A Market Mechanism for Sustainable and Efficient Resource Use under Uncertainty☆

Martin F. Quaas[a,], Ralph Winkler[b]

[a] *Department of Economics, University of Kiel, Wilhelm-Seelig-Platz 1, 24118 Kiel, Germany.*
[b] *Department of Economics and Oeschger Centre for Climate Change Research, University of Bern Schanzeneckstrasse 1, CH-3001 Bern, Switzerland.*

Abstract

Sustainability and efficiency are potentially conflicting social objectives in natural resource management. We propose a market mechanism to allocate use rights over a stochastic resource to private managers. The mechanism endogenously determines the maximal tenure length guaranteeing that the sustainability goal is obeyed for sure over the entire period. In addition, the mechanism achieves efficiency, i.e. it maximizes the expected present value of resource rents that accrue to society. Potential applications include improved fishing agreements between developing countries and distant-water fishing fleets.

Keywords: auctioning-refunding-mechanism, efficient resource allocation, renewable resources, stochastic resource dynamics, sustainability

JEL: Q20, D44, D82

☆We are grateful to Cyril Monnet, Marc Möller and Olli Tahvonen, and seminar participants at the Universities of Bern, Freiburg and Mnster for valuable comments on earlier drafts.

Email addresses: quaas@economics.uni-kiel.de (Martin F. Quaas), mail@ralph-winkler.de (Ralph Winkler)

1. Introduction

According to established theory, the overuse of natural resources is predominantly caused by a lack of adequate property rights (Gordon, 1954; Scott, 1955; Arnason, 2007). Granting exclusive private use rights is therefore the most promising way to achieve *efficient resource use*. Apart from efficiency, also *sustainable resource use* is the declared and legally binding objective of many societies. This holds, in particular, for the sustainable management of living marine resources (United Nations Convention on the Law of the Sea, UNCLOS, 1982; UN Fish stocks agreement, 1995; Johannesburg Plan of Implementation of the World Summit on Sustainable Development, 2002; United Nations Conference on Sustainable Development Rio +20 Declaration, 2012). Already Clark (1973) recognized that there is a potential clash between efficiency and sustainability: It may be optimal to drive a renewable natural resource to extinction if the sole resource owner's discount rate is too high compared to the regeneration capabilities of the resource. These concerns about the "limits to privatization" of fisheries have recently been re-emphasized (Clark et al., 2010).

In this paper, we introduce a mechanism granting exclusive use rights over a renewable natural resource for a limited tenure such that the resource is managed both efficiently and sustainably. By *efficiency* we mean that the resource is allocated to the agent exhibiting the highest expected net present value of managing the resource. We operationalize *sustainability* as a minimum level of the resource stock that must not be undercut at all times. Various reasons for such a sustainability goal are conceivable. For example, it may represent the stock leading to the maximum sustainable yield (as demanded, for example, for marine resources by the Johannesburg Plan of Implementation of the World Summit on Sustainable Development, 2002) or the minimal stock of a natural resource that is necessary to maintain specific ecosystem functions (Millennium Ecosystem Assessment, 2005).

The mechanism is designed to deal with three major challenges. First, standard models in resource economics often assume a unique market interest rate, in contrast to experimental studies showing that consumption discount rates of individual agents vary substantially (Andersen et al., 2008; Coller and Williams, 1999; Curtis, 2002; Harrison et al., 2002). In addition, there is no agreement on appropriate social discount rates to use in cost-benefit analysis (Weitzman, 2001). Variations in discount rates may be attributed to individual differences in pure rates of time preferences, economic conditions such as access to credit lines, or expectations about economic development. The discount rate of the owner of the resource use right matters for both the efficiency and the sustainability of private resource use. In particular, the sustainability of resource use may be impaired if the owner's discount rate is too high (Clark et al., 2010). Thus, it is in society's interest to grant resource use rights only to users with sufficiently low discount rates. The challenge here is to design a mechanism that elicits the discount rates of potential resource managers which are private information.

Second, uncertainties about future development matter. We therefore account for the stochastic development of the natural resource and its market price. We show that stochastic resource prices may jeopardize the sustainability goal, as the resource manager's optimal harvest is increasing in the resource price. Uncertainties about the future development may explain the common practice to grant resource use rights only for a limited-tenure, so called *concessions* (Bromley, 2009; Costello and Kaffine, 2008). Under limited-tenure use rights, society may re-assess the privatization policy if the stock dynamics turn out to be unfavorable or the price development turns out to be too favorable. The challenge with limited tenure is that the resource user has an incentive to mine the resource at the end of tenure. Costello and Kaffine (2008) propose to overcome this incentive by the right choice of tenure length and a sufficiently high probability that the concession is renewed, both of which depend on the discount rate of the resource user. Here, we study how to overcome the incentive to mine the resource at the end of tenure even if the discount rates are private knowledge and unknown to the regulator.

Third, an issue heavily debated with respect to fisheries and grandfathered individual transferable quotas (ITQs) are the windfall gains which accrue to the concession owners. Accordingly, instruments (such as charges) have been proposed so that society may capture some fraction of the resource rents (Grafton, 1994, 1995). We seek a mechanism that allows society to extract virtually all resource rents from the resource owner.

The mechanism proposed here determines the maximal concession tenure length for which the optimal harvesting strategy of the most patient resource manager is compatible with the sustainability goal and his willingness to pay for such a concession exceeds the corresponding opportunity costs of the society. We identify the most patient resource manager and the corresponding maximum tenure length by a second-price sealed-bid auction with minimum bids. The minimum bids ensure that the resource rights are only sold if (i) resource managers are sufficiently patient not to infringe the sustainability goal and (ii) the willingness to pay exceeds the expected opportunity costs of society. If the resource rights are sold for a limited time period a refunding scheme compensates the resource user at the end of tenure for the foregone gains of resource mining. In addition to guaranteeing the sustainability goal, the mechanism ensures efficiency in the sense that resource rights are given to the agent who values them most and maximizes the expected revenues for society. There is little informational need for the mechanism to work properly. In particular, the mechanism deals with asymmetric information with respect to discount rates.

Potential fields of application for our mechanism include the sustainable and efficient management of marine fisheries. In recent years, fishing effort has been moving from industrialized countries to the developing world, in particular to fishing grounds in African exclusive economic zones (Worm et al., 2009). A problem for developing countries is their limited capability to enforce their fishing rights, and accordingly illegal fishing prevails (Agnew et al., 2009), resulting in unsustainable and inefficient over-use of the fish stocks. Auctioning limited-tenure fishing rights would have several advantages for the developing countries in this situation: The mechanism proposed in this paper would ensure the sustainability of these fisheries and raise revenues for the countries who own the fish stocks. In addition, concession holders would support the enforcement of use rights in their own interest.

Our contribution is related to two strands of literature. One is the literature on efficient and sustainable use of natural resources already referred to, and in particular those contributions that study resource management by means of concessions (Bromley, 2009; Costello and Kaffine, 2008; Rocha et al., 2006). With a short fixed tenure period, concession holders have an incentive to over-use the resource, for example in the case of forest concessions (Amacher et al., 2012). As indicated above, the mechanism proposed in this paper provides incentives for sustainable resource use independently of the concession owner's willingness to apply for a new concession at the end of the limited tenure and the government's willingness to re-grant the concession to the concession incumbent. The other relevant strand of literature studies the privatization of natural resources by means of auctions. It focuses mainly on non-renewable resources (Osmundsen, 1996; Cramton et al., 2007; Cramton, 2009; Chouinard, 2005; Libecap, 2007), or on the question of efficiency in the regulation of common resources (Montero, 2008).

The remainder of the paper is organized as follows. In Section 2 we introduce a stochastic renewable natural resource model. We derive some preliminary results on optimal harvesting by a private resource manager holding a concession and the maximum sustainable tenure length in Section 3. We introduce our auctioning-refunding mechanism and prove propositions about its properties in Section 4. Model assumptions and possible extensions of the model are discussed in Section 5. Section 6 concludes.

2. The Model

We consider a regulator representing a society that owns a renewable natural resource. The regulator seeks to maximize the expected present value of resource rents from using the resource under the constraint of a *sustainability goal*, i.e. a minimum level $\hat{s}$ of the natural resource stock that must not be undercut at all times. The sustainability goal may reflect different social concerns such as resource yield, maintaining ecosystem services and biodiversity conservation. In order to achieve his twofold objective, the regulator has two options: (i) she may either manage the resource herself or (ii) delegate the resource management to a private resource manager by selling off or renting out the resource use rights.

In case of the latter option the regulator has to find a mean to ensure that the sustainability goal is obeyed at all times. We assume that learning about the stock level in period t induces a fixed positive monitoring cost m when the resource manager does not manage the resource herself. Thus, the option to delegate the resource management is less attractive the more monitoring is needed to ensure that the resource manager is obeying the sustainability goal. We further assume that a private resource manager's liability for violating the sustainability goal is limited: the harshest punishment the regulator can enforce in case of non-compliance with the sustainability goal is to revoke the (temporary) use right of the resource. As a consequence, the sustainability goal cannot be guaranteed by a contract that forbids harvesting below the sustainability goal. In particular, the problem of resource mining at the end of tenure remains, as revoking the use right after it has expired does not constitute a credible punishment preventing the resource manager from violating the contract.

In the following, we first introduce a discrete time model framework. Then, we develop a mechanism that allows the regulator to determine whether delegating the resource management to a private resource manager maximizes her expected present value, and, if so, ensures that the sustainability goal is always obeyed with a minimum of monitoring costs (in fact, only one monitoring event at the end of tenure is necessary). In addition, the mechanism determines whether it is optimal to sell the resource for good or rather rent out use rights for a limited tenure.

2.1. Resource Dynamics, Harvesting Technology and Resource Prices

Following the literature (e.g. Reed, 1979; Costello and Kaffine, 2008), we assume that the resource develops stochastically according to the equation of motion

$$x_{t+1} = z_t \, f(s_t) \ , \tag{1}$$

where s_t is the resource quantity remaining in stock after harvesting, i.e. $s_t = x_t - h_t$ is given by the initial stock x_t minus the harvest h_t in period t. In the fisheries economic literature, s_t is referred to as the 'escapement'. The expected stock of the natural resource in period $t + 1$ is given by the function $f(s_t)$, which is assumed to be twice differentiable, increasing and concave. The actual resource stock x_{t+1} is uncertain and described by the expected stock $f(s_t)$ times a random variable z_t, the sequence of which is independently and identically distributed with bounded support $[\underline{z}, \overline{z}]$ and unit mean, $0 < \underline{z} \leq 1 \leq \overline{z} < \infty$.

We further assume $f(0) = 0$, $\underline{z} f'(0) > 1$ and $\lim_{s\to\infty} \overline{z} f'(s) < 1$. These assumptions have the following implications. First, they ensure that extinction is not a stable steady state, or, in ecological terms, that the minimum viable population is zero.[1] Second, they imply that there exist recruitment levels $\underline{s} = \underline{z} f(\underline{s})$ and $\overline{s} = \overline{z} f(\overline{s})$ such that without harvest the resource level will eventually enter and henceforth never leave the interval $[\underline{s}, \overline{s}]$.[2] Third, all recruitment levels $s \in (0, \underline{s})$ are *self-sustaining*, i.e. $x_{t+1} > s_t$ with probability one. Fourth, there exists a unique escapement level s_{MSY} that generates the maximal expected surplus, or expected maximum sustainable yield, which is implicitly defined by $f'(s_{\mathrm{MSY}}) = 1$.

All potential resource managers and the regulator have access to the same harvesting technology, described by the unit harvesting cost function, which depends on the current resource level y,

$$c(y) = \kappa y^{-\theta} \;, \qquad \kappa, \theta > 0 \;. \tag{2}$$

Denoting the resource price in period t by p_t, the profits in that period are given by

$$\pi(x_t, s_t, p_t) = \int_{s_t}^{x_t} \big[p_t - c(y)\big]\, dy = p_t\, (x_t - s_t) - \frac{\kappa}{1-\theta}\, \left(x_t^{1-\theta} - s_t^{1-\theta}\right) \;. \tag{3}$$

Let $\tilde{s}(p_t)$ be the open-access escapement level of the resource at price p_t defined by

$$\tilde{s}(p_t) = \max\big[\, \{s \,|\, p_t - c(s) = 0\}\,, 0\big] = \left(\frac{\kappa}{p_t}\right)^{\frac{1}{\theta}} \;. \tag{4}$$

The regulator and the potential resource managers take the resource price p_t in period t as given, i.e. they sell the harvest of the resource on a perfectly competitive market. Assuming

[1]This assumption eases calculations but does not impact qualitatively on our results. In the following we present a mechanism that ensures that the resource population never drops below a certain level $\hat{s}$. If the minimal viable population is strictly positive, setting $\hat{s}$ larger than the minimal viable population always ensures that the population does not become extinct.

[2]The interval $[\underline{s}, \overline{s}]$ represents the stochastic generalization of the constant carrying capacity in deterministic models.

that they cannot foresee stochastic changes on aggregate supply and demand renders the resource price in period t a random variable. We assume that the price of the resource p_t follows the stochastic process

$$p_{t+1} = \eta_t \, p_t \ , \tag{5}$$

where η_t is an independent and identically distributed random variable with bounded support $[\underline{\eta}, \overline{\eta}]$ and unit mean, $0 < \underline{\eta} \leq 1 \leq \overline{\eta} < \infty$. Equation (5) denotes a random walk without drift implying $\mathrm{E}_\eta(p_{t+1}|p_t) = p_t$. In addition, for a given price $p_0 > 0$ in period $t = 0$ the finite upper bound $\overline{\eta}$ connotes a price ceiling $p_t^{\max}$ for the resource price in period t:

$$p_t^{\max} = \overline{\eta}^t \, p_0 \ . \tag{6}$$

2.2. Actors, Information and Timing

In period $t = 0$ the regulator decides what to do with the natural resource. Her objective is to maximize the expected present value of revenues from using the resource from period $t = 1$ onward under the constraint of the *sustainability goal* $\hat{s}$ for the natural resource. To this end, the regulator faces two options.

First, the risk neutral regulator can manage the resource herself. Denoting the regulator's discount factor by $\delta_r \in (0, 1)$, self-management implies an an escapement policy such that

$$EPV^R = \max_{\{s_t\}} \mathrm{E}\left[\sum_{t=1}^{\infty} \delta_r^t \pi(x_t, s_t, p_t)\right] \quad \text{s.t.} \quad (1),\ (3),\ (5),\ s_t \geq \hat{s},\ \text{and}\ s_0,\, p_0\ \text{given.} \tag{7}$$

Second, the regulator can sell off or rent out the use rights of the natural resource to a private resource manager. We speak of a *concession* if the regulator rents out a temporary use right with limited tenure T to a resource manager. We consider a continuum of risk neutral potential private resource managers i who are identical in all other aspects but their discount factors δ_i, which are distributed over the set $\Omega \subset [0, 1]$ with the maximum discount factor $\delta^{\max} = \max\{\Omega\}$.

Discount factors are private knowledge, i.e. all individuals and the regulator only know their own discount factor. In period $t = 0$, the initial stock size x_0, the initial resource price p_0, the resource stock dynamics, the harvesting technology and the resource price dynamics are common knowledge and known to the regulator and all potential resource managers. At the beginning of each period t, the regulator and the resource managers learn about the resource price p_t. In addition, the regulator or the manager, depending on who manages the resource, learn about the actual resource stock x_t. Both pieces of information become available before the harvesting decision h_t is made. If resource management is delegated to a private resource manager, the regulator can learn the escapement level s_t at the end of period t at fixed monitoring costs m.

To ensure that the the sustainability goal is feasible and attainable we impose the assumptions that the regulator's sustainability goal $\hat{s}$ is self-sustaining and the initial stock x_1 satisfies $x_1 \geq \hat{s}$. The second assumption can always be met by waiting a finite time period before selling the concession.

3. Optimal Harvesting Strategies and Maximum Sustainable Tenure Length

In Section 4, we develop an optimal allocation mechanism maximizing the regulator's expected payoff from the resource, at the same time ensuring the sustainability goal to be met at all times. One part of the problem is to identify the most patient resource manager; the other is to determine the maximum tenure length $T^{\max}$ over which the sustainability goal $\hat{s}$ is achieved for sure. As $T^{\max}$ may be finite, our framework provides a rationale for the common practice of granting limited tenure concessions. Before turning to the optimal allocation mechanism, we first analyze the harvesting strategy that is optimal for an arbitrary private resource manager for a concession of arbitrary tenure length and then determine the maximum tenure length over which the regulator's sustainability goal is achieved for sure.

3.1. Optimal Harvest Strategy of Resource Manager

We start by analyzing how a resource manager holding the concession would manage the resource. As resource managers are risk neutral, a resource manager exhibiting discount factor δ_i and holding a concession of tenure length T chooses an escapement policy such as to maximize the expected present value of profits:

$$EPV(\delta_i, T) = \max_{\{s_t\}} \mathrm{E}\left[\sum_{t=1}^{T} \delta_i^t \pi(x_t, s_t, p_t)\right] \quad \text{s.t.} \quad (1),\ (3),\ (5) \text{ and } s_0,\, p_0 \text{ given.} \tag{8}$$

The following lemma states the important insight that for any given tenure length T of the concession, the concession is more valuable to resource managers with higher discount factors δ_i (i.e., more patient resource managers).

Lemma 1. *The expected present value of profits from resource management $EPV(\delta_i, T)$ is strictly increasing in the discount factor if the resource manager expects to harvest in at least one period of the tenure duration.*

Proof. The lemma follows directly by application of the Envelope Theorem:

$$\frac{\partial EPV(\delta_i, T)}{\partial \delta_i} = \mathrm{E}\left[\sum_{t=1}^{T} t\delta_i^{t-1} \pi\left(z_t f\left(s_t^\star\right), s_t^\star, p_t\right)\right] \geq 0, \tag{9}$$

where $s_t^\star$ denotes the optimal escapement level at time t. The inequality holds as profits are non-negative. If the resource manager expects to harvest in at least one period t' with $1 \leq t' \leq T$ then $\mathrm{E}\left[\pi\left(z_{t'} f\left(s_{t'}^\star\right), s_{t'}^\star, p_{t'}\right)\right] > 0$ and the strict inequality holds. □

The optimal escapement strategy that solves (8) is given by (see Appendix A):

$$s_t = \min\left\{s^\star(\delta_i, p_t), x_t\right\}\ , \quad 0 < t < T\ , \tag{10a}$$

$$s_T = \min\left\{\tilde{s}(p_T), x_T\right\}\ , \tag{10b}$$

where $\tilde{s}(p_t)$ is given by (4) and $s^\star(\delta_i, p_t)$ denotes the optimal escapement level of a resource manager exhibiting the discount factor δ_i and facing a resource price p_t. It is given by the solution of

$$p_t - c\big(s^\star(\delta_i, p_t)\big) = \delta_i\, f'\big(s^\star(\delta_i, p_t)\big)\left[p_t - \mathrm{E}_z\left[zc\Big(zf\big(s^\star(\delta_i, p_t)\big)\Big)\right]\right]. \tag{11}$$

Condition (11) states that for the optimal escapement level, the current period's marginal profit from the last unit of resource harvested must equal the discounted expected marginal profit from an additional unit that escapes harvesting. As δ_i is constant for a specific resource manager, the optimal escapement strategy (10) only depends on the resource price in period t. As a consequence, the resource manager would follow a "constant escapement rule" if the resource price were constant (Reed, 1979). The following lemma establishes two important characteristics of the optimal escapement level $s^\star(\delta_i, p_t)$:

Lemma 2. *The optimal escapement level $s^\star(\delta_i, p_t)$ is strictly increasing in the discount factor δ_i and strictly decreasing in the resource price p_t.*

The proof is given in Appendix B. Lemma 2 says that resource managers with higher discount factors δ_i (i.e., more patient resource managers) exhibit a more sustainable optimal escapement strategy. However, it also says that any resource manager would harvest less sustainably when resource prices are high.

It is obvious from Lemmas 1 and 2 that the regulator would like to select the resource manager with the highest discount factor $\delta_i = \delta^{\max}$, as he has the highest willingness to pay for a concession of tenure length T (cf. Lemma 1) and also manages the resource most sustainably (cf. Lemma 2). However, even the most patient resource manager may exhibit an optimal escapement strategy that is inconsistent with the sustainability goal $\hat{s}$ of the regulator. In particular, this holds for the final period T, where the resource manager exploits the resource to the open-access level. But also in the periods $1 \leq t < T$ the optimal escapement level $s^\star(\delta^{\max}, p_t)$ may be below the sustainability goal $\hat{s}$. According to Lemma 2 this is more likely the lower is the discount factor $\delta^{\max}$ of the most patient resource manager and the higher is the resource price p_t.

3.2. Maximal Sustainable Tenure Length

According to equation (6), the resource price p_t at any finite time t in the future is bounded from above by $p_t^{\max}$. As a consequence, we can define the minimal optimum escapement level $s_t^{\min}(\delta_i)$ in period t of a resource manager with discount factor δ_i by:

$$s_t^{\min}(\delta_i) = s^\star(\delta_i, p_t^{\max}) \tag{12}$$

For the minimal optimum escapement level $s_t^{\min}(\delta_i)$ the following properties hold:

Lemma 3. *The minimal optimum escapement level $s_t^{\min}(\delta_i)$ is strictly increasing in the discount factor δ_i, strictly decreasing over time and converges to a finite value $s_\infty^{\min}(\delta_i)$ for $t \to \infty$.*

Proof. The first two properties follow directly from Lemma 2 and equation (6). The third property is derived from the following implicit equation for $s_t^{\min}(\delta_i)$:

$$\frac{1}{\delta_i} = f'\big(s_t^{\min}(\delta_i)\big) \frac{p_t^{\max} - \mathrm{E}_z\left[zc\Big(zf\left(s_t^{\min}(\delta_i)\right)\Big)\right]}{p_t^{\max} - c\big(s_t^{\min}(\delta_i)\big)} \ , \tag{13}$$

For $t \to \infty$ this converges to $1/\delta_i = f'\big(s_\infty^{\min}(\delta_i)\big)$. □

We define the *sustainable discount factor* $\hat{\delta}_t$, which is implicitly given as the solution of the equation[3]

$$s_t^{\min}(\hat{\delta}_t) = \hat{s}. \tag{15}$$

Thus, $\hat{\delta}_t$ is the discount factor the resource manager has to exhibit such that the minimal optimum escapement level in period t equals the sustainability goal. The sustainable discount factor $\hat{\delta}_t$ has the following properties:[4]

[3]Using equations (11) and (12), the sustainable discount factor is explicitly given by

$$\hat{\delta}_t = \frac{1}{f'(\hat{s})} \frac{p_t^{\max} - c(\hat{s})}{p_t^{\max} - E_z\left[z\, c\left(z\, f\left(\hat{s}\right)\right)\right]}. \tag{14}$$

[4]In addition, the sustainable discount factor is strictly increasing in the price p_t and strictly decreasing in the cost parameter κ. Using the specification (2), we have $E_z\left[z\, c\left(z\, f\left(\hat{s}\right)\right)\right] = E_z\left[z^{1-\theta}\right]\, \kappa\, \left(f\left(\hat{s}\right)\right)^{-\theta}$, which is decreasing in environmental stochasticity, as $z^{1-\theta}$ is a concave function of z. This implies that $\hat{\delta}_t$ is decreasing with environmental uncertainty, which is related to the result of Reed (1979) that the optimal escapement level in the stochastic setting is higher than in the corresponding deterministic case.

Lemma 4. *The sustainable discount factor* $\hat{\delta}_t$ *is strictly increasing in* t*, with*

$$\hat{\delta}_\infty = \lim_{T\to\infty} \hat{\delta}_T = \frac{1}{f'(\hat{s})}. \tag{16}$$

Lemma 4 follows directly from Lemma 3. It implies that a resource manager i holding a concession with tenure length T would for sure obey the sustainability goal $\hat{s}$ for all periods $t < T$ if $\delta_i \geq \hat{\delta}_{T-1}$.[5] Neglecting for the time being the problem of resource mining at the end of tenure (which we address in Section 4), it thus follows that there are circumstances under which the regulator does not want to fully privatize the renewable resource, as the private owner might eventually violate the sustainability goal. We find three possible cases:

1. $\delta^{\max} \geq \hat{\delta}_\infty$: The minimal optimum escapement level of the most patient resource manager is always above the sustainability goal. In this case the regulator would ensure the sustainability goal by selling the resource to the most patient resource manager. In selling the resource instead of granting a limited tenure use right also circumvents the problem of resource over-use at the end of tenure.

2. $\hat{\delta}_1 \leq \delta^{\max} \leq \hat{\delta}_\infty$: The minimum optimum escapement level of the most patient resource manager is above the sustainability goal in the short run, but below the sustainability goal in the long run. In this case, there exists a maximum tenure length $T^{\max}$ for the concession, such that the most patient resource manager harvests the resource above the sustainability goal in all periods $t < T^{\max}$. However, the problem of overexploitation at the end of tenure remains.

3. $\delta^{\max} < \hat{\delta}_1$: The minimal optimum escapement level of the most patient resource manager is always below the sustainability goal. In this case, the regulator cannot ensure the sustainability goal by granting concessions to a private resource manager. The sustainability goal and the desire to delegate the resource management are irreconcilable.

[5] According to equation (10), in the final period T of the concession tenure the resource manager would harvest down to the open-acces escapement level $\tilde{s}(p_T)$ independently of her discount factor.

If there is no price uncertainty, i.e. if $\underline{\eta} = \overline{\eta} = 1$, case 2 cannot occur. Depending on the price, which is constant in this case, we are left with either case 1 or case 3. For stochastic prices, $\underline{\eta} \neq \overline{\eta}$, case 2 may be very relevant. The following proposition establishes that the sustainability goal can be ensured only for a finite concession tenure length if the sustainability goal is at or above the expected maximum sustainable yield.

Proposition 1 ($\hat{s} \geq s_{MSY}$ implies finite sustainable tenure length T^{max})**.** *If the sustainability goal is equal to or larger than the escapement level that generates the expected maximum sustainable yield s_{MSY}, there exists a maximal sustainable tenure length $T^{\max}$ such that for any tenure length $T > T^{\max}$ there is no potential resource manager sufficiently patient to ensure the sustainability goal,*

$$\hat{\delta}_T > \delta^{\max} \quad \textit{for all} \quad T > T^{\max}. \tag{17}$$

Proof. If $\hat{s} \geq s_{\text{MSY}}$, we have $f'(\hat{s}) \leq 1$. Hence, $\hat{\delta}_\infty \geq 1 > \delta^{\max}$. Thus, $T^{\max}$ exists by virtue of Lemma 4. □

According to Proposition 1 the maximum sustainable tenure length is finite if the sustainability goal is to maintain at least the stock size that would generate the maximum sustainable yield. For fisheries, this goal has been declared in international agreements such as the Johannesburg Plan of Implementation of the World Summit on Sustainable Development (2002). Some fishing nations, such as Australia, aim at the still higher stock sizes that would generate the so-called maximum economic yield (Dichmont et al., 2010).

Proposition 1 thus provides a rationale for delegating resource management by means of limited tenure concessions in a setting of stochastic prices combined with the regulator's desire to ensure a minimum escapement level of the resource population at all times. As the upper bound for the resource price rises over time, the minimal optimum escapement level of the resource managers decline. If even for the most patient resource manager the long-run minimal optimum escapement level is below the sustainability goal, a limited tenure concession may be preferable over selling the use right of the resource for good.

4. An Optimal Auctioning-Refunding Mechanism

The considerations so far clarified what an optimal allocation mechanism for the resource use rights has to accomplish. First, it has to identify the most patient resource manager, as he harvests the resource most sustainably and has the highest willingness to pay for a concession of given tenure length T. Second, it has to establish the maximum tenure length for which the sustainability goal is ensured by the optimal harvesting strategy of the most patient resource manager. As we have seen, the maximum tenure length may also be zero or infinite. Third, it has to establish whether it is better for the regulator to manage the resource herself or to offer a concession of maximum tenure length to the most patient resource manager. Finally, the mechanism has to ensure that the sustainability goal is also ensured in the final period of the concession tenure if the maximum tenure length is positive but finite. Before we define the auctioning-refunding mechanism and show that the mechanism can achieve all four deliverables by setting the mechanism parameters appropriately, we briefly sketch how the mechanism addresses these four issues.

To provide private resource managers with incentives to keep the resource stock at the sustainable level $\hat{s}$ in the final period T of the concession tenure, the regulator pays a refund $R(s_T, p_T)$ contingent on the escapement level and the resource price in period T:

$$R(s_T, p_T) = \begin{cases} r(p_T) & \text{if} \quad s_T \geq \hat{s} \\ 0 & \text{if} \quad s_T < \hat{s}. \end{cases} \tag{18}$$

If the refund compensates for the loss in profits by refraining from harvesting below the sustainability goal $\hat{s}$, the resource manager holding the concession has no incentive to overexploit the resource in the last period of the concession tenure. At a price p_T the resource manager would not reduce the resource stock below the open-access escapement level $s_\infty(p_T)$. Thus, the regulator would have to compensate the resource manager if a profit could be obtained by harvesting the quantity $\hat{s} - s_\infty(p_T)$. The resource manager has no incentive to harvest the stock below $\hat{s}$ if a refund (18) is paid with

$$r^{\star}(p_T) = \max\left[\pi\big(\hat{s}, s_{\infty}(p_T), p_T\big) + \epsilon, 0\right] \ , \tag{19}$$

where $\epsilon > 0$ is small but positive. Obviously, paying such a refund is costly to the regulator. In addition to the refund, the regulator will also have to pay monitoring costs m in the final period to assess whether the resource manager is eligible for the refund.

In order to decide whether the regulator is better off by managing the resource herself, we consider the regulator's opportunity costs of selling a concession of tenure T. First, by selling a concession the regulator foregoes the expected present value of profits from managing the resource herself for the duration of the concession tenure. Assuming that the optimal harvesting strategy of the regulator, as derived from equation (7), is denoted by $s_t^r(p_t)$ the expected net present value of forgone profits is given by $\mathrm{E}\left[\sum_{i=1}^{T} \delta_r^t \pi\big(x_t, s_t^r(p_t), p_t\big)\right]$. In addition, it may be that the regulator's best harvesting strategy would be to set (in expectation) an escapement level in period T that exceeds the sustainability goal, i.e. $\mathrm{E}[s_T^r(p_T)] > \hat{s}$. In this case the regulator has additional expected costs Δs_T of selling a concession of tenure T, as the resource manager leaves a resource stock equal to the sustainability goal $s_T = \hat{s}$ (if incentives for resource mining are eliminated by an appropriate refund).[6] Finally, selling the concession induces monitoring costs and costs for the refund to ensure the sustainability goal in the last period. In total, the expected present value of the opportunity costs for selling a concession of tenure T are given by:

$$EOC(T) = \mathrm{E}\left[\sum_{i=1}^{T} \delta_r^t \pi\big(x_t, s_t^r(p_t), p_t\big)\right] + \delta_r^T \left\{\Delta s_T + m + \mathrm{E}\left[r^{\star}(p_T)\right]\right\} \ .$$

As a consequence, it is only optimal for the regulator to sell a concession of tenure T if the resource manager buying the concession obeys the sustainability goal and pays at least a price of $EOC(T)$.

[6]The costs Δs_T are given by the difference in the expected net present value of the optimal management of the resource by the regulator over an infinite time horizon between starting with an initial escapement level $s_0 = \mathrm{E}[s_T^r(p_T)]$ and $s_0 = \hat{s}$.

In order to identify the resource manager with the highest discount factor, we exploit the fact that the most patient resource manager not only manages the resource most sustainably but also exhibits the highest willingness to pay for a concession of tenure T (cf. Lemma 1). Thus, if an auction could ensure that resource managers bid their true evaluation of the concession, the most patient resource manager would win the auction. In fact, the Vickrey auction has the property that bidding the true willingness to pay is a weakly dominant strategy. Given that resource managers reveal their true evaluation, we can ensure that a concession of tenure T is auctioned to a resource manager who will always leave an escapement level above the sustainability goal for all periods $t < T$ by asking for a minimum bid of $EPV(\hat{\hat{\delta}}_{T-1}, T) + (\hat{\hat{\delta}}_{T-1})^T \epsilon$, where $\epsilon > 0$ is the same as in equation (19). In period T the sustainability goal will be guaranteed by the refunding rule (18) with $r(p_T)$ set according to (19). If the minimum bid for a concession of tenure T is, at the same time, at least as high as the regulator's expected present value of the opportunity costs $EOC(T)$ then concessions are only sold if this maximizes the regulator's expected profits. Thus, the minimum bids that guarantee efficiency and sustainability for a concession of tenure T are given by

$$b_1^{\min\star} = EOC(1) + \tau \ , \qquad T = 1 \ , \tag{20a}$$

$$b_T^{\min\star} = \max \left\{ EPV(\hat{\hat{\delta}}_{T-1}, T) + (\hat{\hat{\delta}}_{T-1})^T \epsilon, EOC(T) + \tau \right\} \ , \qquad T > 1 \ , \tag{20b}$$

with $\epsilon, \tau > 0$ and arbitrarily small.

Lemma 4 implies that resource managers with discount factors equal to $\hat{\hat{\delta}}_{T-1}$ exhibit a willingness to pay below the minimum bid for concessions with tenure lengths larger than T. By asking resource managers to bid for a concession length T accompanied by the price they are willing to pay for such a concession, the proposed mechanism is able to determine the maximum tenure length $T^{\max}$ that ensures the sustainability goal and makes the regulator better off than managing the resource herself, and for which the most patient resource manager exhibits a true evaluation of the concession above the minimum bid.

In summary, we define the allocation mechanism as follows

Definition 1 (Auctioning-Refunding Mechanism)**.** *We define an auctioning-refunding mech-*

anism $ARM\big(\mathbf{b}^{\min}, r(p_T)\big)$ by the following sequence of events:

1. *The regulator announces a vector of minimum bids $\mathbf{b}^{\min} = (b_1^{\min}, \ldots, b_\infty^{\min})$ and a refund $r(p_T)$.*

2. *Bidders submit sealed bids (b_i, T_i), where b_i denotes the price resource manager i is willing to pay for a concession of tenure length T_i.*

3. *All bids with $b_i < b_{T_i}^{\min}$ are removed. Let $T^{\max} = \max_i[T_i]$ be the maximal tenure length of all remaining bids. $T^{\max}$ may be infinite.*

4. *If there are no bids left, the resource remains unsold. Otherwise, the resource manager with the highest b_i for tenure length $T^{\max}$ wins the auction. If two or more resource managers submit the highest bid for a concession of tenure length $T^{\max}$ the winner is determined by a lottery among them. The winner pays the highest non-winning bid for tenure length $T^{\max}$, if it exists, and $b_{T^{\max}}^{\min}$ otherwise. He is granted exclusive use rights over the natural resource for tenure length $T^{\max}$.*

5. *If $T^{\max} < \infty$, the regulator pays a refund $R(s_{T^{\max}}, p_{T^{\max}})$, as given by condition (18), to the resource user at the end of the concession period.*

First, we analyze the optimal bidding strategy of resource managers and the resulting Nash equilibrium given the auctioning-refunding mechanism $ARM\big(\mathbf{b}^{\min}, r(p_T)\big)$ defined above. The following proposition states that all resource managers have an incentive to bid for the highest tenure length for which their true expected value of a concession of such a tenure length exceeds the required minimum bid. In addition, they offer a price equal to their true evaluation for such a concession or abstain from bidding if their expected value of a concession is below the minimum bid for all tenure lengths T. In the Nash equilibrium the resource rights either remain unsold, if all resource managers abstain from bidding, or are sold to a resource manager with the highest discount factor δ^{max}.

Proposition 2 (ARM exhibits unique Nash equilibrium)**.** *Given the auctioning-refunding mechanism* $ARM\big(\mathbf{b}^{\min}, r(p_T)\big)$ *there exists a unique Nash equilibrium in weakly dominated strategies, in which all resource managers i*

(i) either bid $T_i = T_i^{max}$*, where* T_i^{max} *denotes the highest tenure length for which manager i's true expected value of a concession with such a tenure length exceeds the respective minimum bid, and* $b_i = VAL(\delta_i, T_i^{max})$*, where* $VAL(\delta_i, T_i^{max})$ *is resource manager i's true expected value for a concession of tenure length* T_i^{max} *under* $ARM\big(\mathbf{b}^{\min}, r(p_T)\big)$*,*

(ii) or submit no bid if T_i^{max} *does not exist.*

In this Nash equilibrium either a resource manager with the highest discount factor δ^{max} *wins the auction and buys a concession of tenure length* $T^{max} = \arg\max_T \big\{VAL(\delta^{max}, T) \geq b_T^{\min}\big\}$ *or the resource right remains unsold if no bids are submitted.*

The proof is given in Appendix D.

Second, we focus on the auctioning-refunding mechanism where the refund is chosen as in equation (19) and the vector of minimum bids as in equation (20). We show that this particular auctioning-refunding mechanism $ARM\big(\mathbf{b}^{\min\star}, r^\star(p_T)\big)$ satisfies the following propositions.

Proposition 3 (ARM ensures sustainability goal)**.** *The auctioning-refunding mechanism* $ARM\big(\mathbf{b}^{\min\star}, r^\star(p_T)\big)$ *ensures that if a concession is sold the sustainability goal* $\hat{s}$ *is maintained over the whole concession tenure.*

The proof is given in Appendix E.

The intuition for the result is as follows. The refund ensures that a resource manager not harvesting below the sustainability goal in the last period of the concession tenure is in terms of expected net present value better off by $\delta_i^T\epsilon$. Thus, $EPV(\hat{\delta}_{T-1}, T) + (\hat{\delta}_{T-1})^T\epsilon$ represents the expected net present value of a concession of tenure T for a resource manager who exhibits the sustainable discount rate $\hat{\delta}_{T-1}$. Equation (20) guarantees that the minimum bid for a concession of tenure T is at least as high as $EPV(\hat{\delta}_{T-1}, T) + (\hat{\delta}_{T-1})^T\epsilon$. Thus, by virtue of Equation (15) and Lemmas 1 and 3, all resource managers with a true evaluation of a concession with tenure T equal to or above the minimum bid will obey the sustainability goal for all periods $1 \leq t \leq T-1$. In addition, the refund at the end of tenure ensures the sustainability goal in period T.

It may happen that no concession is sold. This is the case if the minimum bid exceeds the true evaluation of the most patient resource manager for all tenure lengths T. According to equation (20) the minimum bids are either determined by the sustainability goal $\hat{s}$ or by the regulator's expected opportunity costs $EOC(T)$, which are increasing in the regulator's discount factor δ_r and the monitoring costs m. Thus, if the auctioning-refunding mechanism cannot allocate a concession, even the most patient resource managers exhibit either an optimal harvesting strategy incompatible with the sustainability goal $\hat{s}$ or a willingness to pay for the concession below the regulator's expected opportunity costs. In either case the resource is best managed by the regulator herself.

The auctioning-refunding mechanism $ARM\big(\mathbf{b}^{\min\star}, r^\star(p_T)\big)$ is also efficient in the sense that the resource use rights are given to the agent with the highest expected net present value of the resource. This may be the regulator, in which case the resource rights remain unsold. If a resource use right is sold to one of the resource managers, the distribution of the expected net present value between seller and buyer depends on the distribution of discount factors among the resource managers. Due to the mechanism design, the regulator can extract more of the willingness to pay of the winning resource manager, the closer is the discount factor of the resource manager with the highest non-winning bid to the discount factor $\delta^{\max}$ of the winning resource manager.

Proposition 4 (Efficiency and distribution of ARM)**.**

1. *The auctioning-refunding mechanism $ARM\big(\mathbf{b}^{\min\star}, r^\star(p_T)\big)$ is efficient with respect to maximizing the sum of seller and buyer surplus.*

2. *If a concession is sold the auctioning-refunding mechanism $ARM\big(\mathbf{b}^{\min\star}, r^\star(p_T)\big)$ extracts the maximum willingness to pay among the population of resource managers if discount factors are densely distributed around δ^{max}.*

The proof is given in Appendix F.

5. Discussion

The auctioning-refunding mechanism introduced in Section 4 ensures that a given sustainability target is reached in the most efficient way. Our results rely on some (although standard) assumptions. In the following, we shall discuss these assumptions and how robust our analysis is against relaxing them.

First, we assumed resource managers maximizing expected net present value of profits. This implies that our resource managers correspond to risk-neutral firms rather than individual entrepreneurs or at least the latter need access to appropriate insurance markets. Risk-averse managers might choose higher escapement levels, but would be willing to pay less than risk-neutral managers with the same discount rates. Thus, it is ambiguous whether risk aversion facilitates the sustainability goal. However, the mechanism works well under conditions of risk aversion, as long as all resource managers exhibit the same degree of risk aversion. Moreover, earlier studies show that the riskiness of the resource dynamics may only have a very small effect on optimal management, even if the manager is risk-averse (Kapaun and Quaas, 2013).

Second, we assumed stochastic prices but constant (marginal) harvesting costs over time. As optimal escapement levels depend on the difference between marginal costs and resource price, it does not matter which of them is stochastic, as long as they follow a similar stochastic process. Thus, the mechanism would work equally well if not prices but the harvest costs follow a random walk without trend, as long as harvesting costs are the same across all resource managers. With technical progress, one would expect a negative trend of harvesting costs. The mechanism works also well if the resource price and/or the harvesting costs exhibit a trend, as long as this trend is common knowledge.

Third, we assumed that the maximal price increase between two periods is bounded. Under these conditions, the sustainability goal can be guaranteed for sure by limiting the tenure length of the auctioned concession. If the stochastic process of the price would allow for unlimited price increases, there would always be some possibility that the sustainability goal would be missed, even for a limited tenure length. In such cases, the regulator would have to specify some confidence limits, or minimum probabilities, for the sustainability goal. A corresponding sustainability notion would be stochastic viability (Béné et al., 2001; Baumgärtner and Quaas, 2009; Martinet, 2011)

Fourth, we assumed that the regulator has the means to manage the resource herself. If this is not an option and the primary goal of the regulator is to ensure sustainability, one can design an alternative mechanism by setting the expected opportunity costs $EOC(T) \equiv 0$ in the definition of the optimal minimum bids in equations (20). The resulting mechanism would still ensure the sustainability goal. In addition, the mechanism would never fail to sell a concession: As the refund guarantees the sustainability goal for such a concession, no minimum bid for a concession lasting one period is necessary. However, for concessions with a one period tenure length the regulator would have to pay refunds and monitoring costs in every period. If such a short concession tenure is not in the interest of the regulator, the mechanism can be extended in a straight forward manner to capture a minimum tenure length $T^{\min} > 1$.[7] However, the sustainability goal $\hat{s}$ may not be compatible with the minimum tenure $T^{\min}$, resulting in an auction with no (valid) bids.

Finally, the mechanism requires large front-up payments by the auction-winning resource manager. This implies that resource managers have to have sufficient funds or have access to financial markets. As a consequence, our mechanism better fits the situation where resource managers are big resource management companies or (developed) countries rather than small-scale subsistence fishermen.

6. Conclusion

In this paper we have introduced an auctioning-refunding mechanism which assures that a stochastic renewable natural resource is managed both sustainably and efficiently. The mechanism is not only compatible with limited-tenure resource rights, but also offers a

[7]The regulator would simply announce the minimum tenure length $T^{\min}$ together with the vector of minimum bids $\mathbf{b}^{\min} = (b^{\min}_{T^{\min}}, \dots, b^{\min}_{\infty})$ and the refund $r(p_T)$ at the first stage and also remove all bids with $T_i < T^{\min}$ in the third stage.

rationale for this common practice. The two main features of the mechanism are that it selects the most patient and, thus, most sustainably harvesting resource manager in a second-price sealed-bid auction with minimum bids and it overcomes the incentive to mine the resource at the end of tenure by announcing a refund in case the sustainability goal is obeyed. Moreover, the mechanism has some favorable properties. It overcomes the asymmetric information problem with respect to discount factors, works well under stochastic natural resource and price development, and maximizes expected resource rents for society.

Appendix

A. Optimal escapement levels

We define

$$Q(x_t, p_t) = p_t\,[x_t - \tilde{s}(p_t)] - \int\limits_{\tilde{s}(p_t)}^{x_t} c(y)\,dy \tag{A.1}$$

which may be interpreted as the "immediate harvest value" of the resource (Costello et al., 2001, 200). Hence, $\pi(x_t, s_t, p_t) = Q(x_t, p_t) - Q(s_t, p_t)$ and the optimization problem reads

$$\max_{\{s_t\}_{t=1}^{T}} \mathrm{E}_\eta\,\mathrm{E}_z \left[\sum_{t=1}^{T} \delta_i^t\,[Q(x_t, p_t) - Q(s_t, p_t)]\right] \tag{A.2}$$

In period T this boils down to

$$\max_{s_T} Q(x_T, p_T) - Q(s_T, p_T) \tag{A.3}$$

The optimal solution is to choose $s_T = \tilde{s}(p_T)$. Given the optimal solution for period T the optimization problem in period $T-1$ yields

$$\begin{aligned} &\max_{s_{T-1}} \big(Q(x_{T-1}) - Q(s_{T-1}) + \delta\,\mathrm{E}_\eta\,\mathrm{E}_z\,\big[Q(x_T) - Q\big(\tilde{s}(p_T)\big)\big]\big) \\ &\quad = -\,\delta\,\mathrm{E}_\eta\,\big[Q\big(\tilde{s}(p_T)\big)\big] + Q(x_{T-1}) + \max_{s_{T-1}} \left(-Q(s_{T-1}) + \delta\,\mathrm{E}_\eta\,\mathrm{E}_z\,[Q(z\,f(s_{T-1}))]\right) \end{aligned} \tag{A.4}$$

The first-order condition for the optimal choice of s_{T-1} is

$$\begin{aligned} p_{T-1} - c(s_{T-1}) &= \delta\,f'(s_{T-1})\;(E_\eta[\eta\,p_{T-1}] - E_z(z\,c(z\,f(s_{T-1})))) \\ &= \delta\,f'(s_{T-1})\;(p_{T-1} - E_z(z\,c(z\,f(s_{T-1})))) \end{aligned} \tag{A.5}$$

By induction, the first-order condition for the optimal escapement in any period $1 \le t < T$ is given by (11).

The proof of Lemma 2 establishes that the right-hand side of equation (11) is strictly decreasing in the escapement level $s^\star$. In addition, it approaches ∞ for $s \to \tilde{s}(p_t)$ and is smaller than unity for $s = \overline{s}$. Thus, for every discount factor $\delta_i \in [0, 1]$ and every resource price p_t there exists a unique solution $s^\star(\delta_i, p_t) \in (\tilde{s}(p_t), \overline{s})$ to equation (11). If the resource stock x_t is below the optimal escapement level $s^\star(\delta_i, p_t)$ the best feasible option for the resource manager is to refrain from harvesting. Together with the result that the optimal escapement level at time T is given by $\tilde{s}(p_T)$ the optimal escapement strategy (10) follows. □

B. Proof of Lemma 2

Condition (11) can be written as

$$\frac{1}{\delta_i} = f'\big(s^\star(\delta_i, p_t)\big)\frac{p_t - \mathrm{E}_z\Big[zc\Big(zf\big(s^\star(\delta_i, p_t)\big)\Big)\Big]}{p_t - c\big(s^\star(\delta_i, p_t)\big)} \ , \tag{B.6}$$

First, we show that for any given p_t the right-hand side of equation (B.6)

$$F(s) = f'(s)\frac{p - \mathrm{E}_z\left[zc\big(zf(s)\big)\right]}{p - c(s)} \ , \tag{B.7}$$

is a strictly decreasing function for all $s \in (\tilde{s}(p_t), \overline{s})$, which proofs the first part of the lemma.

For $\theta = 0$ the proof is trivial. For $\theta > 0$, $p_t = c\big(\tilde{s}(p_t)\big)$ holds. Inserting $c(y) = \kappa y^{-\theta}$, the expectation with respect to z yields

$$\mathrm{E}_z\left[zc\big(zf(s)\big)\right] = \mathrm{E}_z\left[z^{1-\theta}\kappa f(s)^{-\theta}\right] = \kappa f(s)^{-\theta}\mathrm{E}_z\left[z^{1-\theta}\right] = \kappa\left[\mathrm{E}_z\left[z^{1-\theta}\right]^{\theta} f(s)\right]^{-\theta} \ . \tag{B.8}$$

Set $\hat{z} = \mathrm{E}_z\left[z^{1-\theta}\right]^{\theta}$. As $\overline{z} > \overline{z}^{\alpha} > 1 > \underline{z}^{\alpha} > \underline{z}$ for all $\alpha \in (0,1)$, if also follows that $\overline{z} > \hat{z} > \underline{z}$. Thus, we can write F as

$$F(s) = \hat{z}^{-\theta}\left[f'(s)\left(\frac{s}{f(s)}\right)^{\theta}\right]\left[\frac{[\hat{z}f(s)]^{\theta} - \tilde{s}^{\theta}}{s^{\theta} - \tilde{s}^{\theta}}\right] \ . \tag{B.9}$$

Differentiating F with respect to s yields

$$
\begin{aligned}
\frac{\partial F(s)}{\partial s} &= f'(s)\left(\frac{s}{f(s)}\right)^{\theta}\frac{\theta f(s)^{\theta}}{(s^{\theta}-\tilde{s}^{\theta})^2}\left\{s^{\theta-1}\left[\frac{sf'(s)}{f(s)}-1\right]-\tilde{s}^{\theta}\frac{f'(s)}{f(s)}\right\} \\
&\quad+\frac{[\hat{z}f(s)]^{\theta}-\tilde{s}^{\theta}}{s^{\theta}-\tilde{s}^{\theta}}\frac{\theta s^{\theta-1}}{[\hat{z}f(s)]^{\theta}}\left\{\frac{sf''(s)}{\theta}+f'(s)\left[1-\frac{sf'(s)}{f(s)}\right]\right\} \\
&=\frac{\left([\hat{z}f(s)]^{\theta}-\tilde{s}^{\theta}\right)sf''(s)}{(s^{\theta}-\tilde{s}^{\theta})\,[\hat{z}f(s)]^{\theta}}-\frac{\theta}{(s^{\theta}-\tilde{s}^{\theta})^2\,[\hat{z}f(s)]^{\theta}}\left[s^{\theta}\tilde{s}^{\theta}\,[\hat{z}f(s)]^{\theta}\,\frac{f'(s)^2}{f(s)}\right. \\
&\quad\left.+s^{\theta-1}\left(\tilde{s}^{\theta}\,[\hat{z}f(s)]^{\theta}+s^{\theta}\tilde{s}^{\theta}-\tilde{s}^{2\theta}\right)\left\{f'(s)\left[1-\frac{sf'(s)}{f(s)}\right]\right\}\right]<0\ . \qquad \text{(B.10)}
\end{aligned}
$$

F is strictly decreasing, as $\hat{z}f(s)>\tilde{s}$ for all $s\in(\tilde{s},\overline{s})$ ($s\in(0,\underline{s})$ are self-sustaining and $\underline{s}>\tilde{s}$) and $\frac{sf'(s)}{f(s)}\leq 1$ (f is concave).

Second, we re-arrange equation (11) to yield:

$$
\begin{aligned}
G(s,p_t) &= p_t\left[1-\delta_i f'(s)\right]-\left\{c(s)-\mathrm{E}_z\left[zc\big(zf(s)\big)\right]\right\} &\text{(B.11)}\\
&= p_t\left[1-\delta_i f'(s)\right]-\kappa\left[(s)^{-\theta}-\big(\hat{z}f(s)\big)^{-\theta}\right]=0 &\text{(B.12)}
\end{aligned}
$$

with $\hat{z}=\mathrm{E}_z\left[z^{1-\theta}\right]^{\theta}$ as defined above. By virtue of the implicit function theorem ds/dp_t is given by:

$$
\begin{aligned}
\frac{ds}{dp_t} &= -\frac{\partial G(s,p_t)/\partial p_t}{\partial G(s,p_t)/\partial s} &\text{(B.13)}\\
&= \frac{1-\delta_i f'(s)}{\delta_i f''(s)-\frac{\theta\kappa}{s}\left[s^{-\theta}-\frac{s}{f(s)}\big(\hat{z}f(s)\big)^{-\theta}\right]}<0\ . &\text{(B.14)}
\end{aligned}
$$

$ds/dp_t<0$, as $f''(s)<0$ and $sf'(s)/f(s)\leq 1$ (f is concave). □

C. Proof of Lemma 4

According to equation (15), $\hat{\delta}_t$ is given by:

$$
\hat{\delta}_t=\left[f'(\hat{s})\frac{p_t^{\max}-\mathrm{E}_z\left[zc\big(zf(\hat{s})\big)\right]}{p_t^{\max}-c(\hat{s})}\right]^{-1}\ . \qquad \text{(C.15)}
$$

Differentiating $\hat{\delta}_t$ with respect to t yields:

$$\frac{\partial \hat{\delta}_t}{\partial t} = \frac{c(\hat{s}) - \mathrm{E}_z\left[zc\big(f(\hat{s})\big)\right]}{f'(\hat{s})\left(p_t^{\max} - \mathrm{E}_z\left[zc\big(f(\hat{s})\big)\right]\right)^2} \frac{\partial p_t^{\max}}{\partial t} \ . \tag{C.16}$$

From the proof of Lemma 2 follows that $\mathrm{E}_z\left[zc\big(f(\hat{s})\big)\right] = c\big(\hat{z}f(\hat{s})\big)$ with $\overline{z} > \hat{z} > \underline{z}$. Thus, $\hat{z}f(\hat{s}) > \hat{s}$ as $\hat{s} < \underline{s}$. As $f'(s) > 0$, $c'(s) < 0$ and $\partial p_t^{\max}/\partial t > 0$, $\partial \hat{\delta}_t/\partial t > 0$. □

D. Proof of Proposition 2

First, note that resource manager i's true expected value of holding a concession with tenure T, $VAL(\delta_i, T)$, is not necessarily equal to $EPV(\delta_i, T)$, as given by equation (8), but depends on the expected refund at the end of tenure according to the rules of the auctioning-refunding mechanism $ARM\big(\mathbf{b}^{\min}, r(p_T)\big)$. In fact, $EPV(\delta_i, T)$ is a lower bound on $VAL(\delta_i, T)$, as the resource manager can always decide to forego the refund and harvest down to the open-access escapement level $s^{\infty}(p_T)$ in the last period T of the concession tenure. However, it follows directly from Lemma 1 and the definition of the refund (18) that $VAL(\delta_i, T)$ is increasing in the resource manager's discount factor δ_i.

Second, the mechanism is analogous to a two stage game in which resource managers submit a concession length T_i in the first stage and take part in a Vickrey auction for a concession of tenure length T_i with a minimum bid $b_{T_i}^{\min}$ in the second stage. Analogously to the standard Vickrey auction it is a weakly dominant strategy to bid the true expected value $VAL(\delta_i, T_i)$ for a concession of tenure T_i if $VAL(\delta_i, T_i) \geq b_{T_i}^{\min}$ and not to submit a bid if $VAL(\delta_i, T_i) < b_{T_i}^{\min}$.[8] Defining T_i^{max} as the maximum tenure length for which the resource manager i exhibits a true expected value of the concession exceeding the minimum bid

$$T_i^{max} = \arg\max_T \left\{VAL(\delta_i, T) \geq b_T^{\min}\right\} \ , \tag{D.17}$$

and anticipating the outcome of the second stage, it is a weakly dominant strategy to bid $T_i = T_i^{max}$ in the first stage. There is no incentive to bid $T_i < T_i^{max}$, as only the bid with the highest tenure

[8]Although the resource manager is indifferent between submitting $VAL(\delta_i, T_i)$ and abstaining from bidding if $VAL(\delta_i, T_i) < b_{T_i}^{\min}$, we assume that resource managers submit no bid in this case. This assumption is irrelevant for the result, as by the rules of $ARM\big(\mathbf{b}^{\min}, r(p_T)\big)$, as detailed in Definition 1, all invalid bids are not considered.

length has a chance to win the concession. There is also no incentive to bid $T_i > T_i^{max}$, because if it would be the winning bid, the resource manager would have to pay at least $b_{T_i}^{\min}$ which is, by definition, higher than the true expected value $VAL(\delta_i, T_i)$. However, it may be that T_i^{max} does not exist, which is the case if $VAL(\delta_i, T) < b_T^{\min}$ for all T. In this case, it is a weakly dominant strategy to abstain from bidding.

Third, if all resource managers bid according to their weakly dominant strategies outlined above, either all resource managers abstain from bidding, in which case the resource rights remain unsold, or a resource manager with the highest discount factor δ^{max} wins the auction, as $VAL(\delta_i, T)$ and T_i^{max} are (weakly) increasing in δ_i. □

E. Proof of Proposition 3

Note that given the refunding scheme (18) together with $r^\star(p_T)$, as defined in (19), no resource manager holding a concession of tenure T has an incentive to harvest the resource below the sustainability goal in the final period T of the concession tenure. As the resource stock x_T and the resource price p_T in the final period are known before the resource manager decides on the escapement level s_T, the refunding scheme ensures a profit increase of ϵ over harvesting the resource to the open-access level $\tilde{s}(p_T)$. Anticipating the refund at the end of tenure, the true expected value for a concession of tenure T of the resource manager with discount factor δ_i reads:

$$VAL(\delta_i, T) = EPV(\delta_i, T) + \delta_i^T \epsilon \tag{E.18}$$

Thus, $EPV(\hat{\delta}_{T-1}, T) + (\hat{\delta}_{T-1})^T \epsilon$, which is according to equation (20) a lower bound for the minimum bid for a concession of tenure length T, represents the true expected value for a concession of tenure T for a resource manager exhibiting a discount factor equal to the sustainable discount factor $\hat{\delta}_{T-1}$. According to Lemma 3, such a resource manager has a minimal optimal escapement level in period $T-1$ equal to the sustainability goal $\hat{s}$ and minimal optimal escapement levels strictly higher than $\hat{s}$ for all periods $1 \le t < T-1$. Thus, this resource manager would always obey the sustainability goal for all periods $1 \le T \le T-1$ and would also obey the sustainability goal in period T because of the refund. As the minimal optimum escapement level increase in the discount factor, this also holds for all resource managers exhibiting a discount factor larger than $\hat{\delta}_{T-1}$. □

F. Proof of Proposition 4

The first part of Proposition 4 follows directly from Proposition 3 and Lemma 1.

To see the second part, recall that under the auctioning-refunding mechanism the resource manager winning the auction pays the highest non-winning bid for tenure length $T^{\max}$ if it exists and $b^{\min}_{T^{\max}}$ otherwise. If discount factors are densely distributed around $\delta^{\max}$ then, there exists a $\delta_i = \delta^{\max} - \mu$ for any arbitrarily small $\mu > 0$. As a consequence, the highest non-winning bid is arbitrarily close to the bid of the resource manager winning the auction. □

Agnew, D., Pearce, J., Pramod, G., Peatman, T., Watson, R., Beddington, J., Pitcher, T., 2009. Estimating the worldwide extent of illegal fishing. PLoS ONE 4 (2).

Amacher, G., Ollikainen, M., Koskela, E., 2012. Corruption and forest concessions. Journal of Environmental Economics and Management 63 (1), 92–104.

Andersen, S., Harrison, G., Lau, M., Rutstrom, E., 2008. Eliciting risk and time preferences. Econometrica 76 (3), 583–618.

Arnason, R., 2007. Advances in property rights based fisheries management: An introduction. Marine Resource Economics 22 (4), 335–346.

Baumgärtner, S., Quaas, M. F., 2009. Ecological-economic viability as a criterion of strong sustainability under uncertainty. Ecological Economics 68, 2008–2020.

Béné, C., Doyen, L., Gabay, D., 2001. A viability analysis for a bio-economic model. Ecological Economics 36, 385–396.

Bromley, D., 2009. Abdicating responsibility: The deceits of fisheries policy. Fisheries 34 (6), 280–302.

Chouinard, H. H., 2005. Auctions with and without the right of first refusal and national park service concession contracts. American Journal of Agricultural Economics 87 (4), 1083–1088.

Clark, C. W., 1973. Profit maximization and the extinction of animal species. The Journal of Political Economy 81 (4), 950–961.

Clark, C. W., Munro, G. R., Sumaila, U. R., 2010. Limits to the privatization of fishery resources. Land Economics 86 (2), 209–218.

Coller, M., Williams, M., 1999. Eliciting individual discount rates. Experimental Economics 2 (2), 107–127.

Costello, C., Polasky, S., Solow, A., 2001. Renewable resource management with environmental prediction. Canadian Journal of Economics / Revue canadienne d'Economique 34 (1), 196–211.

Costello, C. J., Kaffine, D., 2008. Natural resource use with limited-tenure property rights. Journal of Environmental Economics and Management 55, 20–36.

Cramton, P., 2009. How best to auction natural resources. Working Paper, Economics Department, University of Maryland.

Cramton, P., Humphreys, M., Sachs, J. D., Stiglitz, J. E., 2007. How Best to Auction Oil Rights. Foreword by George Soros. Initiative for Policy Dialogue at Columbia series. New York: Columbia University Press, U MD, pp. 114–151.

Curtis, J., 2002. Estimates of fishermen's personal discount rate. Applied Economics Letters 9 (12), 775–778.

Dichmont, C., Pascoe, S., Kompas, T., Punt, A., Deng, R., 2010. On implementing maximum economic yield in commercial fisheries. Proceedings of the National Academy of Sciences 107 (1), 16–21.

Gordon, H., 1954. The economic theory of a common-property resource: The fishery. Journal of Political Economy 62, 124–142.

Grafton, R., 1994. A note on uncertainty and rent capture in an ITQ fishery. Journal of Environmental Economics and Management 27 (3), 286–294.

Grafton, R., 1995. Rent capture in a rights-based fishery. Journal of Environmental Economics and Management 28 (1), 48–67.

Harrison, G., Lau, M., Williams, M., 2002. Estimating individual discount rates in denmark: A field experiment. American Economic Review 92 (5), 1606–1617.

Kapaun, U., Quaas, M., 2013. Does the optimal size of a fish stock increase with environmental uncertainties? Environmental and Resource Economics 54 (2), 293–310.

Libecap, G. D., 2007. Assigning property rights in the common pool: Implications of the prevalence of first-possession rules for ITQs in fisheries. Marine Resource Economics 22 (4), 407–423.

Martinet, V., 2011. A characterization of sustainability with indicators. Journal of Environmental Economics and Management 61 (2), 183–197.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Synthesis Report. Island Press, Washington DC.

Montero, J.-P., 2008. A simple auction mechanism for the optimal allocation of the commons. American Economic Review 98 (1), 496–518.

Osmundsen, P., 1996. Repeated auctions of franchises for nonrenewable resources. Journal of Regulatory Economics 10 (2), 183–189.

Reed, W. J., 1979. Optimal escapement levels in stochastic and deterministic harvesting models. Journal of Environmental Economics and Management 6, 350–363.

Rocha, K., Moreira, A., Reis, E., Carvalho, L., 2006. The market value of forest concessions in the brazilian amazon: a real option approach. Forest Policy and Economics 8 (2), 149–160.

Scott, A., 1955. The fishery: The objectives of sole ownership. Journal of Political Economy 63, 116–124.

Weitzman, M., 2001. Gamma discounting. American Economic Review 91 (1), 260–271.

Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., Fogarty, M. J., Fulton, E. A., Hutchings, J. A., Jennings, S., Jensen, O. P., Lotze, H. K., Mace, P. M., McClanahan, T. R., Minto, C., Palumbi, S. R., Parma, A. M., Ricard, D., Rosenberg, A. A., Watson, R., Zeller, D., 2009. Rebuilding global fisheries. Science 325 (5940), 578–585.