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PLAYING CHICKEN WITH SALMON

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ABSTRACT:

Wild Atlantic salmon are traditionally harvested from both the sea and spawning rivers during spawning runs. From an economic point of view, the return from sport fishing in rivers is several times higher than marine 'for meat only' harvests. This situation calls for a side payment regime where river owners pay marine fishermen not to fish, and where both parties gain. This paper argues that the reason why such side payment regimes are rarely seen, despite the obvious mutual gain, is due to the potential free-riding incentives among river owners. Although it is shown that the decision each river owner faces can be described as a game of chicken, taking the stochastic ecology into account may reveal a different pay-off structure. It is also demonstrated that the stochastic ecology of salmon, combined with price rigidities in the rivers, may explain the lack of side payment regimes.

Keywords: Atlantic salmon, game of chicken, recreational versus commercial fishing, side payment, stochastic ecology

JEL: Q22, Q26, D81

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Introduction

Here, we analyse the case where wild Atlantic salmon stock is harvested by both recreational anglers and commercial fishermen. Many studies have argued that the share of the total harvest caught in the recreational sector should typically increase because the value of the fish in this sector is greater than that in commercial fisheries (for example, see Cook and McGaw 1996, Laukkanen 2001, and Olaussen and Skonhoft 2005). However, when at least one party has property rights, agents left to their own devices should be able to allocate resources according to the well-known 'Coase Theorem'. Few examples of such arrangements are seen in the real world though, and criticism of the reality of Coasian mechanisms is widely recognized. Even so, some examples exist, e.g., the North Pacific Fur Seal Treaty of 1911, where the shared resource was nationalized to remove incentives to overexploit the fur seal, and where countries that lost their right to harvest were compensated (Wilen 1969). Another example stems from wild Atlantic salmon fisheries: initiated by the North Atlantic Salmon Fund, Faeroe Islands fishermen have been compensated for 'not fishing' their quota of Atlantic salmon since 1991.[i]

Atlantic salmon in Norway are harvested in two ways after they leave their offshore habitats and start their spawning runs.[ii] Before they reach their spawning rivers, they are first harvested by commercial fishermen in the fjords and inlets. During their upstream runs and stays in the rivers, they are next harvested by recreational anglers. Since it is clearly evident that the recreational sector is far more valuable than marine fisheries (Skonhoft and Logstein 2003), and that marine and river fishing rights follow the property rights of coastal and riparian lands, respectively, the situation calls for a bargain. One likely result is a closure of the commercial fishery financed by side payments from river owners.

In Norway, with more than 500 salmon rivers, only one such side payment agreement exists. It was initiated during the 2005 fishing season in the Trondheim fjord, in the middle of Norway. In this paper, we analyse the side payment-type agreement by focusing on the decision process facing river owners. The lack of side payment agreements thus far may be explained by incentives among river owners to act strategically. Since it is not possible to separate salmon with different home rivers before they enter a specific river, a river owner who pays marine fishermen not to fish also increases the fish stock in nearby rivers. Hence, each river owner has an incentive to 'free ride' on other river owners. Moreover, the stochastic ecology of Atlantic salmon makes a side payment less appealing because the contract is signed before actual stock levels are observed in the rivers. We show that these types of contracts, combined with rigid fishing license prices in the rivers, may explain why river owners seem to be reluctant to enter such arrangements.

Several studies have been concerned with the management of natural resources under conditions of uncertainty (see Nøstbakken 2005 for a recent overview). Reed (1979) developed a model where a stochastic ecological process due to multiplicative independent identically distributed environmental shocks takes place between the previous period's escapement and the current period's recruitment. Reed explored a situation where the manager chooses the harvest level after the uncertainty has been resolved; that is, after the actual current stock is observed. He demonstrated that in this setting, the optimal harvest policy is a bang-bang constant escapement rule. However, Clark and Kirkwood (1986) demonstrated that the constant escapement policy is no longer optimal if the manager chooses the harvest policy before the uncertainty is revealed. Weitzman (2002) analysed whether fees are better than quotas in the presence of stock uncertainty. In Weitzman's paper, the regulator chooses a landing fee or harvest quota before the state of the environment can be observed, while fishermen choose their fishing efforts after they observe both the management instrument and fish stock. Weitzman demonstrated that in such a situation, fees are always better than catch quotas under stock uncertainty. The key mechanism is that under stock uncertainty, it is better to control the effort undertaken by the fishermen than to try to directly control the number of fish they harvest.

McKelvey (1997) introduced game theory into a sequential interception fishery where the underlying stock uncertainty is included in the model with a stochastic pay-off function. Laukkanen (2003) built stock uncertainty into Hannesson's (1995) model with cooperative harvesting as a self-enforcing equilibrium supported by the threat of harvesting non-cooperatively forever if deviations are detected. Laukkanen argued that when including stochastic ecology into Hannesson's model, the agent who harvests the initial stock cannot infer if the other harvesting agent defected or not. Therefore, she defines conditions under which cooperative harvesting can be sustained as a self-enforcing equilibrium, even if the actions of one harvester are not observable owing to environmental shocks.

In this paper, river owners do not know current stock levels when they decide on their controls due to stochastic survival. Similar to Weitzman (2002), the control applied by the owners is fees (fishing permits) and not quotas, and the permit prices are set before nature reveals the survival. As opposed to the games in McKelvey (1997) and Laukkanen (2003), the interaction between the two management authorities (river owners) is not by harvesting the same fish stock, but through side payments to a third (marine) harvesting agent. Such agents harvest a fraction of both fish stocks before they enter the fishing zones controlled by the respective river authorities. Therefore, the game is one of side payments (acquisition of marine fishing rights). Equilibrium levels in mixed strategies are used as indicators of the likelihood that each manager cooperates (acquisition of marine fishing rights) or defects (no acquisition). The influence of stochastic survival of recruits on the mixed strategy equilibrium levels is analysed under two different price setting regimes in the rivers: rigid and flexible fishing permit prices. Rigid permit prices are in accordance with present price setting regimes in most salmon rivers because the permit prices are announced in the winter, long before the stock is observed (in summer) and the fishing season opens. Since this rigid price setting lacks motivation in any formal requirements, but rather seems to reflect some traditional practice, we want to analyse an alternative price setting regime that takes the stochastic ecology of salmon into account. Flexible permit prices mean that the permit price is set at the beginning of the fishing season, after the stock size can be determined.[iii] We demonstrate that when ecology is stochastic, rigid and flexible prices may shift the equilibrium mixed strategy levels in opposite directions. To our knowledge, this is the first application of strategic interactions on the management of recreational resources.

Side payments: the case of the Trondheim fjord Atlantic salmon fishery

Atlantic salmon stock spawn in their home river: that is, the river where the stock hatched and spent its presmolt (juvenile) period (approximately three years). After one or more winters in an offshore habitat, the stock returns to its home river to spawn. On this spawning run, the salmon is typically harvested in two sequential ways. As shown in Figure 1, the salmon is first harvested by marine fisheries in the fjords and inlets (see also Figure 1). The escapement from these fisheries reaches the spawning rivers and is harvested by recreational anglers. The remaining stock in the river after the fishing season closes spawns in the late autumn.

FIGURE 1 ABOUT HERE

In the Trondheim fjord, there are many salmon rivers, many river owners, and many marine fishermen. However, the various river owners are usually members of a river-specific organization called the *elveeier-lag* (river owner cooperation), where various management decisions are made by majority.[iv] Marine fishermen are organized into a similar cooperation called *Sør-Trøndelag Grunneiagar-og Sjøfiskarlag*. In late 2004, an organization called *Elvene rundt Trondheimsfjorden* (Trondheim fjord rivers), hereafter labelled *ErT*, was established. *ErT* is a non-profit organization established with the claimed goal of increasing the wild salmon stock in rivers (ErT 2005). The fact that there is no formal connection between *ErT* and the river owners is crucial for the strategic interactions between river owners. *ErT* negotiates with the marine fishermen in order to reach an agreement on acquisition of the marine harvest with respect to both quantity and price. More specifically, they agree on the price per kilo of salmon that the marine fishermen require for not fishing. Each marine fisherman is compensated based of his average yearly catch statistics over the last five fishing seasons. In addition, *ErT* stated that it would call off the deal unless at least 80% of the marine harvest comprised the contract (ErT 2005). Note that we neglect the potential game in price negotiations between *ErT* and marine fisheries throughout the paper. Since the marine fishermen achieve a substantially higher net price per kilo of salmon when they do not fish than when they do, it is evident that the price is pushed by the marine sector in a way that makes the marine fishermen better off. However, sharing rules are beyond the scope of this paper, which focuses on the non-cooperative game between different river owners. Hence, the outcome of negotiations between *ErT* and the marine fishermen is not taken into consideration.[v]

The agreement first took effect in the 2005 fishing season. The contract between *ErT* and the marine fishermen was signed with the intention to last for five years with a possible extension. However, since there are no binding contracts between *ErT* and the river owners, the financial foundation is somewhat loose. The various river owners intend to pay the marine fishermen through *ErT* after the fishing season in the river closes. Since they do not know beforehand how many owners will contribute, their own share of the costs is directly dependent on the decisions of other river owners. This financial question must be solved each year by *ErT*. As such, the decision to pay the marine fishermen has to be taken every year, dependent on the river owners (rivers) commitment to finance the agreement before each fishing season. Hence, if the agreed acquisition level is not financed before any given season, *ErT*, a non-profit organization with no financial power of its own, will be obliged to call off the agreement.

As indicated in Figure 1 and in the Introduction, it is not possible to separate salmon stocks from different rivers before they reach their spawning rivers. Hence, if owners of one river decide to pay the marine fishermen to stop fishing, they also increase the salmon stocks in other rivers in the fjord. From the river owner's point of view, it seems evident that each owner has an incentive to free ride on other owners; that is, providing the other owners decide to finance the acquisitions.

To fix the ideas, we present the management problem facing a river owner *i*, managing stock *i* in river *i*, and where other rivers are represented as j ($i \neq j$). $X_{i,t}$ is the size of the salmon population in river *i*, measured as biomass, (or number of "normalized salmon") year t. The salmon stock is first harvested by the commercial marine fishery, and the fraction $0 \leq h_t \leq 1$ is removed from the stock (see Figure 2). The escapement from this fishery, $(1-h_t)X_{i,t}$, constitutes the available stock in the recreational stream fishery. The effort in the river fishery is given by number of fishing days, $D_{i,t}$, which is the same as the number of fishing permits sold by the river owner. We assume that the offtake in the river follows the Schaefer-type harvest function. Hence, the total river yield is written as:

$$Y_{i,t} = qD_{i,t}\left[(1-h_t)X_{i,t}\right] \tag{1}$$

where $Y_{i,t}$ is the total offtake and q is the catchability coefficient. Note that the content in the bracket on the right-hand side of equation (1) is the total biomass available in the recreational fishery. Moreover we have that the total offtake in river i per definition writes

$$Y_{i,t} = y_{i,t}\left[(1-h_t)X_{i,t}\right]. \tag{2}$$

Hence, from equation (1) and (2), it follows that the fraction of stock removed due to harvesting is $y_{i,t} = qD_{i,t}$, and where $0 \leq y_{i,t} \leq 1$.[vi] The escapement from the recreational fishery takes part in the spawning and contribute to the future stock, $X_{i,t+\kappa}$ [vii], as given by equation (3) (again, see Figure 2).

$$X_{i,t+\kappa} = R\left((1-qD_{i,t})(1-h_t)X_{i,t}\right) = R(S_{i,t}) \quad (3)$$

FIGURE 2 ABOUT HERE

The demand for fishing licenses in the river is increasing in the quality of the fishing experience with respect to the stock $(1-h_t)X_{i,t}$ and decreasing in the fishing permit price $P_{i,t}$ (see Olaussen and Skonhoft (2005)). The river owner acts as a monopolistic supplier of fishing permits, restricting the supply in order to raise the profit. The monopolistic assumption means that the river owner, who offer fishing permits to the recreational anglers, is able to take advantage of the downward slope of the demand curve. The assumption of monopolistic behaviour fits with the behaviour of Norwegian river owners in a typical large salmon river. The competition from owners in other rivers may vary, and the crucial factor is the distance, which may vary between some few kilometres to over two hundred kilometres[viii]. The cost of providing fishing licenses $C\left(D_{i,t}\right)$ includes fixed as well as variable costs and where $C'(D_{i,t}) > 0$ and $C''(D_{i,t}) \geq 0$. The fixed cost are various types of costs associated with preparing the fishery (constructing and maintenance of tracks, fishing huts, and so forth), while the variable costs include the costs of organizing the fishing permit sale and enforcement.

The river owner has one additional control available; $A_{i,t}$, which is acquisition of fishing rights from the commercial fishery, measured in biomass of fish (see below). In the absence of strategic interactions with the other river owner, the owner *i* takes the stock in river *j* as given under the assumption that the river owner *j* makes no acquisitions ($(A_{j,t} = 0)$. As mentioned in the introduction, since it is not possible to separate between salmon with different home rivers before they actually enter a specific river, a river owner who pays marine fishermen not to fish, also unintentionally increases the fish stock abundance in nearby rivers (see Figure 1). The commercial fishing rate decreases with $A_{i,t}$ and is now written

$h(A_{i,t}) = \frac{h(0)\left(X_{i,t} + X_{j,t}\right) - A_{i,t}}{\left(X_{i,t} + X_{j,t}\right)}$, and thus, $h'(A_i) < 0$ $h''(A_i) = 0$, and $h(0) > 0$. Hence, per definition, $h(A_{i,t}) = h(0)$ when $A_{i,t} = 0$, and $A_{i,t}* = h(0)\left(X_{i,t} + X_{j,t}\right)$ defines the maximum acquisition level since $h(A_{i,t}*) = 0$. The yearly cost of acquisition, $G(A_{i,t})$, may contain both fixed and variable costs with $G'(A_{i,t}) > 0$, $G''(A_{i,t}) \geq 0$, and $G(0) \geq 0$ (see the numerical specification and results section).

We write the profit function for the river owner *i* simply as a function of the stock, permits and acquisition: $\pi_t = \pi(X_t, D_t, A_t)$ (omitting subskript *i* and $A_{j,t} = 0$). The stock dynamics is written $X_{t+\kappa} - X_t = R(X_t, D_t, A_t) - X_t = R(S_t) - X_t$.

With the discount factor $\psi^t = \frac{1}{\left(1+\delta\right)^t}$ where δ is the yearly rate of discount, the river owner maximises $L = \sum_{t=0}^{T-1} \psi^t \left\{\pi(X_t, D_t, A_t) + \psi^\kappa \lambda_{t+\kappa}(R(X_t, D_t, A_t) - X_t)\right\} + \psi^T J\left(X_T\right)$. $J(X_T)$ is the scrap value at time T while $\lambda_{t+\kappa}$ is the shadow price of the stock at time $t+\kappa$. The river owner thus maximises the object function (profit) over the whole planning period $t = 0...T$ subject to the ecological constraint. Note that as the shadow price $\lambda_{t+\kappa}$ is interpreted as the value of an additional unit of $X_{t+\kappa}$ from the perspective of period $t+\kappa$, the shadow price is discounted ψ^κ to be comparable with the object function, $\pi_t = \pi(X_t, D_t, A_t)$, that represent a value in period t (Conrad and Clark (1987)). In addition, acquisitions are bounded by the restriction $0 \leq A_t \leq A_t*$, while the restriction $D_t \geq 0$ is neglected. When appending the constraints to the multipliers w_1 and w_2 the bounded current value Hamiltonian is written (see Kamien and Schwartz (1991))

$$H = \pi(X_t, D_t, A_t) + \psi^\kappa \lambda_{t+\kappa}(R(S_t) - X_t) + w_1 A_t + w_2\left(A^* - A_t\right) \tag{4}$$

The Hamiltonian with specific functional forms is presented in the numerical specification and results section.

As previously mentioned, acquisitions are side payments from river owners to the marine fishermen to make them reduce their harvest. Hence, marine harvest activity is a decreasing function of the acquisition level. Since the marine harvest must be non-negative, there exists a maximum level of acquisitions, $A_i = A_i *$, where the marine harvest is zero. On the other hand, if the cost of acquisitions is high, the owner decides not to pay the marine fishermen and $A_i = 0$ corresponds to the marine harvest activity in the absence of acquisitions. Generally, all acquisition levels, $0 \le A_i \le A_i *$, are possible outcomes of the maximization problem facing the river owner. However, as previously mentioned, *ErT* demands that at least 80% of the marine harvest is covered by the contract. Hence, there exists a lower limit, A^L, on the possible acquisition level if the owner chooses $A_i > 0$ such that $A_i^L \le A_i \le A_i *$. To make the exposition as simple as possible in the rest of the paper, we let $A_i^L = A_i *$, such that the owner chooses between $A_i = 0$ and $A_i = A_i *$.[ix] We summarize the possible acquisition choices for river owner *i* as:

$$A_i = \begin{cases} A_i * \ if \ A_i > 0 \\ A_i = 0 \ \ otherwise \end{cases} \tag{5}$$

Deterministic environment, non-cooperative game

The model is presented with two river owners, 1 and 2, who manage two different rivers, 1 and 2, in a fully deterministic environment. The owners and rivers are assumed identical with respect to all relevant matters. These simplifying assumptions are for expositional tractability only; as will be discussed below, the key mechanisms in the model will be the same with more owners and rivers. By introducing strategic interactions between the two river owners when deciding on the control $A_i \ \ (i = 1,2)$, we show that these interactions result in a pay-off structure in accordance with the game of chicken (for example, see Dutta 1999). What is essential for the symmetric 2-player chicken game structure to hold is that $A_i = A_i *$ is the optimal choice for each owner given that the other owner plays $A_j = 0$, $j \ne i$. Since it is not possible to separate salmon with different home rivers before they actually enter a specific river, each owner has an incentive to free ride on the other river owner (see Figure 1 above).

As explained in the previous section, the agreement between the marine fishermen and the river owners is reached by the negotiating organization called *ErT.* Before the fishing season, each owner decides if they want *ErT* to pay the marine fishermen, and *ErT* divides the costs between the owners choosing $A_i = A_i*$. In this two-player scenario, *ErT* decides to pay the marine fishermen if at least one of the owners chooses $A_i = A_i*$. Hence, each river owner is able to bear the full cost of acquisition on his own. We start out by presenting the one-shot game followed by an extension to the repeated game.

The sequence of the deterministic one-shot game is as follows:

i) Each river owner i (i=1, 2) simultaneously makes their acquisition decision and reports it to *ErT* ($A_i = 0$ or $A_i = A_i*$) before the fishing season.
ii) The fishing permit price decision is determined by each owner's own acquisition decision and accompanying expected stock level.[x]
iii) *ErT* divides the costs of acquisition between the owners playing $A_i = A_i*$.

For notational convenience, let $\pi_i^{A,0}$ denote the pay-off to owner *i* if he buys fishing rights (plays $A_i = A_i*$) and the other owner decides not to buy fishing rights (plays $A_j = 0$). Let $\pi_i^{A,A}$ be the pay-off to owner *i* if both play $A_i = A_i*$. Furthermore, $\pi_i^{0,A}$ is the pay-off to owner *i* if he plays $A_i = 0$ and the other owner plays $A_j = A_j*$. Finally, $\pi_i^{0,0}$ is the pay-off to owner *i* when neither owner buys fishing rights. The game has a chicken-type structure as long as $\pi_i^{0,A} > \pi_i^{A,A} > \pi_i^{A,0} > \pi_i^{0,0}$. With this structure, it is easily recognized that there are two Nash equilibriums in pure strategies for the game. These are characterized as ($A_1 = A_1*, A_2 = 0$) and ($A_1 = 0$, $A_2 = A_2*$).

We now introduce the well-known notion of mixed strategies. In the game of chicken, as under many other pay-off schemes, both players would like to outguess the other. As stated by Osborne and Rubinstein (1994), mixed strategies entail a deliberate decision by a player to introduce randomness into his behaviour, just as it is optimal for poker players to randomly decide to 'bluff'. However, as discussed by Osborne and Rubinstein (1994), interpretation of the motivation for playing mixed strategies is not clear cut. Despite this, in our setting we interpret the mixed strategy as an indicator of the incentive for the owners to free ride on each other (see below). Hence, if owner 1 is certain that owner 2 will play $A_2 = 0$, then he has no incentive to free ride. On the other hand, if he is certain that owner 2 will choose $A_2 = A_2{*}$, then he has no incentive not to free ride. The mixed strategies equilibrium characterizes the situation in which an owners anticipation about the other owners choice is such that he is indifferent between playing $A_i = 0$ or $A_i = A_i{*}$. If both river owners follow a mixed strategy, we can show that a mixed strategy set exists for each owner in which they play either $A_i = 0$ or $A_i = A_i{*}$ with given probabilities.

Let $\rho_i(A^*)$ denote the probability that owner *i* plays $A_i = A_i{*}$, and that $\rho_i(0)$ is the probability he plays $A_i = 0$ and where $\rho_i(A^*) + \rho_i(0) = 1$. Playing a mixed strategy, it is straightforward to show (see Appendix B) that owner 1 plays $A_1 = 0$ when owner 2 plays $A_2 = A_2{*}$ with a probability greater than *m*, where *m* is given by:

$$m = \frac{\pi_1^{A,0} - \pi_1^{0,0}}{\pi_1^{A,0} - \pi_1^{0,0} + \pi_1^{0,A} - \pi_1^{A,A}}. \tag{6}$$

It follows directly from equation (6) that under the game of chicken, the pay-off structure *m* decreases when $\left(\pi_1^{0,A} - \pi_1^{A,A}\right)/\left(\pi_1^{A,0} - \pi_1^{0,0}\right)$ increases. Note that $\pi_1^{0,A} - \pi_1^{A,A}$ is the gain from free-riding when owner 2 plays $A_2 = A_2{*}$, while $\pi_1^{A,0} - \pi_1^{0,0}$ is the gain from not free-riding (or loss from free-riding) when owner 2 plays $A_2 = 0$. Hence, equation (6) shows that the mixed strategy equilibrium level decreases if the gain from free-riding when owner 2 plays $A_2 = A_2{*}$ increases relative to the loss from free-riding when owner 2 plays $A_2 = 0$. Recollect that owner 1 plays $A_1 = 0$ when owner 2 plays $A_2 = A_2{*}$ with a probability greater than *m*. Hence, when *m* decreases, owner 1 will free ride (plays $A_1 = 0$) in cases where the probability that owner 2 plays $A_2 = A_2{*}$ is lower. Furthermore, if *m* is zero, owner 1 always plays $A_1 = 0$.[xi] In this sense, we interpret the mixed strategy equilibrium level as an indicator of the incentive to free ride. Thus, the probability that owner 1 will free ride increases as *m* decreases. In that sense, we interpret the mixed strategy equilibrium level *m* as an indicator of the incentive to free ride.

If extended to an infinitely repeated game, and with the owners playing credible punishment (trigger) strategies, they may both play $A_i = A_i*$. Hence, the overall yearly pay-off is $2\pi_i^{A,A}$, with a discount factor close enough to one (for example, see Gibbons 1992, Dutta 1995). This is analogous to the 'Folk Theorem', which states that the cooperative solution of the repeated 'prisoner's dilemma' can be supported as a Nash equilibrium. However, credible threats may be difficult to impose in the game of chicken because the punisher gains from deviating from their punishment strategy. Thus, it is unlikely to be in the interest of the punisher to punish (Fudenberg and Maskin 1986). In addition, if there is any reputation-building, as introduced by Kreps and Wilson (1982), then the long-term outcome of the game will certainly coincide with the one-shot Nash equilibriums of the game. However, in the short-term, reputation manipulation and an initial phase where no owner wants to reveal that they would gain from unilateral deviations may occur. Nevertheless, once one of the owners deviate and play $A_i = A_i*$, their reputation as an $A_i = 0$ player is destroyed, and their opponent may safely play $A_j = 0$ forever.[xii] Hence, in the case of reputation manipulation, any of the Nash equilibrium outcomes of the one-shot game, $A_1 = A*,\ A_2 = 0$, and $A_1 = 0,\ A_2 = A_2*$, is also supported as the long-term Nash equilibrium after an initial phase of both playing $A_i = 0$.

Stochastic game

In this section, we consider the extent in which the game is affected by relaxing the deterministic ecology assumption. According to Hvidsten, Fiske, and Johnsen (2004), the stochastic ecology involved makes the wild salmon stock in any given year very difficult to predict based on the number of recruits in the cohort. When the wild Atlantic salmon survival rate is stochastic, we expect owners to be less willing to buy fishing rights from the marine harvesters. With random survival, the economic consequences of a bad year (low survival) are shared between the owners and the marine fishermen as they both face a risk of low salmon survival. If the owners buy the marine fishing rights, they pay (or commit to pay) a fixed sum to the marine fishermen not to fish before the survival is observed. This means that the outcome in the marine fisheries no longer depends on random survival, but rather yields a deterministic profit to the marine fishermen. On the other hand, the river owners suddenly undertake the whole risk due to the uncertainty they used to share with the marine fishermen. Therefore, this suggests that owners face greater uncertainty with respect to pay-offs if they buy the marine fishing rights. Consequently, assuming risk-neutral or averse river owners, we expect the owners to be less eager to buy fishing rights in a stochastic environment than in the deterministic environment analysed earlier. As it turns out, we note that this belief is correct only under certain assumptions, and that the crucial factor is how license price determination in the river takes place.

As described above, the contract between river owners and marine fishermen is signed via *ErT* before the fishing season opens. The acquisition price per kilo of salmon, as well as the total quantity, is determined. The quantity decision is based on the average marine harvest reported in historical catch data over the five previous seasons. Since this is based on average catches, the river owners commit themselves to a binding contract where their only adjustment due to the stochastic ecology after the acquisition decision is made is through the fishing permit sale. That is, the acquisition payment represents a sunk cost once the contract is signed. In the deterministic world, the river owners know the spawning stock for certain, and hence could set the license price based on the actual stock size. As discussed, we address two different price setting regimes in the recreational fishing sector: i) rigid (sticky) permit prices; and ii) flexible permit prices.

i) Rigid permit prices (*rp*): The owner decides on whether to buy fishing rights, as well as the cost of the fishing licenses, before the stochastic move by nature is observed.[xiii] Rigid permit prices are in accordance with the present price setting regimes in most salmon rivers because permit prices are announced in the winter, long before the stock is observed (in summer) and the fishing season opens.

ii) Flexible permit prices (*fp*): Flexible permit price setting means that the river owner is able to adjust the price at the beginning of the fishing season.

In the absence of strategic interactions, flexible permit price setting is, in principle, exactly the same as rigid permit prices in the deterministic case. However, flexible permit prices differ from the deterministic rigid price setting in that a free-riding river owner is able to adjust the permit price, not only because of stochastic ecology, but also because of the choice of acquisition by the other river managers. Thus, it is the actual stock size and not acquisitions or favourable ecological conditions that determine the permit price decision. Hence, in order to compare the stochastic and deterministic case, flexible prices will also need to be considered in the deterministic case.

Let the random component affecting survival at stage t be statistically independent, uniformly distributed, and denoted z_t. The mean value is equal to 1, $E(z_t) = 1$. Hence, expected survival is equal to the deterministic survival rate (see section below for more details). The interpretation of a given z_t is that it expresses the random component in the survival from recruitment to spawning age (caused by some environmental stochasticity, e.g., due to changes in river (or sea) temperature or parasite density in the fjords when the smolt leave the river).[xiv]

Provided that the only unpredictable events affecting the stage return and the stage transformation at stage t are those occurring at stage t, and not any earlier (a Markov decision process), the maximization problem may be formulated as a stochastic dynamic programming problem without any additional state variables (Kennedy 1986). As noted by Kennedy (1986), the optimal control path cannot be found by tracking forward from the initial state without knowing the exact sequence of the random events. Furthermore, the optimal decision choice $\left(A_i = A_i^*, A_i = 0\right)$ is the same in the stochastic and deterministic cases as long as $E(z_t) = 1$ (Kennedy 1986). Hence, decisions expected under the stochastic environment assumed here are the same as those in the deterministic case. This is easily interpreted into the actual problem facing each owner. Since they are unable to predict actual stock size in any given year, they base their decision on the expected stock: that is, the average stock size. This may be referred to as the 'rule of thumb management', which actually take place in these kinds of recreational fisheries.[xv]

Let $\pi(rp)_i$ denote the profit to owner *i* when survival is stochastic and the permit price decision is rigid, and let $\pi(fp)_i$ denote the profit when the permit price decision is flexible. For the chicken game structure to hold, $\pi(\ )_i^{0,A} > \pi(\ )_i^{A,A} > \pi(\ )_i^{A,0} > \pi(\ )_i^{0,0}$ must occur for both rigid and flexible permit prices. Furthermore, we let *m(rp)* and *m(fp)* denote the mixed strategy equilibrium levels under rigid and flexible prices, respectively. Hence, analogous to the discussion for equation (6), and provided the chicken game structure holds, the mixed equilibrium levels are characterized by:

$$m(rp) > m \quad if \quad \frac{\pi(rp)_1^{0,A} - \pi(rp)_1^{A,A}}{\pi(rp)_1^{A,0} - \pi(rp)_1^{0,0}} < \frac{\pi_1^{0,A} - \pi_1^{A,A}}{\pi_1^{A,0} - \pi_1^{0,0}} \tag{7}$$

and

$$m(fp) > m \quad if \quad \frac{\pi(fp)_1^{0,A} - \pi(fp)_1^{A,A}}{\pi(fp)_1^{A,0} - \pi(fp)_1^{0,0}} < \frac{\pi_1^{0,A} - \pi_1^{A,A}}{\pi_1^{A,0} - \pi_1^{0,0}} \tag{8}$$

In the next section, the relationship between *m*, *m(rp)*, and *m(fp)* is analysed under the empirical specifications given below and in Appendix A.

Numerical specifications and results

The parameter values are reported in Appendix A. Biological and economic data are in accordance with a typical large Atlantic salmon river in Norway. A biological investigation conducted by Hvidsten et al. (2004) provides the only data available worldwide that estimates the recruitment function in a large Atlantic salmon river, more exactly, the river Orkla some 40 kilometres west of Trondheim. They find that the recruitment function $R(.)$ is close to the Beverton Holt type, but that neither the Cushing nor the Ricker type recruitment can be ruled out. It is therefore convenient to write it as the Sheperd (1982) recruitment function[xvi]:

$$R(.) = \left[\frac{srS}{1 + \left(\frac{S}{K} \right)^{\gamma}} \right], \tag{9}$$

Where *s* is the deterministic survival of recruits, *r* is the maximum recruits per spawning salmon, and *K* is the stock level where density dependent mortality factors start to dominate stock independent factors.[xvii] Finally, the compensation parameter γ is the degree to which density-independent effects compensate for changes in stock size. We assume for simplicity that the random ecology variable, z, takes only two values: 0.6 and 1.4, and hence the mean value is equal to 1 and corresponds to the deterministic ecology in Hvidsten et al (2004). In Hvidsten, Fiske and Johnsen (2004), the estimated standard deviation for the Trondheim fjord salmon stock is even higher (0.45), but are based on very rough estimates for the period 1997-2003 (except 2002) according to the authors. As already mentioned, the most straightforward interpretation of the stochastic component is that the survival of recruits from spawning to mature age is stochastic, and hence that the stochastic survival rate is 0.07 and 0.03 in good and bad years respectively, such that the expected survival rate is consistent with the deterministic rate of 0.05 and *zs* replaces *s* in equation (9)[xviii].

The inverse demand function for recreational fishing permits reads

$$P(D,X) = \alpha q(1-h(A))X - \beta D \ . \tag{10}$$

The choke price α gives the maximum willingness to pay when the quality-translated catch is one fish per day, whereas β reflects the price response in a standard manner. The demand function is linear in number of permits while a stock increase shifts demand up through catch per day (see e.g. Skonhoft and Logstein 2003). The cost function is specified as $C(D) = C + cD$, where C and c are the fixed and the marginal costs of providing fishing permits, respectively. In addition the acquisition cost function is specified as $G(A) = G + gA$ where G and g are the fixed and marginal costs of buying up marine fishing rights respectively. The calibration of the model is discussed in Appendix A since the parameter values are crucial for the motivation of the chicken structure of the game. With specific functional forms, the present version of equation (4) is written

$$\begin{aligned} H &= \left[\alpha q(1-h(A_t))X_t - \beta D_t\right]D_t - C - cD_t - G - gA_t \\ &\quad + \psi^{\kappa}\lambda_{t+\kappa}\frac{sr(1-h(A_t))(1-qD_t)X_t}{\left[1+\left[\frac{(1-h(A_t))(1-qD_t)X_t}{K}\right]^{\gamma}\right]} + w_1 A_t + w_2(A^* - A_t) \end{aligned} \tag{11}$$

Since the time lag in recruitment is 5 years, the stock dynamics is given by a fifth order differential equation, and hence no analytical solutions are obtainable[xix]. However, running numerical simulations by applying the Excel Solver is straightforward. The profit of the river owners are maximized over the planning period given the stock dynamics and with restrictions on possible acquisition levels and permit price flexibility. The results presented in Tables 1-4 are based on 100 iterations over a 20 year planning period. However, the results are not sensitive to longer planning horizons. Stochastic survival is added by the random number generator[xx]. The mean values are reported in the tables below, and in the stochastic case the average bad and good year results are reported as well (inside brackets).

Deterministic ecology, rigid prices

The pay-off matrix in the deterministic environment is reported in Table 1, and shows that the expected return on acquisitions is strictly dependent on the choice of the other river owner. Since the owners and rivers are identical, a full bi-matrix with the results of both owners is superfluous: the results in river 2 are identical to the results in Table 1 in the upper-left and lower-right cell. Furthermore, if river owner 1 yields the results in the upper-right cell, e.g., $\pi_1^{0,A} = 3266$ (in 1000 NOK), the numbers in the lower-left cell represent the results in river 2, in that $\pi_2^{A,0} = 1709$, and vice versa. Hence, the overall river owner profit in the two Nash equilibrium outcomes is NOK 4975. Note that the overall river owner profit in the two rivers taken together is highest in the case where both owners buy fishing rights (NOK 2692*2=5384).

The fishing permit price in river 1 increases (NOK 0.280→ NOK 0.400) due to the increased demand accompanying the increasing stock entering the river if owner 1 plays A_1*.[xxi] Total fish stocks are more or less the same while the fishing effort in the river increases as a result of more fish entering the river. The explanation is that an increasing fishing effort in the river dampens the direct stock effect following the acquisition. Note that when river owner 1 is a successful free rider, his permit price does not increase (Table 1, upper-right cell). This is because each owner bases his permit price on his own acquisition decision, as described in above (this assumption is relaxed below). Although these results support the chicken game structure, they are of course sensitive to the baseline values reported in Appendix A. Generally, an increasing willingness to pay for fishing licenses and/or decreasing acquisition costs strengthens the chicken game pay-off structure. On the other hand, a decreasing willingness to pay for fishing permits and increasing acquisition costs pulls in the direction of a prisoner's dilemma-type pay-off structure.

TABLE 1 ABOUT HERE

Stochastic ecology, rigid prices

As previously discussed, when the ecology is stochastic, river owners do not have reliable indications of stock sizes before the fishing season starts. By rigid prices, we mean that owners do not adjust permit prices during the fishing season. Acquisition and price decisions are taken under anticipation that survival takes on average values.

TABLE 2 ABOUT HERE

In this case, the expected returns facing river owners change from the deterministic case, as shown in Table 2. It is likely that owners face a lower pay-off from any outcome other than in the deterministic case as they will generally set the wrong permit price because of stochastic survival. Note that in years with low salmon abundance, acquisitions yield a loss, even if both owners play $A_i = A_i *$. In addition, the relative expected outcomes of playing $A_i = 0$ and $A_i = A_i *$ are generally altered. This is illustrated by inserting the profit values reported in Tables 1 and 2 into equation (6). Recollect that *m* and *m(rp)* denote the mixed strategy threshold values with rigid prices in the deterministic and stochastic cases, respectively (Tables 1 and 2). We find that free rider incentives are strengthened in the stochastic case because $m = 0.09$ while $m(rp)$ is not defined. This is due to the pay-off structure of the game being turned into the prisoner's dilemma; hence, the pure strategy $A_i = 0$ strictly dominates $A_i = A_i *$.[xxii] As a result, in the stochastic case, we have a new Nash-equilibrium, $A_i = 0 \ \ (i = 1 \wedge 2)$, with finite repetitions and $A_i = A_i * \ \ (i = 1 \wedge 2)$ in the infinitely repeated game according to the standard prisoner's dilemma theory (for example, see Gibbons 1992). The yearly river owner surplus increases substantially in the 'cooperative' $A_i = A_i * \ \ (i = 1 \wedge 2)$ solution compared with the $A_i = 0 \ \ (i = 1 \wedge 2)$ situation. Note also that the average stock size and price of permits, and hence the number of permits, are quite similar under deterministic and stochastic survival. However, in the stochastic case, permit prices are generally incorrect because they are based on the expected stock level. Thus, in a year with low salmon stock, the permit price based on the average stock size is too high, and the demand is reduced below that which is optimal. In the same manner, in a year with high salmon stock, the price is below its potential. Consequently, due to the fact that permit prices will be generally wrong, the losses connected to acquisitions when survival is low are substantial, and vice versa: the gains when survival is high are below their potential. This will be demonstrated in Table 4.

Flexible prices

In this sub-section, we assume that the permit price decision is taken during the fishing season, just after the river owner observes the salmon stock in the rivers: that is, just after it is possible to observe if it is a 'good' or 'bad' year with respect to survival. As mentioned above, in order to compare the deterministic and stochastic case, we recalculate the deterministic outcome for a free rider under the assumption that they are able to adjust the permit price according to actual salmon stock. Hence, the free rider is able to adjust the permit price if he observes a large salmon stock due to an acquisition by the other river owner. The new deterministic pay-off matrix is presented in Table 3, and the results for the stochastic case are given in Table 4.

TABLE 3 AND 4 ABOUT HERE

Note first that under deterministic conditions, the only difference from the rigid price setting in Table 1 is in the upper-right cell. This shows that the gain from successful free-riding in the Nash-equilibrium is higher (NOK 3675 versus NOK 3266) when the permit price decision is made flexible. Inserting from Table 3 into equation (6), we find that the new mixed strategy threshold level under deterministic ecology and flexible permit prices is $m = 0.05$ (as opposed to $m = 0.09$ with rigid prices). This means that the incentive to free ride is higher than under sticky prices in the deterministic case. On the other hand, in this case the stochastic ecology of salmon pulls the free-riding incentives in the other direction. This is seen by calculating the mixed strategy threshold level under stochastic ecology and flexible permit prices, which yield $m(fp) = 0.27$ (inserted in equation (6) from Table 4). The reasoning is straightforward as the losses from acquisitions in years with low survival rates are reduced, and the gains in good years are increased. This is only partly counterbalanced by the increased gain from a successful free rider strategy.

Discussion and some concluding remarks

The acquisition question considered in this paper analyses Coasian mechanisms and a potential reason as to why Coasian solutions often seem hard to achieve in cases of natural resource management. We demonstrate that the stochastic ecology of wild Atlantic salmon may explain the lack of side payment agreements in Norwegian fjords. In a game apparently described as having a chicken game pay-off structure, the game may in reality be of the prisoner's dilemma type when stochastic ecology is taken into account. Moreover, we find that if the river owners take stochastic ecology into account, the way they set permit prices is crucial for acquisition decisions. As previously mentioned, the 'as if myopically omniscient' regulator benchmark in Weitzman (2002) coincides with our flexible price setting regime. By combining the rigid versus flexible price setting aspect with strategic interactions, we gain additional insights. Rigidities characterizing the permit price decision today may explain why river owners are reluctant to buy fishing rights by strengthening the incentive to free ride. With rigid prices and stochastic survival, the owners earn less when survival is high, and may even face potential losses when survival is low.

The model presented here may seem restrictive in its assumptions, e.g., with only two homogenous river owners. On the other hand, the gain is that we could focus solely on how stochastic ecology affects strategic interactions. Thus, we could neglect other potential and previously more extensively studied reasons as to why Coasian solutions may not arise, such as transaction costs, many agents, and so forth. In addition, from this simple set up it is easy to see when these restrictions are crucial for results, when they are not, and what economic driving forces determine the structure of the game. As previously mentioned, if there are more than two rivers (or owners), the same type of game structure may be achieved as long as each owner is large enough to benefit, even if they must bear the costs of acquisitions on their own.[xxiii] We may also translate the model into terms of two groups of rivers, where the Nash equilibrium is characterized by a group of rivers that pay for acquisitions and a group that do not. Moreover, if the two rivers (or groups of rivers) considered are heterogeneous, e.g., with respect to river size and salmon stock abundance, the same type of argument holds. The crucial point is that each river owner may benefit, even if they bear the costs of acquisitions on their own. Generally, the larger the stock in river 2 is relative to the stock in river 1, the more likely free-riding in river 1 will occur since the cost of acquisitions increases, and vice versa: smaller stock size in river 2 makes acquisition payments in river 1 more likely.

The present analysis sheds some light over other situations in which different agents utilize the same ecological resource, and where seemingly obvious gains from side payment regimes appear to be neglected. For example, this is often the case where one harvesting agent is more cost efficient than another. However, in spite of all the potential side payment solutions in natural resource management, few examples of such arrangements exist. The influence of stochastic ecology on the strategic management decisions analysed here is one of the factors that may help explain why such Coasian outcomes are rarely seen.

Table 1. *Deterministic ecology. Pay off matrix for river owner 1, given the simultaneously taken acquisition decision by the other river owner. A_i is acquisition of fishing rights by river owner i (i=1,2), π_1 is the profit in river 1 (in NOK 1000), P_1 is the fishing permit price in river 1 (in NOK 1000), X_1 is the salmon stock level in river 1 (in 1000 salmon), D_1 is the number of number of fishing permits (in 1000 fishing permits), A_1 is acquisition level (in 1000 salmon).*

	$A_2=0$	$A_2=A^*$
$A_1=0$	**$\Pi_1=1656$** $P_1=0.280$ $X_1=15.6$ $D_1=7.2$	**$\Pi_1=3266$** $P_1=0.280$ $X_1=15.7$ $D_1=14.2$
$A_1=A^*$	**$\Pi_1=1709$** $P_1=0.400$ $X_1=15.9$ $D_1=10.5$ $A_1=9.5$	**$\Pi_1=2692$** $P_1=0.400$ $X_1=15.9$ $D_1=10.5$ $A_1=4.8$

Table 2. *Stochastic ecology: Rigid permit price. Pay off matrix for river owner 1, given the simultaneously taken acquisition decision by the other river owner. Results in average values when survival is 0.03 and 0.07 with uniform distribution: Values inside brackets indicate average values with survival equal to 0.03 and 0.07 respectively.* A_i *is acquisition of fishing rights by river owner i (i=1,2),* π_1 *is the profit in river 1 (in NOK 1000),* P_1 *is the fishing permit price in river 1 (in NOK 1000),* X_1 *is the salmon stock level in river 1 (in 1000 salmon),* D_1 *is the number of number of fishing permits (in 1000 fishing permits),* A_1 *is acquisition level (in 1000 salmon).*

	$A_2=0$	$A_2=A^*$
$A_1=0$	**Π_1=1576** [138,3013] P_1=0.280 X_1=15.4 [9.5, 21.3] D_1=7.0 [0.6,13.1]	**Π_1=3051** [1173, 5014] P_1=0.280 X_1=15.2 [9.6, 20.7] D_1=13.5 [5.1, 21.8]
$A_1=A^*$	**Π_1=1307** [-1546, 4159] P_1=0.400 X_1=15.1 [9.7, 20.6] D_1=10.0 [1.2,17.5] A_1=9.1 [5.8, 12.4]	**Π_1=2290** [-563, 5142] P_1=0.400 X_1=15.1 [9.7, 20.6] D_1=10.0 [1.2, 17.5] A_1=4.5 [2.9, 6.2]

Table 3. *Deterministic ecology: Flexible permit price. Pay off matrix for river owner 1, given the simultaneously taken acquisition decision by the other river owner.* A_i *is acquisition of fishing rights by river owner i (i=1,2),* π_1 *is the profit in river 1 (in NOK 1000),* P_1 *is the fishing permit price in river 1 (in NOK 1000),* X_1 *is the salmon stock level in river 1 (in 1000 salmon),* D_1 *is the number of number of fishing permits (in 1000 fishing permits),* A_1 *is acquisition level (in 1000 salmon).*

	$A_2=0$	$A_2=A^*$
$A_1=0$	**$\Pi_1=1656$** $P_1=0.280$ $X_1=15.6$ $D_1=7.2$	**$\Pi_1=3675$** $P_1=0.400$ $X_1=15.9$ $D_1=10.5$
$A_1=A^*$	**$\Pi_1=1709$** $P_1=0.400$ $X_1=15.9$ $D_1=10.5$ $A_1=9.5$	**$\Pi_1=2692$** $P_1=0.400$ $X_1=15.9$ $D_1=10.5$ $A_1=4.8$

Table 4. *Stochastic ecology: Flexible permit price. Pay off matrix for river owner 1, given the simultaneously taken acquisition decision by the other river owner. Results in average values when survival is 0.03 and 0.07 with uniform distribution. Values inside brackets indicate average values with survival equal to 0.03 and 0.07 respectively.* A_i *is acquisition of fishing rights by river owner i (i=1,2),* π_1 *is the profit in river 1 (in NOK 1000),* P_1 *is the fishing permit price in river 1 (in NOK 1000),* X_1 *is the salmon stock level in river 1 (in 1000 salmon),* D_1 *is the number of number of fishing permits (in 1000 fishing permits),* A_1 *is acquisition level (in 1000 salmon).*

	A_2=0	A_2=A*
A_1=0	**Π_1=1924** [516, 3332] P_1=0.280 [0.170, 0.390] X_1=15.6 [9.5, 21.7] D_1=7.1 [4.3, 9.8]	**Π_1=4255** [1216, 7293] P_1=0.400 [0.240, 0.560] X_1=15.8 [9.6, 22.0] D_1=10.4 [6.4, 14.3]
A_1=A*	**Π_1=2289** [-750, 5327] P_1=0.400 [0.240, 0.560] X_1=15.8 [9.6, 22.0] D_1=10.4 [6.4, 14.3] A_1=9.5 [5.8, 13.2]	**Π_1=3272** [233,6310] P_1=0.400 [0.240, 0.560] X_1=15.8 [9.6, 22.0] D_1=10.4 [6.5, 14.3] A_1=4.7 [2.9, 6.6]

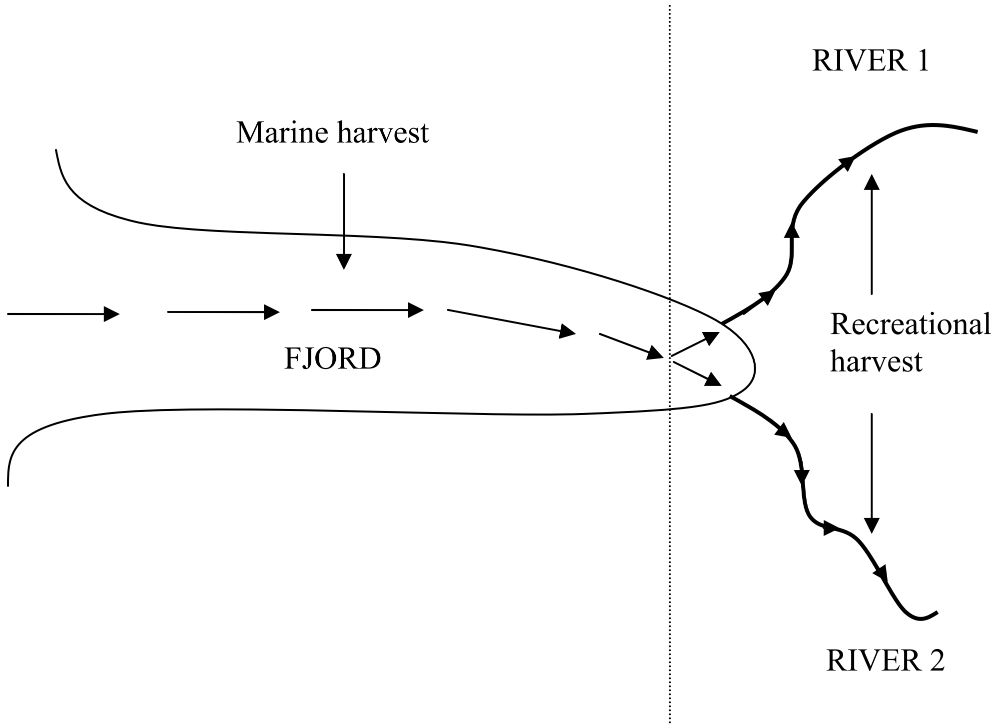

Figure 1. Marine and recreational harvest.

The direction of the spawning run of salmon is indicated by arrows. Spawning takes place in the rivers in the late autumn after the fishing season closes.

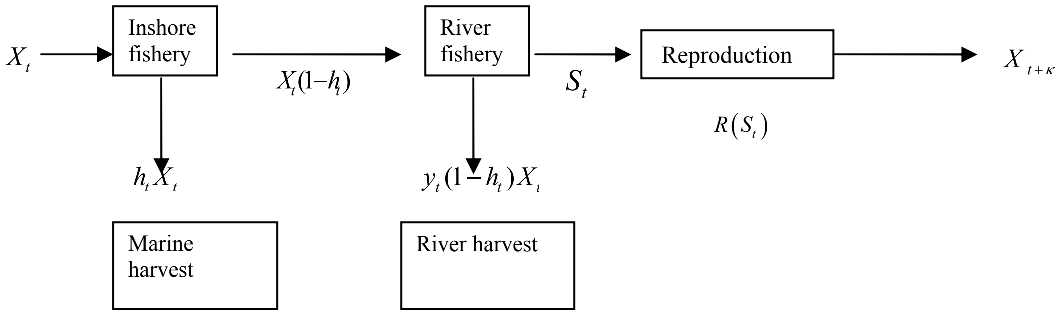

Figure 2. Harvest and reproduction

t is time subscript, X is stock size, h is marine and y is river harvest rate, S is spawning stock, R the recruitement function, and κ *is the time lag in recruitment.*

Appendix A: parameter values

The parameter definitions, values, and sources are presented in table A1. As mentioned, the ecological values are based on the Orkla survey by Hvidsten et al (2004). The economic values are calibrated to fit with a typical large Atlantic salmon river such as Orkla. Hence, willingness to pay fits both with survey (postal CV) results in Aas, Birkelund, and Thrane (2000) and Olaussen (2005) as well as with the actual fishing permits prices in the river Orkla. Moreover, the number of fishing permits and the recreational harvest rate fits with the actual situation in the river Orkla.

The crucial question for the chicken game structure to hold is: How much does the willingness to pay among anglers increase if the available salmon stock in the river increases? In Olaussen (2005), Norwegian salmon anglers were asked how much their willingness to pay per daily fishing permit increased if the available stock in the rivers increased by 30%, which is in accordance with the average stock increase in the river due to A=A* (no marine harvest). The reported average increase in the willingness to pay was NOK 0.120 per fishing permit (n=231), which is in accordance with the results presented supporting the chicken game pay off structure (the permit price increases from NOK 0.280 to NOK 0.400 per fishing permit).

Another crucial factor is the acquisition costs. The values in Table A1 are in accordance with the costs of acquisitions in 2005, where the price per kilo salmon was NOK 0.07 per kilo according to *ErT (2005)*. The baseline fixed cost of acquisitions (transaction costs) is set equal to zero. Sensitivity analyses show that in the two deterministic cases, the pay off structure changes to the Prisoners dilemma type when $G >$ NOK 53, while it takes NOK 365 in the stochastic case with flexible permit prices. All parameters are defined and the baseline values are summarized in Table A1.

Table A1: Baseline values prices and costs, ecological and other parameters.

Parameter	Parameter description	Value	Reference/Source
r	Maximum recruitment per spawning salmon	270 (smolt per spawning salmon)	Hvidsten et al. (2004)
γ	Decides to which extent density independent factors compensates for stock changes	0.00106	Hvidsten et al. (2004)
K	Stock level where density dependent mortality dominates density independent factors	1489 (number of spawning salmon)	Hvidsten et al. (2004)
s	Deterministic survival rate recruits	0.05	Hvidsten et al. (2004)
α	Reservation price when catch per day is 1	1.500 (1000NOK/salmon)	Olaussen (2005)/calibrated
β	Price effect demand	0.00003 (1000NOK/day^2)	Olaussen (2005)/ calibrated
c	Marginal cost fishing permit sale	0.05 (1000NOK/day)	calibrated
C	Fixed cost fishing permit sale	0	Birkelund, Lein, and Aas (2000)/ calibrated
q	Catchability coefficient	0.00003 (1/day)	Fiske and Aas (2001)
h	Marine harvest rate	0.3	NOU (1999:9) Hvidsten, Fiske, and Johnsen (2004)
κ	Time lag recruitment	5 years	NOU (1999:9) Hvidsten, Fiske, and Johnsen (2004)
g	Marginal cost of acquisition	0.07 (NOK/Kg)	ErT (2005)
G	Fixed cost acquisition agreement.	0	ErT (2005)
z	Stochastic ecology parameter	u.d: (0.6, 1.4)	Hvidsten, Fiske and Johnsen (2004a)

Appendix B:

Given the outputs in the pay off matrix above, the owner in river 1 hence maximises (see e.g. Varian 1992)

$$\max_{\rho_1(A^*),\rho_1(0)} \quad \rho_1(0)\left[\rho_2(0)\pi_1^{0,0}+\rho_2(A^*)\pi_1^{0,A}\right]+\rho_1(A^*)\left[\rho_2(0)\pi_1^{A,0}+\rho_2(A^*)\pi_1^{A,A}\right]$$

s.t. $\rho_1(0)+\rho_1(A^*)=1$, $\rho_2(0)+\rho_2(A^*)=1$, $\rho_1(0)\geq 0$, $\rho_1(A^*)\geq 0$, and $\rho_2(0)\geq 0$, $\rho_2(A^*)\geq 0$.

The Lagrangian takes the form

$$\underset{\rho_1(A^*),\rho_1(0)}{L} = \pi_1^{0,0}\rho_1(0)\rho_2(0)+\pi_1^{0,A}\rho_1(0)\rho_2(A^*)+\pi_1^{A,0}\rho_1(A^*)\rho_1(0)+\pi_1^{A,A}\rho_1(A^*)\rho_2(A^*)-$$
$$\lambda\left[\rho_1(0)+\rho_1(A^*)-1\right]-\mu_0\rho_1(0)-\mu_A\rho_1(A^*)$$

where λ, μ_0 and μ_A are the Kuhn-Tucker multipliers on the constraints. Differentiating with respect to $\rho_1(0)$ and $\rho_1(A^*)$ gives the Kuhn-Tucker conditions for river owner 1 as

$\pi_1^{0,0}\rho_2(0)+\pi_1^{0,A}\rho_2(A^*)-\lambda-\mu_0=0$ and $\pi_1^{A,0}\rho_2(0)+\pi_1^{A,A}\rho_2(A^*)-\lambda-\mu_A=0$.

We only consider the mixed strategies where $\rho_1(0)>0$ and $\rho_1(A^*)>0$ since the pure strategy solutions $A_1=0$ and $A_1=A_1{}^*$ are easily recognised, and hence the complementary slackness condition implies that $\mu_0=\mu_A=0$. Recollecting that $\rho_2(0)+\rho_2(A^*)=1$, we may solve for $\rho_2(A^*)$, and by following the same procedure for river owner 2 we find $\rho_1(A^*)$. Owner i`s best-response correspondence is dependent on what he believes the other owner will do. Since we have that $\rho_2(0)=1-\rho_2(A^*)$, owner 1`s expected pay off by playing $A_1=0$ and $A_1=A_1{}^*$ is $\pi_1^{0,0}-\rho_2(A^*)\pi_1^{0,0}+\rho_2(A^*)\pi_1^{0,A}$ and $\pi_1^{A,0}-\rho_2(A^*)\pi_1^{A,0}+\rho_2(A^*)\pi_1^{A,A}$ respectively. Hence, owner 1 is indifferent between these two strategies if

$\pi_1^{0,0}-\rho_2(A^*)\pi_1^{0,0}+\rho_2(A^*)\pi_1^{0,A}=\pi_1^{A,0}-\rho_2(A^*)\pi_1^{A,0}+\rho_2(A^*)\pi_1^{A,A}$, and solving for $\rho_2(A^*)$ yields $\rho_2\left(A^*\right)=\dfrac{\pi_1^{A,0}-\pi_1^{0,0}}{\pi_1^{A,0}-\pi_1^{0,0}+\pi_1^{0,A}-\pi_1^{A,A}}=m$ (equation (2) in main text).

References:

Aas, Ø., H. Birkeland, and C. Thrane. 2000. Laksefiskere I Orkla, Namsenvassdraget, Altaleva og Eibyelva: fiskevaner, holdninger til fiskevaner og økonomisk forbruk. *NINA Oppdragsmelding 665*.

Birkelund, H, K. Lein, Ø. Aas. 2000. Prosjekt: elvebeskatning av laksefisket: sammenheng mellom regulering, beskatning og verdiskapning av fisket: dokumentasjon av informasjonsinnhenting. *ØF rapport/Østlandsforskning* 2000:3.

Bjørndal, T. 1988. The Optimal Management of North Sea Herring. *Journal of Environmental Economics and Management* 15: 9-29.

Bjørndal, T. 1990. A Bioeconomic Analysis of North Sea Herring, in Rodrigues, A. G. (ed) Operations Research and Management in Fishing. *Kluwer Academic Publishers*: 175-189.

Carlsen, F. 1994. Asymmetric information, reputation building, and bureaucratic Inefficiency, *Public Finance* 49(3): 350-357

Clark, C. W and G. P. Kirkwood. 1986. On Uncertain Renewable Resource Stocks: Optimal Harvest Policies and the Value of Stock Surveys. *Journal of Environmental Economics and Management* 13: 235-244.

Clark, C. W. 1976. A delayed-recruitment model of population dynamics, with an application to Baleen whale populations. *Journal of Mathematical Biology* 3: 381-391.

Clark, C. W. 1990. *Mathematical Bioeconomics*. New York: John Wiley.

Conrad, J. M. and C. W. Clark. 1987. *Natural Resource Economics. Notes and Problems.* Cambridge University Press.

Cook, B. A., and R.L. McGaw. 1996. Sport and Commercial Fishing Allocations for the Atlantic Salmon Fisheries of the Miramichi River. *Canadian J. of Agricultural Economics* 44, 165-171.

ErT. 2005. http://www.elvene.no/eng/default.asp

Dutta, P. K. 1995. A Folk Theorem for Stochastic Games. *Journal of Economic Theory* 66: 1-32

Dutta, P. K. 1999. *Strategies and Games Theory and Practice.* The MIT Press, Cambridge, Massachusetts.

Fudenberg, D. and E. Maskin. 1986. The Folk Theorem in Repeated Games with Discounting or with Incomplete Information. *Econometrica* 54 (3): 553-554.

Gibbons, R. 1992. *Game theory for Applied Economists*. Princeton University Press, New Jersey.

Hannesson, R. 1995. Sequential fishing: cooperative and non-cooperative equilibria. *Natural Resource Modelling* 9: 51-59.

Hvidsten, N.A., P. Fiske, and B.O. Johnsen. 2004. Innsig og beskatning av Trondheimsfjordlaks. *NINA Oppdragsmelding 858.*

Hvidsten, N.A., B.O. Johnsen, A.J. Jensen, P. Fiske, O. Ugedal, E.B. Thorstad, J.G. Jensås, Ø. Bakke, T. Forseth. 2004. Orkla- et nasjonalt referansevassdrag for studier av bestandsregulerende faktorer av laks. *Nina fagrapport 079.*

Kaitala, V., and M. Lindroos. 1998. Sharing the Benefits of Cooperation in High Seas Fisheries: A Characteristic Function Game Approach. *Natural Resource Modeling* 11: 87-108.

Kamien, M. I. and N. L. Schwartz. 1991. *Dynamic Optimization. The calculus of Variations and Optimal Control in Economics and Management, Second edition*. North-Holland

Kennedy, J. O. S. 1986. *Dynamic Programming. Applications to Agriculture and Natural Resources*. Elsevier Applied Science Publishers.

Kreps, D. and R. Wilson. 1982. Reputation and Imperfect Information. *Journal of Economic Theory* 27(2): 253-279.

Lande, R., S. Engen, B-E. Sæther. 2003. *Stochastic Population Dynamics in Ecology and Conservation.* Oxford Series in Ecology and Evolution, Oxford University Press.

Laukkanen, M. 2001. A Bioeconomic Analysis of the Northern Baltic Salmon Fishery: Coexistence versus Exclusion of Competing Sequential Fisheries. *Environmental and Resource Economics* 18: 293-315.

Laukkanen, M. 2003. Cooperative and non-cooperative harvesting in a stochastic sequential fishery. *Journal of Environmental Economics and Management* 45: 454-473.

Li, E. 1998. Cooperative High-Seas Straddling Stock Agreement as a Characteristic Function Game. *Marine Resource Economics* 13 (4): 247-58

McKelvey, R. 1997. Game-theoretic Insights into the International Management of Fisheries. *Natural Resource Modeling* 10(2): 129-171.

NOU. 1999. *Til Laks åt Alle Kan Ingen Gjera?* NOU 1999:9.

Nøstbakken, L. 2005. *Essays on the Economics of Fisheries Management.* Dissertation submitted for the degree of Dr. Oceon, Norwegian School of Economics and Business Administration.

Olaussen, J. O. and A. Skonhoft. 2005. The Bioeconomics of a Wild Atlantic Salmon (Salmo salar) Recreational Fishery. *Working paper series 14/2005*, Department of Economics, Norwegian University of Science and Technology

Olaussen, J.O. 2005. Documentation of CV-survey on Wild Atlantic salmon, Report. Department of Economics, Norwegian University of Science and Technology (in Norwegian).

Osborne, M. J. and A. Rubinstein. 1994. *A Course in Game Theory*. The MIT Press.

Reed, W. J. 1979. Optimal Escapement Levels in Stochastic and Deterministic Harvesting Models. *Journal of Environmental Economics and Management* 6: 350-363.

Skonhoft, A. and R. Logstein. 2003. Sportsfiske etter Laks. En Bioøkonomisk Analyse. *Norsk Økonomisk Tidsskrift* 117(1): 31-51.

Shepherd, J.G. 1982. A versatile new stock-recruitement relationship for fisheries, and the construction of sustainable yield curves. *Journal du Conseil, Conseil Internationale pour L`Exploration de la Mer* 40 (1): 67-75

Varian, H.R. 1992. *Microeconomic Analysis, Third Edition*. W.W. Norton & Company.

Weitzman, M. L. 2002. Landing Fees vs Harvest Quotas with Uncertain Fish Stocks. *Journal of Environmental Economics and Management* 43: 325-338.

Wilen, J. E. 1969. Common Property Resources and the Dynamics of Overexploitation: the Case of the North Pacific Fur Seal. *Department of Economics Research Paper No. 3*. University of British Columbia, Vancouver.

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[i] The expenditures were shared by Norway (55%), England (22%), Ireland (17%), and Iceland (6%) based on the composition of the Faeroe Islands catch.

[ii] More than one-third of Atlantic salmon stock spawns in Norwegian rivers. The remaining stock is distributed across a number of countries, including Scotland, England, Wales, Ireland, Iceland, Russia, Sweden, Finland, Canada, and the US (F1999).

[iii] Note that this is, in effect, the same as the 'as if myopically omniscient' regulator case, which serves as a benchmark in Weitzman (2002).

[iv] This is regulated by law (lov om laksefisk og innlandsfisk §25); however, exceptions are given for small rivers.

[v] See Kaitala and Lindroos (1998) and Li (1998) for examples of expositions of sharing rules in fisheries.

[vi] Note that this result owes to the specification of the Schaefer type harvest function. A more general specification, e.g. $Y_1 = qD_1^{a1}\left[(1-h)X_1\right]^{a2}$ yields $y = qD_1^{a1}\left[(1-h)X_1\right]^{a2-1}$, and where a2=1 reduces to $y_1 = qD_1^{a1}$, and a1=a2=1 reduces to the result in the main text.

[vii] We hence have a delay-difference recruitment model as in Clark (1976). See also Bjørndal (1988, 1990). The average lag time for salmon, κ, is 5 years (Hvidsten et al. (2004)).

[viii] As one anonymous reviewer pointed out, monopolistic competition between river owners may occur. One straightforward interpretation of the somewhat stylized monopolistic assumption is that we consider the case where anglers do not switch between rivers due to a long distance between them. Moreover, the assumption is also justified by a study by Birkelund, Lein, and Aas (2000). They asked river owners if they would change their permit price if other river owners changed their price. On average 58% would leave their own price unchanged, 24% would change their price while the remaining 18% were uncertain. See also Olaussen and Skonhoft (2005) for an analysis of various management regimes in Atlantic salmon rivers.

[ix] Technically, a river owner choosing A_i* simply indicates that the first order condition with respect to *A* gives $H_A \geq 0 \quad when \;\; A = A*$.

[x] Note that the manager determines the permit price instead of the number of permits. However, this is merely a matter of exposition. Thus, the permit price is the inverse of the demand function, and the effect is exactly the same.

[xi] Note that since *m* is a probability, it is only defined for $m \geq 0$. Thus, in e.g., a pay-off scheme such as the prisoner's dilemma, it is not defined, simply because the only Nash equilibrium is the $A_i = 0 \quad (i = 1 \wedge 2)$ solution.

[xii] See also Carlsen (1994) for an analysis of reputation manipulation in a sponsor-bureau framework where both players apply mixed strategies.

[xiii] Note that this is the same condition under which fees are set by the management authority in Weitzman (2002).

[xiv] Hence, we only consider environmental stochasticity and neglect demographic stochasticity. This is a valid simplification as long as populations are dense because the environmental stochasticity will dominate in large populations (for example, see Lande, Engen, and Saether 2003).

[xv] Recollect, for example, that the acquisition quantity is also based on average yearly catch statistics over the five previous fishing seasons.

[xvi] The Shepherd function produces the Cushing recruitment function when γ<1, the Beverton Holt recruitment function when γ=1, and the Ricker recruitment function when γ>1.

[xvii] Note that the numbers reported in Hvidsten et al. (2004) are measured as recruits per egg per square metre. However, we have translated them into the corresponding number of recruits per spawning salmon in the river (available on request).

[xviii] Note that this is the same type of stochasticity (good and bad years) as considered by Mckelvey (1997), only he formulated the underlying stock uncertainty (good and bad seasons) directly in terms of profit in the model.

[xix] However, the equilibrium stock and effort levels are quite straightforward to derive, even though the expressions are quite messy (available on author's request).

[xx] Excel files available on author's request.

[xxi] Acquisitions increase salmon stock, and the salmon stock shifts demand up due to an increased catch per day, as explained in above.

[xxii] Note also that equations (7) and (8) only hold under the chicken game pay-off structure (see also footnote xiii).

[xxiii] By the same structure, we mean that $A = A*$ is the optimal choice if the other players choose $A = 0$. However, the chicken game notion is restricted to games with two players and symmetric pay-off schemes.