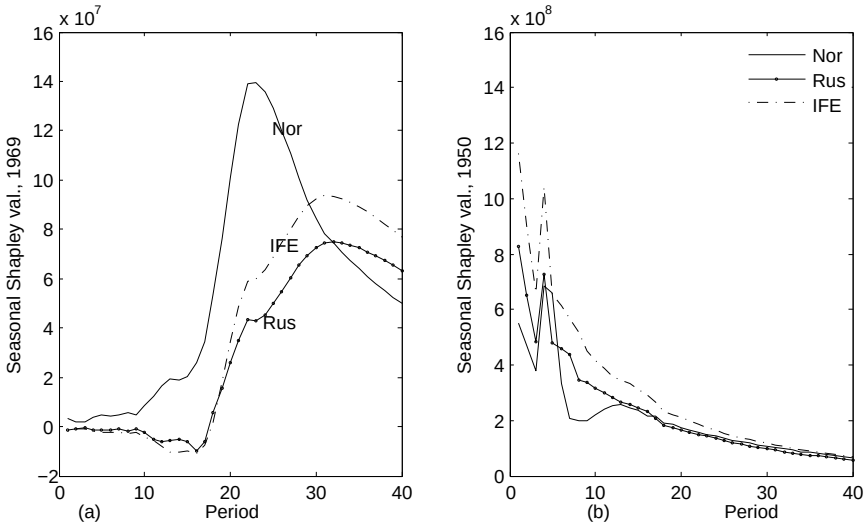

Figure 3: Effect of initial stock biomass on the seasonal Shapley values, assume $\alpha_j = [0, \frac{1}{2}, \frac{1}{2}]$, $c_j = [2.0, 0.875, 0.875]$, $j \in \{\text{Nor}, \text{Rus}, \text{IFE}\}$. (a) Low initial biomass: $B_0^{SS} = 86Kt, \varphi_j^{Shap} = [44\%, 25\%, 31\%]$; (b) High initial biomass: $B_0^{SS} = 16.6Mt$, $\varphi_j^{Shap} = [28\%, 31\%, 41\%]$.

So far, all results are based on assumption that the initial stock ($B_0^{SS} = 5.58Mt$) is slightly above the high critical biomass level ($B_{high}^{SS} = 5.0Mt$). Due to discounting of future payoffs, initial state is expected to matter for our results. Indeed, we find that a low initial stock leads to higher benefit shares for Norway, while a high initial stock has an opposite effect. The reason is three-fold: first, when stock is sufficiently small, it takes time for the stock to recover and the period during which Norway controls the stock is prolonged; second, it is more costly for IFE and Russia to harvest a small stock due to lower fish density they experience in their zones; third, as stock recovers to certain critical level over which the player is no longer constrained by the local density, her

fishing income increases with the decreases of harvest costs due to more fishable stock in her zone. Figure 3 is a support of this reasoning, based on examples of two extreme years: in year 1969 when the initial stock is extremely low ($B_0^{SS} = 0.086Mt$), Norway's seasonal Shapley value surpasses her competitors' with a great margin until the stock recovers. As a result, Norway earns as much as 44% of the total benefits; in year 1950 when initial stock is extremely high ($B_0^{SS} = 16.6Mt$), Norway who is the least efficient(highest c) player receives less than a third of the total benefits.

Is it in the interest of Norway to keep total stock so low that she becomes the sole owner of the herring fishery? Norway is in the unique position in our model to achieve this. To investigate this question, we vary B_{low}^{SS}, the low critical biomass level, from $0.3Mt$ to $4.0Mt$ and compute singleton solutions for the representative case from Table 2 in section 4.2. The high critical level is kept unchanged. We find that, in a fully competitive game, the stock biomass in the terminal year (B_{40}) is always above the low critical biomass level[4] (B_{low}^{SS}), see Figure 4a. However, we do see tendency that B_{40} approaches B_{low}^{SS} as the latter increases. Along the way, Norway increases the reference fishing mortality, but other two countries harvest less (Figure 4b). Our results suggest that when B_{low}^{SS} is low, the opportunity cost is too high for Norway to push down the stock all the way to the bottom in order to maintain her sole ownership. As a major owner with costs independent of stock-size ($\alpha = 0$), Norway is primarily interested in a relatively large, productive stock. Whether the fish will spill over to other zones is immaterial; when B_{low}^{SS} is high, Norway has better control over the stock, because the sole ownership can be achieved now without depressing the stock too much. Norway thus increases her harvest. If her competitors would follow suit, they risk of loosing the stock. It can be seen here that a high B_{low}^{SS} can act as a threaten point for minor players. The described strategic interactions among the players push the stock away from the low critical level.

5 Discussion and Conclusions

In this paper we have studied cooperation outcomes in the presence of dynamic stock distribution, using NSSH fishery as a case study. In some important ways, our model is more realistic than earlier game-theoretic harvesting models. Catch function in our model is density-dependent, reflecting variable stock density in each zone that fishermen

[4]During the stock transition years, the total biomass can fall below B_{low}^{SS}.

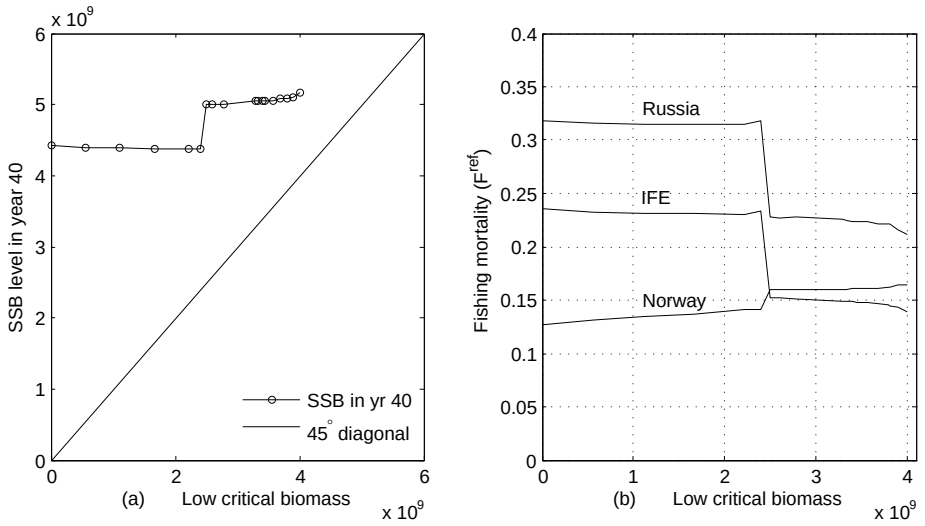

Figure 4: Effect of low critical biomass on stock biomass and fishing mortality, $\alpha_j = [0, \frac{1}{2}, \frac{1}{2}]$, $c_j = [2.0, 0.875, 0.875]$, $j \in \{\text{Nor}, \text{Rus}, \text{IFE}\}$. $B_{high}^{SS} = 5Mt$, $B_0^{SS} = 5.58Mt$.

often experienced in practice, and allowing for unit costs of harvesting to depend on stock size. Furthermore, we use a reference fishing mortality as the control parameter that determines annual catch quotas, a practice that is common in real fishery management, rather than control fishing effort. Treating fishing mortality as the control variable makes fishing effort a dynamic variable that reflects changes in stock biomass.

We find that the likelihood of a stable grand coalition is positively correlated with the degree of asymmetry in player's cost per unit effort. The finding that 'asymmetry strengthens stability' has also been reported in recent literature on international environmental (McGinty 2007, Fuentes-Albero and Rubio 2010) and fishery agreements (Pintassilgo et al 2010). Indeed, increased asymmetry in harvesting costs enables a coalition to exploit the resource in a more cost-effective way: the most efficient (the lowest c) player in a coalition becomes the dominant exploiter of the coalition, and the least efficient (highest c) player is compensated by receiving side-payment from the more efficient one(s). From a single player perspective, an increase in c or α reduces her free-riding incentive due to rising harvest costs, hence the player is more inclined to join a coalition. When a grand coalition is not stable, a partial coalition always stands out as the optimal set-up, a singleton is an equilibrium strategy but not optimal because it always brings players worse outcomes.

In case of stable grand coalitions, their "externality-free" Shapley values, a rule to

divide cooperative benefits for partition function games, respond drastically to players' efficiency levels. It is not unexpected that a player's potential benefits of cooperation increase with her relative efficiency. We show that if Norway were the least efficient player, it may happen that IFE countries (Iceland, Faroe Islands and EU) and Russia would receive higher benefit shares than Norway. This finding is somewhat surprising because Norway has a unique position in our model: first, she has a share of at least 54% of the stock (whatever distribution pattern prevails); second, the stock density in her zone is inherently much higher than elsewhere. In 2003, the international agreement for managing NSSH was suspended when Norway, based on the high affinity of NSSH to the Norwegian EEZ, was requesting a higher quota than what the existing agreement gave her (60%). However, our finding suggests that the high Norwegian 'ownership' cannot secure her quota shares in excess of what stock distribution would suggest. Neither does it guarantee that the economic benefits are shared in proportion to stock ownership. In 2007, Norway returned the NSSH agreement without an increased quota share. This may be nothing more than a coincidence, but our model does show that the geographical advantage of Norway might be offset by high cost of harvesting. Notice that in the model, cost of harvesting only comes from cost per unit effort; in reality costs will also include fixed labour costs, capital costs, etc.

The Shapley values are also sensitive to the initial stock state: a low initial stock level brings greater benefit shares to Norway, and a high initial stock does the opposite. A problematic effect can arise from a high stock: we found cases where a stable grand coalition breaks down after the initial stock becomes sufficiently high. Similar observation has been made by Hannesson (2006) who found that improved ocean condition (in terms of higher environmental carrying capacity) can put full cooperation under strain. Indeed, when stock is abundant, cooperation becomes less necessary for minor players, and a more lucrative deal would probably have to be offered in order to ensure participation. Under certain circumstances, full cooperation cannot generate sufficient payoffs to satisfy all parties.

We find that it is not in the interest of Norway to push down the equilibrium stock to the biomass level B_{low}^{SS}, under which she becomes a sole owner. This result is robust against change of B_{low}^{SS}. Earlier herring studies presented mixed findings. Bjørndal et al. (2004) showed non-migratory strategy is not attractive for Norway because 'open access with closures' gives better outcomes. Their result is based on one particular biomass level,

i.e. $B_{low}^{SS} = 500$ kt. We confirm that the result can also hold for other values, namely any value in the range of 300 kt–4 Mt. Hannesson (2006) indicated it can be optimal for Norway to keep stock at the B_{low}^{SS} level if its level is high enough. However, he derived optimal stock based on assumption both pla is ignored and the goal is to maximize rent per year. In other words, fishing down the current stock has no economic consequence. The goal in our model is to maximize net present values, and a high harvest rate in current period will spoil future payoffs. Even though we found it is not optimal to keep the equilibrium stock below the assumed low critical level, stock in transition years indeed can sometimes go below it (typically between years 6–9), and the higher is the B_{low}^{SS} level, the longer duration in which the transition stock tends to stay.

Our model has provided new insights into management of a dynamic resource. Nevertheless, there are still many areas that can be looked into in future research. Our current model is deterministic, whereas a key feature of Norwegian spring-spawning herring is the highly variable, uncertain recruitment; Lindroos (2004) have already shown that biological uncertainty can reduce stability of full cooperation in herring. The management regime in our model is quite rigid, and allowing for more flexibility may provide more insights from real fishery management perspective. For example, one could allow players to fish both in their own exclusive economic zones and the high seas, and to stop fishing when it is not profitable.

A Appendix

Table A1: Stock share in representative years.

	Stock shares (%)			
Country	1950	1959	1972	1983
Norway	33.0	39.7	100	88.3
Russia	24.7	21.8	0	8.0
IFE	42.3	38.5	0	3.7

Table A2: Age-specific parameters

Age class	Selectivity s	Natural mortality M (yr^{-1})	Maturity ogive O	Individual weight in the stock W^S (kg)	Individual weight in the catch W^C (kg)
0	0	0.9	0	0.001	0.007
1	0	0.9	0	0.0135	0.0548
2	0	0.9	0	0.025	0.1085
3	1	0.15	0.005	0.0745	0.159
4	1	0.15	0.155	0.152	0.2105
5	1	0.15	0.7125	0.2343	0.2508
6	1	0.15	1	0.2995	0.2955
7	1	0.15	1	0.3468	0.3237
8	1	0.15	1	0.3598	0.352
9	1	0.15	1	0.3825	0.3668
10	1	0.15	1	0.3875	0.376
11	1	0.15	1	0.4017	0.3718
12	1	0.15	1	0.4037	0.386
13	1	0.15	1	0.3945	0.39
14	1	0.15	1	0.4053	0.395
15	1	0.15	1	0.4033	0.3967
16	1	0.15	1	0.4138	0.3975

Table A3: Notational summary and age-unspecific parameters. 'e' denotes the unit of fishing effort.

Subscripts	definition	Subscripts	definition
i	age	1	Norway
j	country/player	2	Russia
t	time	3	IFE
Variables	**definition**		**unit**
N	abundance		
N^{tot}	total fishable abundance		
B^{SS}	spawning stock biomass		Mt
C^{tot}	catch target		
C	catch		
E	effort rate		e
F^{ref}	reference fishing mortality		yr^{-1}
ρ	local density		
τ	critical season length		yr
τ^e	effective season length		yr
π	partition function		NOK
v	valuation function		NOK
θ	proportional stock share		
NPV	net present value		NOK
Parameters	**definition**	**value**	**unit**
α	stock elasticity	0, $\frac{1}{2}$	
p_0	price	1.3	NOK/kg
c	cost per unit effort		NOK/e
r	discount rate	5%	
h	density parameter	1	
β	recruitment parameter	78.4	1/kg
γ	recruitment parameter	3045	mill kg

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