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Innovative Applications of O.R.

On shared use of renewable stocks

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ABSTRACT

Considered here is multi-party exploitation of common property, renewable resources. The parties play various dynamic games differing in degree of cooperation and commitment. Comparisons of steady states clarify issues on collective choice and individual welfare.

Motivation stems from shared use of fish stocks which straddle the high seas between and in exclusive zones. An important instance, observed in the North-East Atlantic, is the object of computation and discussion. Not surprisingly, full cooperation yields efficiency but strategic instability. By contrast, fully noncooperative play comes out glaringly inefficient but stable. Interestingly, on middle ground, suitable quota transfers may substitute for side payments and, to tolerable measure, bring both efficiency and stability.

1. Introduction

Challenges as to governing the commons are ubiquitous (Gordon, 1954; Ostrom, 1990). Many pressing instances turn on shared use of renewable resources - including the environment - for which property rights are neither well established nor local (Johannesen & Skonhoft, 2009). Considered here are natural stocks, coupled in dynamics and exploited by several parties. Motivation comes from important, multi-nation fisheries in the North-East Atlantic – all of common but conflicting interests.

That particular setting – alongside other instances which can be accommodated here – fits the frames of discounted, dynamic games. Reasonably suppose that play unfolds in discrete time with no end. What sort of behaviors, strategies and games ought then be singled out? Instead of making any specific selection, we consider *several* modes of play - each with a related solution concept. We ask: How might diverse game instances be compared? Can they be ranked somehow, thereby offering views on possible improvements of welfare? Motivated by our important real case, we also ask: Can some regime be implemented so as to Pareto dominate each of the inefficient games?

Upon addressing these questions, we cannot preclude cooperation among players – full or partial.[1] In addition, it complicates matters that agents might be strategists in each period *and* over time. Here, however, for simplicity, suppose interaction operates merely over time, via the system dynamics. Also for simplicity, let data and dynamics be deterministic – and regard the overall structure as stationary. Important issues on contracts, legal disputes, institutions and governance are not addressed (Ostrom, 1990).[2] Center stage is rather taken by analysis, computations and solution concepts.[3]

Besides operations research (Arnason, 2009; Bjørndal, Herrero, Newman, Romero, & Weintraub, 2012; Bjørndal, Lane, & Weintraub, 2004; Lane, 1989; Ni & Sandal, 2019), the study relates to *resource economics* (Hanley, Shogren, & White, 2007), *ecology* (Huse et al., 2012; Jennings, Kaiser, & Reynolds, 2001), and *game theory* (Finus & Rundshagen, 2015; Kaitala, 1986; Mesterton-Gibbons, 1993; Osborne & Rubinstein, 1994). For tractable *economics* let all players be price-takers in separate factor and product markets.[4] For tractable

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[1] Regarding incentives for cooperation, we will not straightjacket any player. Each should be allowed to choose freely whether to cooperate or "free-ride."

[2] The paper adds though to the literature on multi-national fisheries agreements, and it links thereby to treaties on environmental protection (Finus & Rundshagen, 2015).

[3] Even within so narrow optics, queries remains as to the stability, uniqueness and viability of various arrangements or outcomes. These fall outside the scope of this study.

[4] This is relaxed in the sensitivity analysis.

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ecology, we posit that population dynamics be logistic but coupled.[5]

Regrettably, *game theory* seldom offers easy escapes from complexity in agents' behavior - whether cooperative or not (Osborne & Rubinstein, 1994). Here, either mode of play is permitted.[6] Further, in noncooperative settings, players differ in degrees of commitments. On that account, two extreme instances come straight to the fore. One, called *open-loop,* relies on full commitments - this making computation "easy" but equilibrium (subgame) imperfect. The opposite extreme, called *closed-loop*, avoids commitments all together - this making computation "hard" but equilibrium perfect (Basar & Olsder, 1982). Between these polar instances, we shall also accommodate intermediate games, marked by partial cooperation.

To no surprise, full cooperation is marvelously efficient. Moreover, granted convexity in dynamics and preferences, solutions are computed by single agent programming. However, absent suitable side payments, the attending recommendations are difficult to implement. By contrast, closed-loop, non-cooperative play is often grossly inefficient – and harder to compute - but rather easily implemented by the players themselves.

Links extend to several strands of literature. So, the study addresses diverse readers. Included are operation researchers, resource economists and game theorists. General terms connect to dynamic programming (Ross, 1993) and recursive methods (Stokey & Lucas, 2011) as well as to discounted, dynamic games (Amir, 1996; Sundaram, 1989). More specific themes, on resource economics (Hanley et al., 2007), bridge between tragedies of the commons – via prisoners' dilemma – to full cooperation. Broadly, under *one* umbrella, the study covers open-access fisheries (Gordon, 1954), fish wars (Levhari & Mirman, 1980), and governance of the commons (Ostrom, 1990).

Novelties come with accommodating various games, by comparing them for efficiency and welfare – and finally, by computations for specific fisheries.

The paper is planned as follows. Section 2 fixes notations and provides preliminaries. Section 3 formalizes various discounted, dynamic games. Section 4 attempts to compare them. Section 5 specializes to fishery games. For application, Section 6 considers multi-nation use of several stocks, each straddling the North-East Atlantic. Section 7 outlines the indicative results. In Section 8, following a discussion of the initial results, we propose an alternative way to redistribute the benefits from cooperation. Section 9 concludes.

2. Notations and preliminaries

To set the stage, this section briefly describes *states*, *players,* system *dynamics*, and any player's *single-period payoff* (or profit) as well as his overall *objective*.

The state x of the system belongs to - and evolves in - a nonempty, compact, convex set $X \subset R^S_+$, referred to as *the commons*. S is a finite list of renewable stocks. Component $s \in S$ of a vector $(x_s) = x \in X$ reports the abundance (biomass) $x_s \in R_+$ of species s. The ambient Euclidean space R^S is ordered in the customary, component-wise manner.

Time $t \in \{0, 1, ..., T\}$ is discrete. Occasionally, for computations or recursions, the horizon T is finite, but - unless stated otherwise - in the main, $T = +\infty$. Let $x_t = (x_{st}) \in X$ denote the system state which prevails at the beginning of time period t. That state is perfectly observed by each concerned party.

[5] That specification is, however, not essential for the subsequent frame.

[6] Few studies address multi-nation, multi-species fisheries as non-cooperative games. For (notable) exceptions, see Doyen, Cisse, Sanz, F Blanchard, and Péreau (2019), Salenius (2018).

Players form a fixed, finite ensemble I, $\#I \geq 2$. The members are economic agents, all infinitely-lived and interacting at each time t. To avoid repetitions of arguments, by slight abuse of terms, call any non-empty subset $\mathcal{I} \subseteq I$ a *coalition*. A coalition $\mathcal{I}$ is *cohesive* if the aggregate non-cooperative payoff does not exceed the coalitional one (Eyckmans & Finus, 2004). $\mathcal{I}$ is declared *internally stable* if no member, ceteris paribus, has incentives to *leave*; it's *externally stable* if no outside agent wants to *join* (D'Aspremont, Jacquemin, Gabszewicz, & Weymark, 1983).

The action of agent $i \in I$, at any time t, is to catch or consume some "quantity" $q_{it} \in Q_i \subset R^S_+$ from the commons. The set Q_i is compact convex and contains 0. For later purposes, write $Q := \Pi_{i \in I} Q_i$ and $Q_{-i} := \Pi_{j \neq i} Q_j$.

Dynamics are deterministic and time-homogenous. For succinct statement, briefly omit mention of time here. So, single-period, *aggregate catch* $q_I := \Sigma_{i \in I} q_i$, taken out of the commons in state x, leaves end-of-period, after-catch *escapement* $\chi = x - q_I$. Such investment or saving generates *gross growth*

$$\chi \in X \mapsto G(\chi) \in X. \tag{1}$$

Thus, endowment $x = G(\chi)$ becomes available, and is commonly observed, at the beginning of the subsequent period. Like standard production functions, let the mapping G (1) be concave, continuous and increasing (jointly and component-wise).

Single-period payoff or profit to agent i is a function

$$(x, q_i) \in X \times Q_i \mapsto \pi_i(x, q_i) \in R. \tag{2}$$

By economic considerations, $\pi_i(x,\ q_i)$ is presumed continuous, hence bounded,[7] jointly concave, strictly so in q_i - and separately increasing in x.

The objective of agent i, as of any time t, in face then of state $x = x_t \in X$, is to maximize his *actualized value*

$$v_{it}(x) := \sum_{\tau \geq t} \delta_i^{\tau - t} \pi_i(x_\tau, q_{i\tau}) \tag{3}$$

over the periods to go. He uses a fixed *discount factor*$\delta_i \in [0, 1)$.[8] Clearly, the value $v_{it}(x)$ (3) is not well defined unless $q_{j\tau}$ be specified - or perfectly predicted - for *each* rival player $j \neq i$ and time $\tau \geq t$.

Bounded value functions $v : X \to R$ form a real vector space V. That space is complete with *norm* $\|v\| := \sup_{x \in X} |v(x)|$.[9]

Values to a coalition are recursively defined by foreseeing the choices made by rival players. That is, if state $x = x_t$ prevails at time t, and coalition $\mathcal{I} \subseteq I$ predicts the aggregate quantity $q_{-\mathcal{I}} := \sum_{j \notin \mathcal{I}} q_{jt}$, immediately taken by the outsiders $j \notin \mathcal{I}$, then $\mathcal{I}$ can aim at joint value

$$v_{\mathcal{I},t}(x) = \sup_{q_{\mathcal{I}}} \{\pi_{\mathcal{I}}(x, q_{\mathcal{I}}) + \delta_{\mathcal{I}} v_{\mathcal{I},t+1}(x_{+1})\} \tag{4}$$

with $x_{+1} = G(x - q_{\mathcal{I}} - q_{-\mathcal{I}})$. Here, $\delta_{\mathcal{I}} \in [0, 1)$ is a common discount factor, and - as a matter of perfect cooperation:

$$\pi_{\mathcal{I}}(x, q_{\mathcal{I}}) := \sup \left\{ \sum_{i \in \mathcal{I}} \pi_i(x, q_i) : \sum_{i \in \mathcal{I}} q_i = q_{\mathcal{I}},\ \ q_i \in Q_i \right\}. \tag{5}$$

The convention $\sup \varnothing = -\infty$ applies in (4) and (5).[10] Format (4) invites dynamic programming with finite horizon T and specified terminal value function $v_{\mathcal{I},T+1}(\cdot)$.

[7] This assumption, maintained until other notice, is problematic if $\lim \pi_i(x,\ q_i)$ tends to $-\infty$ when some x_s approaches its extinction level.

[8] With no loss of generality, one may suppose that every value function $v_i(\cdot)$ be non-negative. This feature is, however, not important in any subsequent arguments.

[9] In terms of functional analysis, V is a *Banach space.*

[10] It's a conceptual devise to account for infeasibility. For practical purposes, one can replace $-\infty$ by any number $< \sum_{i \in \mathcal{I}} \min \pi_i(x, q_i)$.

If each rival $j \notin \mathcal{I}$ commits to state-independent, *open-loop* play $\tau \mapsto q_{j\tau} \in Q_j$ from some time $t < T$ onwards, then, most conveniently, the function $v_{\mathcal{I},t}(\cdot)$ becomes concave and increasing on its *effective domain* $\{x \in X : v_{\mathcal{I},t}(x) \in R\}$.

By contrast, if each rival $j \notin \mathcal{I}$ implements a stationary, *closed-loop* policy $x \in X \mapsto q_j(x) \in Q_j$, it becomes harder to have $v_{\mathcal{I},t}(\cdot)$ concave increasing. However, as recompense, under such play, with $T = +\infty$, recursion (4) takes the time-invariant form

$$x \in X \mapsto v_{\mathcal{I}}(x) = \max_{q_{\mathcal{I}}} \{\pi_{\mathcal{I}}(x, q_{\mathcal{I}}) + \delta_{\mathcal{I}} v_{\mathcal{I}}(x_{+1})\} \tag{6}$$

where $x_{+1} = G(x - q_{\mathcal{I}} - \sum_{j \notin \mathcal{I}} q_j(x))$ and (5) remains in vigor. Then moreover, $v_{\mathcal{I}}$ is the unique fixed point of the contraction operator $v \in V \mapsto Tv \in V$, defined by

$$[Tv](x) := \max_{q_{\mathcal{I}}} \{\pi_{\mathcal{I}}(x, q_{\mathcal{I}}) + \delta_{\mathcal{I}} v(x_{+1})\} \ \forall x \in X.$$

If each $q_j(\cdot)$ is continuous, so is also $v_{\mathcal{I}}(\cdot)$.

It is, of course, conceivable that agents play open-loop up to some interim time $t < T$ and shift then to closed-loop strategies. However, given the stationary setting, such switching of behavioral modus will not be considered.

Remark. (*on single-period allocation of catch*). Given any state $x \in X$, subproblem (5) might be solved by direct exchanges (Flåm, 2016a), markets (Flåm, 2019) or double auctions (Flåm, 2021) for quotas. Note that any *shadow price* $P \in \frac{\partial}{\partial q_{\mathcal{I}}} \pi_{\mathcal{I}}(x, q_{\mathcal{I}})$ on "quotas", alongside any *efficient allocation* $(q_i)_{i \in \mathcal{I}}$ of fixed aggregate $q_{\mathcal{I}}$, yields

$$P \in \frac{\partial}{\partial q_i} \pi_i(x, q_i) \text{ and}$$
$$q_i \in \arg\max \{\pi_i(x, \tilde{q}_i) - P \cdot \tilde{q}_i : \tilde{q}_i \in Q_i\} \ \forall i \in \mathcal{I}.$$

3. Discounted, dynamic games

This section singles out four game forms - ordered by decreasing degree of coordination and commitment. They range from *perfect cooperation* - via *single-agent defection* and Nash *noncooperative play* - to the extreme instance of *myopic fish wars*.

Perfect cooperation emerges when the *grand coalition* $\mathcal{I} = I$, upon facing any state $x_0 \in X$, decides to shoot at maximal joint value $v_I(x_0)$. In this optic, granted a stationary structure, the distinction between open and closed loop disappears. Thus, format (4) coincides with (6). Consequently, for computation, one may fix a distant horizon $T < +\infty$ and solve a representative agent's problem

$$v_I(x_0) \approx \max_{(q_{It})} \sum_{t=0}^{T} \delta_I^t \pi_I(x_t, q_{It}). \tag{7}$$

Alternatively, initiating with any bounded concave proposal $v_I : X \to R$, iterated updates (6):

$$v_I(x) \longleftarrow \max_{q_I} \{\pi_I(x, q_I) + \delta_I v_I(x_{+1})\}$$

converge to the correct function $v_I(\cdot)$ - whence the particular value $v_I(x_0)$ comes up. For each approach and stage, the function $\pi_{\mathcal{I}}$ (5) applies with $\mathcal{I} = I$.

Granted convex dynamics and preferences - and no randomness - we prefer problem format (7) to iterated value updates - for *three* reasons: *First*, (7) amounts to tractable concave programming; *second*, it automatically takes care of single-period allocation (5) - and *third*, it avoids paying much attention to states never visited.

Single-player defection means that *one* agent i refrains from all sorts of cooperation or commitment, leaving such concerns entirely to others. Let $-i := I \setminus \{i\}$ denote the residual ensemble, comprising at least two members who cooperate perfectly. On this premise, suppose the defector free-rides, relegating the task of intertemporal allocation to the coalition. Specifically, when facing whatever state $x \in X$, the single defector i chooses

$$q_i(x) := \arg\max_{q_i} \pi_i(x, q_i), \tag{8}$$

thereby behaving as though $\delta_i = 0$. As upshot, he plays predictable closed-loop, performing thus as a short-sighted, strategic dummy - somewhat like a Stackelberg follower. Consequently, up front, coalition $-i$ faces *either* the reduced, single-shot problem

$$v_{-i}(x_0) \approx \max_{(q_{-it})} \sum_{t=0}^{T} \delta_{-i}^t \pi_{-i}(x_t, q_{-it}, q_i(x_t)) \tag{9}$$

for distant planning horizon $T < +\infty$, *or* the task of iterated, recursive programming

$$v_{-i}(x) \longleftarrow \max_{q_{-i}} \{\pi_{-i}(x, q_{-i}) + \delta_{-i} v_{-i}(G(x - q_{-i} - q_i(x))\}.$$

In both cases the joint, single-period payoff $\pi_{-i}(x, q_{-i})$ is defined by (5) with $\mathcal{I} = -i = I \setminus i$. Note that the objective of problem (9) can lack (or loose) concavity - whence become less amenable than that of (7).

Noncooperative play in which each player $i \in I$ implements a closed-loop, stationary strategy $x \in X \mapsto q_i(x) \in Q_i$ is most difficult to handle; see Amir (1996), Levy (2015), and Sundaram (1989). Yet - discretizing X, Q and modifying G accordingly - attractive computation may rely on iterated linear programming as follows: Given any tentatively proposed strategy profile $x \mapsto q(x) \in Q$,

• *Select a player* $i \in I$ and find his value function $v_i(\cdot) \in R^X$ by solving:

$$\min \sum_{x \in X} v_i(x) \text{ s.t. } v_i(x)$$
$$\geq \max_{q_i \in Q_i} \{\pi_i(x, q_i) + \delta_i v_i(G(x - q_i - q_{-i}(x)))\} \ \forall x \in X. \tag{10}$$

• *Update his strategy* by letting $q_i(x)$ equal the maximizing choice in state x.

• *Continue*, by some protocol, to *select a player* until convergence.

Alternatively, by a diagonal procedure, iteratively update value $v_i(x)$ *and* best choice $q_i(x)$ - as in (6) with $\mathcal{I} = \{i\}$.

Note that the same two approaches serve for *perfect cooperation* and *single-agent defection*. Moreover, either can accommodate stochastic dynamics.

Myopic fish wars emerge if *each* player $i \in I$, whenever he faces any state x, implements (8). Broadly, everybody behaves as though $\delta_i = 0$. This rent-dissipating scenario is thoroughly analyzed, all too frequently seen, and much deplored (Clark, 1990; Gordon, 1954; Ostrom, 1990).

4. Comparison of games

Introduced above was an ensemble

$$\Gamma := \{perfect\ cooperation,\ single - agent\ defections,\ Nash\ noncooperative\} \tag{11}$$

of labels γ in capital.[11] Can the said games somehow be compared, ordered or ranked? To that end, suppose each game $\gamma \in \Gamma$ leads to a stable, long-run, steady state x^γ – held up by a corresponding stationary strategy $q^\gamma(x^\gamma) \in Q$. On this presumption, let us say that game $\hat{\gamma}$ *Pareto dominates* γ written

$$\hat{\gamma} \succsim \gamma \quad \text{iff} \quad v_i^{\hat{\gamma}}(x^{\hat{\gamma}}) \geq v_i^\gamma(x^\gamma) \text{ for each } i \in I.$$

[11] Thus, Γ accommodates $\#I + 2$ different frames. Moreover, some can be played in either open or closed loop.

Further, a game $\bar{\gamma} \in \Gamma$ is declared *strictly Pareto efficient to level* $\lambda \in (0, 1]$ iff

$$\lambda v_i^{\bar{\gamma}}(x^{\bar{\gamma}}) \geq v_i^{\gamma}(x^{\gamma}) \quad \text{for each } i \in I \text{ and } \gamma \neq \bar{\gamma}. \tag{12}$$

It is commonly observed that non-cooperative play entails inefficiencies – reminiscent of the *prisoners' dilemma*. So, to no surprise, *perfect cooperation* serves as goal and benchmark game, henceforth labelled $\bar{\gamma}$. However, being difficult to implement, that game calls for compromises. For this purpose, given any steady state $x \in X$, upheld by a constant profile $q \in Q$, let $v_i(x)$ denote the attending present value which would accrue then to agent i.

Definition 1. (on implementation). *A steady state* $x \in X$, *and associated constant profile* $q \in Q$, *implements a game* $\bar{\gamma} \in \Gamma$ *up to level* $\lambda \in (0, 1]$ *iff*

$$v_i(x) \geq \lambda v_i^{\bar{\gamma}}(x^{\bar{\gamma}}) \text{ for each } i \in I. \tag{13}$$

Clearly, for each player to find a steady state x attractive, the level λ in question must not be far from 1.

Proposition 1. *(on steady state implementation). Suppose cooperative game* $\bar{\gamma} \in \Gamma$ *satisfies (12). Then, any steady state* x *which implements* $\bar{\gamma}$ *up to level* λ *(13) satisfies*

$$v_i(x) \geq \lambda v_i^{\bar{\gamma}}(x^{\bar{\gamma}}) \geq v_i^{\gamma}(x^{\gamma}) \text{ for each } i \in I \text{ and } \gamma \neq \bar{\gamma}. \qquad \square$$

Returning now to game ensemble Γ *(11), we computed steady states for perfect cooperation and the single-agent defections as long-run limits of single-shot programs (7) and (9) – emanating from various initial states* x_0.

The more challenging, Nash noncooperative instance stands out. Iterated linear programming (10) or repeated value updates (6) may both indicate the steady state. It is more tempting though, to seek that state directly by applying individual optimality conditions to a rest point. For that, suppose a steady pair (x, q) *be interior to* $X \times Q$. *Presuming differentiability, the state* $x \in int(X)$ *and associated profile* $i \mapsto q_i \in int(Q_i)$ *should then solve the following equation system:*

For time-invariant best choice q_i *of player* $i \in I$,

$$\frac{\partial}{\partial q_i}\pi_i(x, q_i) = \delta_i v_i'(x)\frac{\partial}{\partial q_i}G(x - q_I) \text{ with } v_i'(x) = \frac{\partial}{\partial x}\pi_i(x, q_i), \tag{14}$$

and for a time-invariant pair (x, q),

$$x = G(x - q_I) \quad \text{with} \quad q_I = \sum_{i \in I} q_i. \tag{15}$$

Eq. (15) explain themselves. The first equation in (14) derives from differentiating the bracket on the right hand side of the Bellman equation

$$v_i(x) = \max_{q_i \in Q_i}\{\pi_i(x, q_i) + \delta_i v_i(G(x - q_I))\}$$

with respect to q_i. *The second equation in (14) stems from the envelope theorem - as applied in this context by Benveniste and Scheinkman (1979).*

5. Competitive fishery games

For application, consider harvest from common fish species $s \in S$. A box

$$X := [\underline{x}, \bar{x}] := \left\{x \in R^S : \underline{x} \leq x \leq \bar{x}\right\}$$

serves as state space. It features a lower level $\underline{x} \in R^S_+$, below which the system is not viable. The upper level $\bar{x} >> \underline{x}$ reflects the carrying capacities of the habitat.

In practice and any period, no agent makes $q_i \in Q_i \subseteq X$ his chief decision vector. Rather, his catch q_{is} from species s, derives from *effort* e_{is}, expressly directed at that species. Thus, effort e_{is} - as part of his primary, single-period decision - is chosen within a prescribed, compact convex set $\mathcal{E}_{is}(x_s) \subset R_+$, containing 0. In these terms, let

$$q_{is} = \mathfrak{Q}_{is}(e_{is}|x_s), \tag{16}$$

where production function $(e_{is}, x_s) \mapsto \mathfrak{Q}_{is}(e_{is}|x_s)$ is jointly continuous, strictly concave and increasing. Naturally, $\mathfrak{Q}_{is}(0|x_s) = 0$, and $x_s < \underline{x}_s \Longrightarrow q_{is} = \mathfrak{Q}_{is}(e_{is}|x_s) = 0$.[12] Given $x_s \geq \underline{x}_s$, there is a one-to-one mapping $q_{is} \leftrightarrow e_{is}$ defined by (16) and the partial inverse function $\mathfrak{Q}_{is}^{-1}(\cdot|x_s)$, to the effect that

$$e_{is} = \mathfrak{Q}_{is}^{-1}(q_{is}|x_s).$$

Agent i takes home single-period payoff

$$\pi_i(x, q_i) := \sum_{s \in S} \pi_{is}(x_s, q_{is})$$

where

$$\pi_{is}(x_s, q_{is}) := \left\{p_{is}q_{is} - c_{is}(e_{is}) : e_{is} = \mathfrak{Q}_{is}^{-1}(q_{is}|x_s)\right\}. \tag{17}$$

Here, p_{is} denotes a competitive market price per quantitative unit of species s.[13] $c_{is}(\cdot)$ accounts for the agent's cost of effort. To the extent that x_s affects (16), payoff depends indirectly on stock abundance. Like above, let $\chi := x - \sum_{i \in I} q_i$ denote *escapement* which generates concave, increasing gross growth (1).

There are, of course, concerns with system viability. It causes no worries that χ_s comes close to $\bar{x}_s$. By contrast, as a minimal and natural requirement, suppose

$$\chi_s \searrow \underline{x}_s \Longrightarrow e_{is} \text{ (and hence } q_{is}) \searrow 0 \text{ for all } i.$$

Reflecting on this, given state $x \in X$, then - by tacit assumption, outside regulation, or fishermens' own concerns with profitability and sustainability - the catch profile $q = (q_i) \in Q$ always satisfies the feasibility restriction

$$\chi := x - q_I := [x_s - \sum_{i \in I} q_{is}]_{s \in S} \in X. \tag{18}$$

Inclusion (18) would automatically hold if *either*

* prudent agents foresee catastrophes if $\chi_s < \underline{x}_s$ - whence hold back on effort - *or*

* payoffs become negative at low stock levels, at which some players would exit the game.

In sum, for computations, it's convenient to let efforts $e_{is} \in \mathcal{E}_{is}(x_s)$ be the basic, single-period decisions. Accordingly, to eliminate quantity q_{is} as companion variable, let *harvest fractions* $f_{is}(\cdot) \geq 0$, $\sum_{i \in I} f_{is}(\cdot) = 1$ be defined implicitly by (16), $q_{Is} := \Sigma_{i \in I} q_{is}$, and

$$q_{is} = f_{is}(e_{is}|x_s)q_{Is}.$$

6. Application

Nation ensemble $I := \{\text{Iceland, Norway, and UK}\}$[14] harvest and share fish species $s \in S := \{\text{herring, mackerel, and blue whiting}\}$. The fisheries are of considerable commercial importance, and the stocks straddle the North-East Atlantic, various exclusive economic zones (EEZ) and the high seas (Bjørndal, 2009; Bjørndal & Ekerhovd, 2014).

[12] If $\mathfrak{Q}_{is}(e_{is}|x_s)$ comes linear in x_s, concerns with possible extinction of species s become particularly pressing.

[13] Generalization to *Cournot oligopoly* is possible, but not considered here; see Flåm (2016b).

[14] Norway, Iceland, Faroe Islands, Greenland, and Russia as well as various members of the EU participate. Their status—as coastal states or distant water exploiters—varies across species.

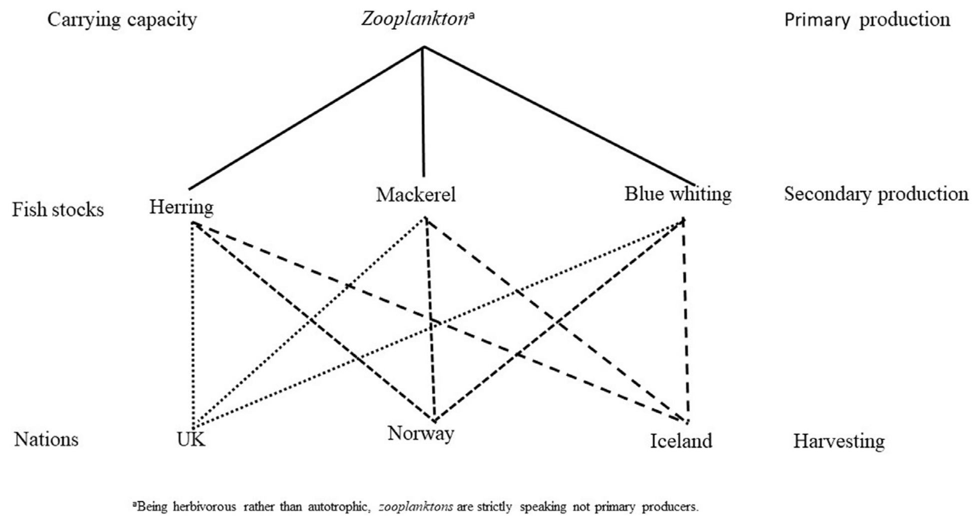

Fig. 1. The Norwegian Sea pelagic complex.

The species impact each other by feeding on the same lower-level strata (Huse et al., 2012). All forage on the plankton *Calanus finmarchicus* - itself of limited commercial interest. Its abundance—regarded as exogenous here—largely links and determines the dynamics of the three stocks. By assumption, predator species have insignificant impacts.

The three stocks are coupled in dynamics, of contested exploitation - and some species even might collapse (Bjørndal, Kaitala, Lindroos, & Munro, 2000; Ekerhovd, 2010; Hannesson, 2013; Spijkers & Boonstra, 2017; Toumasatos & Steinshamn, 2018). It is feared that the mackerel stock will outcompete the other two - thereby upending environmental and economic sustainability.

Fig. 1 illustrates the stylized web structure, sometimes called "The Norwegian Sea pelagic complex" (Ekerhovd & Kvamsdal, 2017).

Given after-catch escapement $\chi_s \in [\underline{x}_s, \bar{x}_s]$ of species s and aggregate biomass $\chi_S := \Sigma_{s\in S}\chi_s$, the ensuing gross growth $G_s(\cdot)$ of species s is logistic:

$$(\chi_s) =: \chi \mapsto G_s(\chi) = \chi_s + r_s\chi_s(1-\chi_S/k) =: x_s.$$

Here $k > 0$ denotes the habitat's maximal, carrying capacity, furnished by lower-level, ecological strata, supposed independent and stable. If isolated and viable, species s would grow at linear rate $r_s > 0$. The lower levels $\underline{x}_s$, below which the system is not viable, are fixed, for each species, at reference minimum biomass levels recommended by the International Council for the Exploration of the Seas (ICES, 2016). At stock escapement biomass levels below these limits catch is nil.[15]

Agent i's harvest from stock s at time t is

$$q_{ist} = \frac{e_{ist}}{e_{st}}q_{st} = \frac{e_{ist}}{e_{st}+1}x_{st}$$

where $e_{st} := \Sigma_{i\in I}e_{ist}$ denotes aggregate effort directed at species s, and

$$q_{st} = \frac{e_{st}}{e_{st}+1}x_{st}.$$

The constant 1 in the denominator acts as unit of effort and normalizing factor.[16] Consequently, agent i directs effort

$$e_{ist} = \frac{q_{ist}}{x_{st}-q_{st}}$$

towards species s at time t.

6.1. Parametrization

Parameters, drawn from empirically based information, are summarized in Table 1, while the relevant data and estimation statistics are in Appendix.

The ICES provides data on stock sizes and harvest levels (ICES, 2016). The Norwegian purse seiners' cost and harvest data comes from the Norwegian Directorate of Fisheries' profitability survey on the Norwegian fishing fleet for 1998–2011 (Fiskeridirektoratet, 2012). Historic stocks development is not observed directly, but derived from stock assessments. The stock data are generated using virtual population analysis, rich in its coverage of catch, mortality, and stock size information. Mortality and stock size series are generated variables based on biological assumptions, actual catch levels, and assumed decay functions (Jennings et al., 2001). It is problematic that generated regressors are endogenous, and a least square estimator produces inconsistent and inefficient estimates. Therefore, we use instrumental variable techniques to address this issue (Ekerhovd & Gordon, 2013; Ekerhovd & Kvamsdal, 2017; Ekerhovd & Steinshamn, 2016). The data used, covering the years 1998–2010, are presented in Table A1.

The growth functions are derived from the multi-species model G_s, which consist of three regression equations, each having their own dependent growth variable and a set of exogenous explanatory variables. Each equation could be estimated separately. However, the equations are clearly related by the fact that the sum of all three escapement levels are a common component of an explanatory variable in the equations. Moreover, the common carrying capacity parameter, k, links the equations in a nonlinear way. Therefore, the multi-species model was estimated using a nonlinear, seemingly unrelated regression. The estimated parameters, r_s and k, are listed in Table A2.

Lacking information on total costs for the combined harvest of herring, mackerel, and blue whiting, we used the available operation costs (1998–2010) for licensed Norwegian purse seiners in million NOK (see Table A1). Prices and cost for UK and Iceland, on the other hand, were not obtained from empirical estimates, but instead scaled to the Norwegian prices and costs based on infor-

[15] The minimum escapement levels are presented in Table 1.

[16] The constant could have been replaced by coefficients dependent on both ecological parameters (e.g. interspecies) and on economic parameters (e.g. preference) (Doyen et al., 2019). Here such features are captured through other elements of the model such as growth, prices, costs, and discounting. Admittedly, the format being somewhat *ad hoc*, it generates though, qualitative properties that appear robust; namely that catch rates are higher if the fish population is larger, and that the total catch rate is increasing and concave in effort.

Table 1
Model subscripts, variables, and parameters.

Symbol	Definition	Herring	Mackerel	Blue Whiting	Unit
s	Subscript	1	2	3	Stock/fishery
t	Time				Year
i	Actor		Norway United Kingdom (UK) Iceland		Nationality
r_s	Growth rate	.358	.589	.808	
k	Carrying capacity		27,462		Thousand tonnes
$\underline{x}_s$	Minimum escapment	2500	1,800	650	Thousand tonnes
p_{si}	Prices, Norway	3.55	9.48	1.54	Norwegian kroner (NOK)
	Prices, UK	3.02	8.30	2.05	
	Prices, Iceland	1.53	2.37	1.03	
c_s	Cost parameter	15,655,111	16,886,829	1,154,117	Thousand NOK (2010)

Table 2
Sum profit 10^6 NOK[a] over 20 years in steady state for various coalition structures.

Country[b]	NO	UK	ICE	Total
Coalition structure				
Fully cooperative	509.5	1.8	−11.6	499.7
(ICE,UK), (NO)	36.2	10.3	0.2	46.7
(ICE,NO), (UK)	42	7.4	0.9	50.3
(UK,NO), (ICE)	143.2	1.4	0.3	144.9
Fully non-cooperative	39.8	7.3	1	48.1

[a] Norwegian kroner (NOK)
[b] Norway (No), United Kingdom (UK), and Iceland (ICE).

Table 3
Coalitions and their stability properties.

Case	Leaving/entering coalition/nation	Coalition structure	Int/ext stable
1	(NO,UK,ICE)[a]	(NO,UK,ICE)	no/yes
2	(UK,ICE)	(UK,ICE),(NO)	no/no
3	(NO)	(UK,ICE),(NO)	yes/ yes
4	(NO,ICE)	(NO,ICE),(UK)	no/no
5	(UK);	(NO,ICE),(UK)	yes/no
6	(NO,UK)	(NO,UK),(ICE)	no/yes
7	(ICE)	(NO,UK),(ICE)	yes/no
8	(NO)	(NO),(UK),(ICE)	yes/yes
9	(UK)	(NO),(UK),(ICE)	yes/no
10	(ICE)	(NO),(UK),(ICE)	yes/no

[a] Norway (No), United Kingdom (UK), and Iceland (ICE).

Table 4
Harvest levels by country[a] and stock biomass[b] under various coalition structures.

Coalition structure	Species	NO	UK	ICE	Stock
(NO,UK,ICE)	Herring	0	0	363	2863
	Mackerel	3147	0	0	16,309
	Blue Whiting	0	213	0	863
(ICE,UK),(NO)	Herring	965	0	337	6526
	Mackerel	617	312	0	3196
	Blue Whiting	121	360	0	1337
(ICE,NO),(UK)	Herring	1179	152	0	6662
	Mackerel	636	312	0	3257
	Blue Whiting	0	138	243	1060
(UK,NO),(ICE)	Herring	1209	0	0	6325
	Mackerel	1385	0	0	4948
	Blue Whiting	0	238	113	1006
(NO),(UK),(ICE)	Herring	1046	101	173	6603
	Mackerel	654	288	0	3,231
	Blue Whiting	0	201	205	1,126

[a] Norway (No), United Kingdom (UK), and Iceland (ICE).
[b] Harvest levels and stock sizes in thousand tonnes.

mation from other sources (Lappo, 2013). The background for this is discussed in more detail in Appendix.

The Norwegian purse seiners' (NO) effort in fishery s at time (year) t indicates the relationship between their harvest, q_{sNOt}, and final escapement level, χ_{st}. Hence, the effort, $e_{sNOt} = q_{sNOt}/\chi_{st}$, (cf. Eq. (6)) was regressed on the Norwegian purse seiners' costs for 1998–2010. The results from the cost function calibration are shown in Table A3.

Accordingly, we scaled UK and Icelandic costs and prices to the Norwegian parameters in the following way: For the costs we decided to scale the Icelandic costs to the Norwegian cost parameters, cf. Table 1, by a factor of 0.5; for the UK, the fisheries costs are assumed equal to the Norwegian costs (factor = 1.0). Similarly, the Norwegian mean prices and UK and Icelandic prices were scaled accordingly and are presented in Table 1.

7. Results and sensitivity

This section provides net present values from each coalition structure - and explores sensitivity to selected parameters.

7.1. Results

We posit that $\delta_i \approx 1$ for each $i \in I$. The optimization problem is solved using KNITRO in a GAMS environment. Each computational run extends over 25 years, and the profits are summed across the last 20 years, the system then being close to a steady state. The latter is achieved by running the relevant model twice, using the tentative steady-state already found in the first run as the initial state to the second. Table 2 lists each nation's undiscounted, steady-state payoffs in the three different regimes: fully cooperative, partially cooperative, and, finally, completely non-cooperative. With just three players, five coalition structures are possible.

Table 2 indicates some stability properties of various arrangements. Table 3 clarifies these matters.

Harvest patterns are summarized in Table 4. Note that the cooperative case that stands out both with respect to stock composition and harvest composition. Norway takes more than 3 million tonnes mackerel out of a stock larger than 16.3 million tonnes. The herring stock is less than half of what it is in the other cases, the blue whiting stock is below 1 million tonnes, whereas the mackerel stock is more than twice as high. In all other cases, the herring stock varies around 6.5 million tonnes, the mackerel stock varies a bit more from 3.2 to 5 million tonnes, whereas the blue whiting stock varies from 1 to 1.3 million tonnes.

Not surprisingly, the grand coalition is internally unstable. Iceland wants to break out because its payoff is negative. Further - or afterwards - UK wants to leave as well. In the first place, Iceland might already foresee the ensuing collapse of coalitions. What finally emerges, via actions and reactions, is a largest consistent solution, reflecting farsighted stability; see Chwe (1994). Here, since Iceland fares best alone and will leave behind an internally unsta-

Table 5
Actual harvest levels by country[a] and spawning stock biomass assessment[b] in 2014 and 2015.

Year	Species	NO	UK	ICE	Stock
2014	Herring	263	4	59	5,154
	Mackerel	278	288	173	5,229
	Blue Whiting	399	27	183	4,050
2015	Herring	176	0	43	4,798
	Mackerel	242	248	169	5,195
	Blue Whiting	489	31	214	4,229

[a] Norway (No), United Kingdom (UK), and Iceland (ICE).
[b] Harvest levels and stock biomass in thousand tonnes (ICES, 2016).

ble coalition, what results is the fully non-cooperative regime. As observed in reality, cooperation appears unlikely (Table 3, cases 8, 9, and 10), no matter which coalition structure we start with.

Unfortunately, as we have seen from the stability analysis above, full noncooperative competition is the most likely outcome. It is therefore interesting to compare the different outcomes from the model with what we actually see in reality.

Actual stocks and harvests in 2014 and 2015 are shown in Table 5. It is seen that these numbers are much closer to the cases with at least one singleton than with the cooperative case. The actual herring stock is around 5 million tonnes which is comparable to the 6.5 million tonnes found in most cases except the grand coalition. Mackerel and blue whiting stocks vary around 5.2 and 4.1 million tonnes, respectively. The real mackerel stock is, in other words, much lower than the 16 million tonnes advocated in the cooperative case, but comparable to the stock found in the cases with one singleton, which varies from 3.2 to 4.9 million tonnes, cf. Table 4. Blue whiting, being the least profitable stock, is in the real world not fished down in order to accommodate the two other stocks but is also around 4 million tonnes. In the model runs, blue whiting varies between 1 and 2 million tonnes, and is highest in the cooperative case, cf. Table 4.

When it comes to harvest, the real world pattern seen from Table 5 indicates that Norway harvests all three species, UK specializes in mackerel and Iceland specializes in mackerel and blue whiting. It is difficult to find exactly this pattern with any of the coalition structures. The cooperative case is perhaps the one that is furthest away from it. In reality also other nations harvest on these stocks, and the true figures are therefore lower than the results from the model, as in the model we assume that only these three nations harvest.

Unsurprisingly, full cooperation largely avoids the non-cooperative tragedy. Indeed, full cooperation offers 10 times greater profit than the non-cooperative regime. Thus, if suitable sharing rules—or feasible side payments—are implemented, the stability criteria are apt to become different. Then, Iceland helps others harvest more mackerel. If side payments were possible, the grand coalition might become stable. Norway and UK might then pay Iceland to harvest (mainly) more herring. Unfortunately, monetary side payments between fishing nations have hardly been observed. By contrast, negotiation over quotas or access to each others waters are more common. We have therefore used the model to suggest some relatively undramatic transfers of quotas between agents that surprisingly closely mimic the cooperative case and simultaneously restore stability. These are detailed later.

7.2. Sensitivity analysis

In this section we present the results of sensitivity analysis with respect to some of the main economic parameters. More specifically, we look at the discount factor, the cost parameters and the price. Regarding price, we investigate the effect of diverging from the hypothesis that all are price-takers, and look at the case where there is some degree of market power. A more detailed description of the sensitivity analysis is relegated to Appendix. The main results are summarized below.

A stable second-best solution, not very far from the first-best, still exists under 10% discounting. We have also investigated the effect of discounting on the intermediate cases (coalitions of two and one singleton) and get the same results, namely only marginal quantitative effects and no qualitative effects.

The cost per unit effort is assumed to be the same between species, due to similar technology, but vary between nations. In the main analysis Norway and UK have the same cost whereas Iceland has 50% lower cost. As Norway already is the most profitable country, we do not see any point in reducing its cost. Instead, we varied the UK and Icelandic cost factors, one at the time ceteris *paribus*, by 10%. The results, comparable to Table 2, are presented in Tables A4 and A5 for UK and Iceland, respectively.

We find that a change in the cost parameter to some extent affects the profitability of the country for which the cost parameter is altered, but not very much, and for the other two countries there is hardly any effect at all.

Basically, other properties of the solutions such as the stability of the grand coalition and the most likely outcome of the game, and as discussed in detail later, cooperation and the division of labor, and partial cooperation and efficiency, appears robust to reasonable changes in the relative cost differences between countries.

With both agent- and species-specific prices we have already nine different prices. The possible number of combinations for changing the prices is very high, and we do not see any point in starting to try out all these combinations. Instead we look at a case where one agent has market power for one of the species. As Norway's catch of mackerel is among the largest catches, and in addition mackerel is the economically most important species, this occur as an obvious case of possible market power to be analyzed. It is assumed that the other two countries remain price-takers, so does Norway for herring and blue whiting.

All in all, replacing the fixed price by a downward sloping demand function does not make very significant changes, and the changes that are noticeable are as expected, see Appendix for details.

8. Discussion

Full cooperation emphasizes efficiency in allocation and sharing. Consequently, that paradigm brings out division of labor or specialization of tasks. Parties, enjoying comparative advantages in location or payoffs, concentrate on different stocks, cf. Table 4. Best situated agents harvest relatively more, and sharper selection mirrors differences in migration patterns. A feedback mechanism reinforces these features. Indeed, the most profitable stock (i.e. mackerel) grows better if the others be held down. In extremis, Iceland catches herring, Norway mackerel, and UK blue whiting. Thereby, Iceland incurs losses; it suppresses the herring stock to accommodate more mackerel, mainly to the benefit of Norway.

Partial cooperation, somewhat surprisingly, does not necessarily improve efficiency. To wit, if Norway free-rides, while Iceland and UK cooperate, total net revenue is less than under full lack of cooperation (Eq. (10)). Broadly, if the best-placed party free-rides in face of cooperation among its rivals, that party may deepen the tragedy of the commons.

On collapse of stocks – a potential and serious threat here - *two* things stand out. *First*, each species is partly protected by high harvest costs under low abundance. Yet all remain vulnerable by moving in schools; the herring stock already provided striking illustration. *Second*, if one species is markedly more valuable, economic rationality may drive the other species (close) to extinction.

Table 6
Steady-state profits 10^6 NOK[a] over 20 years under competition/cooperation with/without quota transfers.

Country[b]	NO	UK	ICE	Total
Coalition structure:				
Fully cooperative	509.5	1.8	−11.6	499.7
Cooperative with transfer	478.3	10.3	1.0	489.6
Fully non-cooperative	39.8	7.3	1.0	48.1

[a] Norwegian Kroner (NOK).
[b] Norway (No), United Kingdom (UK), and Iceland (ICE).

In principle, the fully cooperative scenario can threaten ecological diversity. On this account, we observe that minimal escapement ($\underline{x}$) binds under cooperation, otherwise not. Paradoxically, the non-cooperative regime safeguards the system's dimensionality and diversity; economic rationality impacts two stocks negatively.

Practical management points to Norway and UK as the most lucrative—and realistic—two-member coalition, mainly because the bulk of revenues comes from mackerel. Weakening such rationality protects the less profitable species. Again, upon relaxing the restrictions on escapement, the difference between cooperation and competition becomes even greater.

Monetary benefits – supported by side payments – are displayed in Table 2. In reality, up-front agreements are frequently modified thereafter by bilateral quota transfers - or by access to other exclusive zones. Moreover, total allowable catches are often decided stock-by-stock. Regrettably, such procedures rarely facilitate cooperation - or outright, they block it. Yet the preceding analysis shows that, although cooperative costs and benefits be unevenly distributed, there is ample room to satisfy each party. Here, Iceland, being a "fringe player," faces relatively low costs of efforts but low prices for landings. By contrast, Norway - with higher costs and prices - gains most from full or partial cooperation. For UK and Iceland, the cooperative incentives are less clear cut. This indicates that Norway - to entice or incentivize cooperation - should transfer some of its gains.

We indicate some second-best alternatives, realized rather by quota transfers. For that, we re-run the cooperative instance with the added restriction that UK and Iceland should receive no less payoff than their best alternatives, which for Iceland is under full competition, and for UK in a bilateral coalition with Norway. The main message is that Norway should—in some form or to some approximation—"take over" the unprofitable Icelandic herring fishery. In return, Iceland should harvest more blue whiting. In fact, UK must give Iceland its blue whiting quota, in return for a part of the mackerel quota. Table 6 exhibits the attending quota transfers alongside the cooperative and competitive payments, reproduced from Table 2. With such "simple means", all nations improve over the fully competitive scenario. Compared with the unstable, first-best regime of full cooperation, the total revenue drops by merely 2%. Moreover, total stock sizes and harvest quantities are almost unchanged. Only the harvest (or quota) distribution between nations is altered. So, modulo modest quota transfers, a desirable but notoriously unstable first-best solution, yields a stable second-best solution, almost as efficient.

9. Concluding remarks

Motivated by multi-species, multi-nation fisheries, we have viewed various regimes as discounted, dynamic games. By comparing their steady states, bones of contention are identified - and prospects for improvement become clearer.

In particular, fully cooperative behavior may serve then as benchmark and focal point. Often though, such management is notoriously unstable, markedly specialized – and at variance with biological diversity. Yet, in our leading case, we find that minor quota transfers may, to tolerable approximation, yield efficiency *and* stability. Attending transfers, observed in reality, can substitute for monetary side payments. Incentives for walking that line derive from the fact that *partial* cooperation can occasionally prove worse than none at all. And clearly, by comprehensive agreements on reallocations and take-outs, the parties can circumvent the deadlocks of species-by-species management and bilateral deals.

Further, the optimal cooperative solution entails specialization both between agents and with respect to stocks, which may be unfavorable for biodiversity. In fact, the suboptimal fully competitive situation may, modulo quota transfers, be the one that best preserves a balanced composition of stocks.

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Appendix

The appendix presents the relevant data and estimation statistics behind the parameters introduced in Section 6, Table 1, as well as the background for scaling of UK and Iceland costs and price to Norways', and the details of the sensitivity analysis.

Parameter estimation

Ecological parameters. Our goal here is to model the fisheries by drawing on empirically based information without having to rely on comprehensive econometric studies of the market and harvesting processes.

Scaling of costs and prices. According to Lappo (2013), UK vessels had higher costs, 39–79% per tonne landed over the years 2008–2010, compared to Norwegian vessels. Icelandic vessels had the lowest costs, 43–48% less compared to the Norwegian purse seine vessels. Regarding profits per tonne landed, the order was vice versa. UK vessels earned on average 48–270% higher profits per tonne than Norwegian vessels. Generally, the Icelandic vessels were the least profitable. The Icelandic profits varied from being 5% higher to being 74% lower, compared to the Norwegian purse seine vessel's profits. Further, UK fishing vessels achieved about 15% lower price on herring compared with Norwegian vessels and about 12.5% less on mackerel, but 33% higher prices on blue whiting than the Norwegians. Icelandic vessels, on the other hand, achieved lower price on all three species compared with Norwegian prices. More specifically, the Icelandic prices were 57%, 75%, and 23%, lower than the Norwegian prices on herring, mackerel, and blue whiting, respectively (Lappo, 2013).

The fact that costs and prices appear to vary between countries may seem somewhat puzzling, and the explanation for it may be complex. Important factors are differences in fisheries management and fishing industry structure between countries. Take, for instance, Norway and Iceland: As to the structure of the Icelandic industry, the government in 1991 adopted new legislation allowing full transfer of quotas between companies. This caused a major change in the structure of the Icelandic industry and the majority of resources are now concentrated in a few big vertically integrated companies (Kvalvik, Nøstvold, & Young, 2014). In Norway, on the other hand, legislation hinders vertical integration, and with a few exceptions, no company has control over the full value chain.

Table A1
The 1998–2010 operation costs (billion NOK) of the licensed Norwegian purse seine fishery; Norwegian purse seiners catch; and total escapement levels (thousand tonnes), respectively, of herring, mackerel, and blue whiting; and the Norwegian consumer price index (CPI).

Year	Norwegian purse seine Costs	Norwegian purse seine catch (h_{snt}) Herring	Mackerel	Blue whiting	Escapement (X_{st}) Herring	Mackerel	Blue whiting	Norwegian CPI
1998	1691	363	103	434	4120	1476	2119	0,78
1999	1700	383	111	474	4610	1556	1820	0,79
2000	1977	381	122	465	4426	1434	1707	0,82
2001	2377	235	127	496	4417	1436	1527	0,84
2002	2436	238	129	455	5281	1144	2621	0,85
2003	2122	213	117	710	5257	1290	2205	0,88
2004	2389	235	111	827	5612	1028	2621	0,88
2005	2555	301	81	819	6751	1238	2699	0,89
2006	2223	292	82	524	6913	1442	2625	0,91
2007	2489	441	91	456	6306	1561	2687	0,92
2008	2669	517	83	363	6445	1630	2400	0,96
2009	2580	513	86	181	6480	1835	2646	0,98
2010	2867	440	167	165	6061	1735	2907	1,00

Table A2
Results from fitting a multi-species logistic growth model to stock and harvest data[a].

Species	Herring	Mackerel	Blue whiting
Parameters			
r_s	.358	.589	.808
	(.089)[b]	(.133)	(.193)
k		27,462[c]	
		(6,925)	

[a] Stock and harvest data for 1998–2010, as treated and presented in (Ekerhovd & Steinshamn, 2016).
[b] Standard errors in parentheses.
[c] Thousand tonnes.

Table A3
Results from calibrating the cost function parameters, c_n, of the Norwegian purse seine fleet (thousand NOK[a]) for 1998–2010.

Herring	15,655,111
	(5,154,785)
Mackerel	16,886,829
	(6,120,300)
Blue whiting	1,154,117
	(1,699,684)

[a] Norwegian Kroner (NOK). Standard errors in parentheses.

The fact that the Icelandic industry is dominated by vertically integrated companies implies that Icelandic companies maximize the profit of the vertically integrated chain. In Norway the vessel owners are maximizing vessel profit. This may in part explain why the first hand (quay side) prices in Norway are higher than in Iceland. Furthermore, in Iceland the fishing quotas are concentrated on fewer vessels than in Norway meaning that landings per vessel are substantially higher for Icelandic vessels than for Norwegian vessels. This may explain why Norwegian vessels have higher cost per tonne landed than Icelandic vessels.

Taking this information into account, keeping in mind that in our model costs are defined per unit of effort, not per tonne landed, we scaled UK and Icelandic costs and prices to the Norwegian parameters presented in Table 1.

Sensitivity analysis

In the main analysis we have used zero discounting. We wish to compare this with a 10% discount rate. A change in the discount rate is not expected to affect the competitive case or the singletons, as in this case all agents are myopic, and discounting cannot make them more myopic than they already are.

It is, therefore, the cooperative case that is of most interest. First, we notice that the distribution of harvest between countries is not affected. Iceland is still only catching herring, the catch is increased by 17%, and Iceland still harvests with loss. Norway catches only mackerel as before, and more or less the same amount too. UK catches blue whiting as before, and also here the catch is increased by 17%. The steady state stock levels decrease marginally (between 2% and 12%). In other words, fairly small consequences of 10% discounting compared to zero. A bit higher harvest and lower stocks are as expected when discounting increases.

The cost per unit effort is assumed to be the same between species, due to similar technology, but vary between nations. In the main analysis Norway and UK have the same cost whereas Iceland has 50% lower cost. As Norway already is the most profitable country, we do not see any point in reducing its cost. Instead, we

Table A4
Sensitivity analysis of cost differences. Varying UK's cost factor by 10%, *certeris paribus*. Undiscounted profits 10^6 NOK[a] over 20 year for various coalition structures.

UK's cost factor	1.1				0.9			
Country[b]	NO	UK	ICE	Total	NO	UK	ICE	Total
Coalition structure								
Fully cooperative	509.5	0.5	−11.0	498.9	509.6	2.7	−11.6	500.7
(ICE,UK),(NO)	48.4	5.7	0.2	54.3	22.5	20	0	42.5
(ICE,NO),(UK)	60.2	3.2	1.2	64.6	25.6	14.9	0.6	41.1
(UK,NO),(ICE)	142.9	0.8	0.6	144.3	143.2	2.2	0.3	145.7
Fully non-cooperative	52.2	2.8	1.6	56.6	25.4	16.6	0.4	42.4

[a] Norwegian kroner (NOK)
[b] Norway (No), United Kingdom (UK), and Iceland (ICE).

Table A5
Sensitivity analysis of cost differences. Varying Iceland's cost factor by 10%, *certeris paribus*. Undiscounted profits 10^6 NOK[a] over 20 year for various coalition structures.

Iceland's cost factor	0.55				0.45			
Country[b]	NO	UK	ICE	Total	NO	UK	ICE	Total
Coalition structure								
Fully cooperative	509.3	1.8	−13.9	497.2	509.8	1.8	−9.4	502.2
(ICE,UK),(NO)	38	10.6	0	48.6	31	10.6	1.4	43
(ICE,NO),(UK)	42	7.8	0.6	48.6	42.1	7	1.2	50.3
(UK,NO),(ICE)	166.7	1.8	0.1	168.6	116.7	0.9	1.3	118.9
Fully non-cooperative	41.7	8.2	0.6	50.5	35.2	6.6	2.8	44.6

[a] Norwegian kroner (NOK)
[b] Norway (No), United Kingdom (UK), and Iceland (ICE).

varied the UK and Icelandic cost factors, one at the time, *ceteris paribus*, by 10%. The results, comparable to Table 2, are presented in Tables A4 and A5 for UK and Iceland, respectively.

For mackerel, Norway goes from a fixed price of NOK 9.48 to a demand function given by

$$p(h) = 11.8 - 0.002 \cdot h.$$

This means that for a catch equal to 1.16 million tonnes, the price is the same as the fixed price.

We look at the two extreme cases, namely full competition and full cooperation. In the competitive case, hardly anything changes with respect to herring and blue whiting. Also for mackerel the effect is relatively small. It is seen that market power leads Norway to harvest more mackerel and not less. Norway's harvest goes from round 650 to 715 thousand tonnes. The reason for this is that this is on the elastic part of the linear demand function.

In the cooperative case, on the other hand, market power implies change in the harvest distribution for mackerel, but no effect on total harvest, total stock or on the other two species. The harvest distribution of mackerel is changed such that instead of Norway harvesting close to 3 million tonnes, now UK harvest 2.15 million tonnes and Norway only 800 thousand tonnes. The reason is, of course, that a harvest around 800 thousand tonnes gives Norway a price close to NOK 9.9 whereas the old harvest of almost 3 million tonnes would give a price equal to NOK 5.5.

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