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Markets for Sustainable Resource Use: Auctioned Limited-Tenure Use Rights with Refunding

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Abstract: Efficiency and sustainability often clash if limited-tenure use rights for renewable natural resources are rented to private resource managers. We introduce a mechanism reconciling these two issues for a stochastically developing natural resource. The mechanism 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 if a sustainability goal is obeyed. In addition, the mechanism ensures efficiency and is self-financing in expectation.

Keywords: auctioning-refunding-mechanism, efficiency, renewable resource, stochastic model, sustainability

JEL-Classification: Q20, D44, D82

1 Introduction

According to the established theory, the overuse of natural resources is caused by a lack of adequate property rights (Arnason 2007). Therefore, granting exclusive private use rights is the most promising way to achieve *efficient resource use*. Apart from efficiency, also *sustainable resource use* is a 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). Clark (1973) shows 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.

In this paper, we study the question how the tension between efficiency and sustainability goals can be reconciled. We introduce a mechanism granting exclusive use-rights over a renewable natural resource for a limited tenure such that the resource is managed efficiently and sustainable. While the efficiency goal is the standard maximization of the present value of resource rents, we operationalize society's *sustainability goal* as the requirement to maintain a minimal level of the resource stock at all times. Various interpretations of such a minimal resource stock 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).

Our mechanism deals with a number of peculiarities present in the context of natural resource use rights. First, it is common practice to grant resource rights only for a limited-tenure, so called *concessions* (Bromley 2009, Costello and Kaffine 2008). On the one hand, society may hold resource managers responsible for the sustainable use of the resource after the end of the tenure. On the other hand, concessions give incentives to resource users to mine the resource at the end of tenure. While Costello and Kaffine (2008) overcome this incentive by the right choice of tenure length and a sufficiently high probability that the concession is renewed, we will introduce an refunding scheme, which compensates the resource user at the end of tenure for the foregone gains of resource mining.

Second, our mechanism deals with the asymmetric information problem with respect to discount rates. Discount rates differ substantially across resource users, yet they are – at least a priori – private knowledge (Andersen et al. 2008, Collier and Williams 1999, Curtis 2002, Harrison et al. 2002). Our mechanism ensures that use rights are only granted to resource managers who exhibit a discount rate which is compatible with the sustainability goal. In essence, this is achieved by a second-price sealed-bid auction with minimum bids and the fact, that use rights are more valuable to resource managers the more patient they are. Thus, the mechanism also ensures optimal concession allocation in the sense that the resource manager for which the use right is most valuable gets the concession.

Third, our mechanism is designed to work in an uncertain environment where both resource dynamics and resource prices are stochastic. In particular, stochastic resource prices may jeopardize the sustainability goal, as the resource manager’s optimal harvest is increasing in the resource price. We model resource prices as a random walk with identically distributed step size for all periods. Thus, the longer the concession tenure, the higher is the probability that resource prices reach a threshold for which the sustainability goal cannot be ensured. As a consequence, our mechanism endogenously determines the maximal concession tenure compatible with the sustainability goal. Moreover, stochastic prices provide a rational why societies may be reluctant to surrender natural resource use rights for good.

Our mechanism has a number of favorable characteristics. There is little informational need for the mechanism to work properly. In contrast to Costello and Kaffine (2008), incentives for sustainable resource use are provided 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 mechanism is self-financing in expectation (at least if society is as at least as impatient as the most patient resource manager). Moreover, it ensures that natural resource use rights are not windfall gains for the concession owners, an issue heavily debated with respect fisheries with grandfathered individual transferable quotas (ITQs), e.g., Grafton (1994, 1995), Osmundsen (1996), Cramton et al. (2007), Cramton (2009), Chouinard (2005) and Libecap (2007). In fact, the auction design with minimum bids ensures that resource rents are shared among society and concession owners.

The remainder of the paper is organized as follows. In section 2 we introduce a stochastic renewable natural resource model. We introduce our auctioning-refunding mechanism in Section 3. For presentational purpose, we first assume constant prices (Section 3.1),

an assumption we relax in Section 3.2. In Section 4 we illustrate the usefulness of our mechanism with an empirical example. Model assumptions and possible extensions of the model are discussed in Section 5. Section 6 concludes.

2 Model

Consider a regulator representing a society that owns a renewable natural resource. The resource stock in period t , x_t , develops according to the following equation of motion:

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

where $s_t = x_t - h_t$ denotes escapement in period t , i.e., the initial stock x_t minus the harvest h_t in period t . 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 variables z_t , the sequence of which is independently identically distributed with a common distribution function $\phi(z)$ with bounded support $[\underline{z}, \bar{z}]$ and unit mean, $0 < \underline{z} \leq 1 \leq \bar{z} < \infty$.

We further assume $f(0) = 0$, $\underline{z}f'(0) > 1$ and $\lim_{s \rightarrow \infty} \bar{z}f'(s) < 1$. The first two assumption ensure that extinction is not a stable steady state, or, in ecological terms, that the minimum viable population is zero.¹ The last two assumptions imply that there exist recruitment levels $\underline{s} = \underline{z}f(\underline{s})$ and $\bar{s} = \bar{z}f(\bar{s})$ such that without harvest the resource level will eventually enter and henceforth never leave the interval $[\underline{s}, \bar{s}]$. Moreover, all recruitment levels $s \in (0, \underline{s})$ are *self-sustaining*, i.e., $x_{t+1} > s_t$ with probability 1 (Reed 1979).

Potential resource managers are risk neutral and differ in their discount factors $\delta_i \in [\underline{\delta}, \bar{\delta}]$ with $0 < \underline{\delta} < \bar{\delta} < 1$. All of them have access to the same harvesting technology which renders profits π in period t :

$$\pi(x_t, s_t, p_t) = \int_{s_t}^{x_t} [p_t - c(y)] dy , \quad (2)$$

¹ This assumption eases calculations but does not impact qualitatively on our results. In the paper we present a mechanism that ensures that the resource population never drops below a certain level s^* . If the minimal viable population is strictly positive, setting s^* larger than the minimal viable population always ensures that the population does not become extinct.

where $c(y) = \kappa y^{-\theta}$, $\kappa > 0$, $\theta \geq 0$, denotes the unit cost function of harvesting at the resource level y . Denote the selling price of the resource in period $t = 0$ by p . The price of the resource p_t in periods $t \geq 1$ follows a stochastic process

$$p_{t+1} = \eta_t p_t , \tag{3}$$

where η_t is an independent and identically distributed random variable with common distribution function $\psi(\eta_t)$ with bounded support $[\underline{\eta}, \bar{\eta}]$ and unit mean, $0 < \underline{\eta} \leq 1 \leq \bar{\eta} < \infty$. In particular, equation (3) implies that $E_{\eta}(p_{t+1}|p_t) = p_t$.

For later use, let $s_{\infty}(p_t)$ be the open-access escapement level of the resource at price p_t , which is implicitly defined by

$$s_{\infty}(p_t) = \max [\{s \mid p_t - c(s) = 0\} , 0] . \tag{4}$$

Due to the monotonicity of c , $s_{\infty}(p_t)$ exists and is unique for all p_t . For ease of notation we denote the a priori expected open access level $s_{\infty}(p)$ by s_{∞} .

The dynamics of the resource stock (1) and the harvesting technology (2) are common knowledge and known to the regulator and all potential resource managers. Discount factors, however, are private knowledge such that the regulator and the resource managers only know their own discount factor.

The regulator wants to delegate the resource harvest to a private resource manager, but also imposes a *sustainability goal* for the natural resource. That is, the resource escapement should reach a minimum level s^* as soon as possible and should never fall below this level thereafter. The sustainability goal s^* may reflect different social concerns such as resource yield, maintaining ecosystem services and biodiversity conservation. To render the regulator's problem feasible and non-trivial, we impose

Assumption 1

The regulator's sustainability goal is self-sustaining and exceeds the a priori expected open-access escapement level, i.e., $s_{\infty} < s^ < \underline{s}$.*

In addition, we assume that the regulator is reluctant to completely surrender control of the natural resource to private resource users. As a consequence, society only gives temporary use rights with limited tenure T , so called *concessions*, to resource managers.

In period $t = 0$ the regulator sells the concession to a resource manager. At that time, the initial escapement s_0 and the initial resource price p are common knowledge. In each

period $t \geq 1$, the resource managers learn about the actual resource stock x_t and the resource price p_t before they decide about escapement s_t .

In the following, we seek an optimal allocation mechanism maximizing the regulator's revenues from selling concessions, at the same time ensuring the sustainability goal to be met.

3 An Optimal Auctioning-Refunding Mechanism

The regulator wants the private resource manager to harvest the resource in the following way. First, if the initial escapement s_0 is below the sustainability goal s^* , the resource manager should refrain from harvesting until the sustainability goal is achieved. Second, once the sustainability goal is achieved, the resource manager should harvest the resource such that escapement s_t never drops below the sustainability goal s^* . Assumption 1 ensures that the former is achievable in finite time and the latter is always possible once the escapement level exceeds s^* .

However, a risk neutral private resource manager, holding a concession of duration T and exhibiting a discount factor δ_i , chooses an escapement path $\{s_t\}_{t=1}^T$ such as to maximize the expected present value of profits from resource management

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

In general, the profit maximizing escapement path clashes with the regulator's sustainability goal. In particular, the profit maximizing escapement in the last period is equal to the open-access level in the last period, i.e., $s_T = s_\infty(p_T)$ (if $x_T \geq s_\infty(p_T)$, otherwise $s_T = x_T$). By Assumption 1 the expected open-access level in period T , s_∞ , is below the sustainability goal. Thus, the allocation mechanism has to give incentives to the private resource manager to refrain from resource overuse in the final period. In addition, the mechanism has to ensure that the resource owner does not harvest below the sustainability goal in the periods $t < T$.

Before we proceed we state the following lemma:

Lemma 1 ($EPV(\delta_i, T)$ is strictly increasing in δ_i)

The expected present value of profits from resource management $EPV(\delta_i, T)$, as given by equation (5), is an increasing function with respect to the discount factor δ_i .

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

$$\frac{\partial EPV(\delta_i, T)}{\partial \delta_i} = \mathbb{E} \left[\sum_{t=1}^T t \delta_i^{t-1} \pi(z_t f(\hat{s}_t), \hat{s}_t, p_t) \right] \geq 0, \quad (6)$$

where \hat{s}_t denotes the optimal escapement level at time t . The equality sign holds if and only if $\pi(z_t f(\hat{s}_t), \hat{s}_t, p_t) = 0$ for all $t = 1, \dots, T$. \square

3.1 Constant price level

We first assume that the price of the resource is constant for all times t , i.e., $p_t = p$ for all t . Then, the open-access escapement level is constant and given by s_∞ . Under these circumstances and given the assumptions on the recruitment function f and the unit cost function c , a resource manager maximizing (5) follows a “constant escapement” rule (Reed 1979):

$$s_t = \begin{cases} s_i^*, & x_t > s_i^* \\ x_t, & x_t \leq s_i^* \end{cases}, \quad 0 < t < T; \quad s_T = \begin{cases} s_\infty, & x_t > s_\infty \\ x_t, & x_t \leq s_\infty \end{cases}, \quad (7)$$

where s_i^* is given by the solution of the implicit equation

$$\frac{1}{\delta_i} = f'(s_i^*) \frac{p - \mathbb{E}_z [zc(zf(s_i^*))]}{p - c(s_i^*)}, \quad (8)$$

and denotes the optimal escapement level of a resource manager exhibiting the discount factor δ_i . We can show the following lemma:

Lemma 2 (s_i^* is strictly increasing in δ_i)

The optimal escapement level s_i^ is a strictly increasing function with respect to the discount factor δ_i .*

The proof is given in the appendix.

Lemma 2 establishes that the right-hand side of equation (8) is a strictly decreasing function of s . In addition, it approaches ∞ for $s \rightarrow s_\infty$ and is smaller than unity for $s = \bar{s}$. Thus, for every $\delta_i \in (0, 1]$ there exists a unique solution $s_i^* \in (s_\infty, \bar{s})$ to equation (8). Thus, apart from the final period T , where it is optimal to harvest to the open-access escapement level s_∞ , the private resource manager harvests the difference between actual stock x_t and the optimal escapement level s_i^* whenever the former exceeds the latter and refrains from harvesting otherwise.

In addition, Lemma 2 implies that the optimal escapement level s_i^* is higher the higher is the discount factor of the private resource manager. Defining

$$\delta^* = \left[f'(s^*) \frac{p - \mathbb{E}_z [zc(zf(s^*))]}{p - c(s^*)} \right]^{-1}, \quad (9)$$

all resource managers with $\delta_i \geq \delta^*$ will manage the resource at an escapement level which is at least as high as the sustainability goal s^* . Thus, apart from the final period, the sustainability goal is met if the allocation mechanism assigns the concession to a resource manager with $\delta_i \geq \delta^*$.

One possibility to prevent private resource managers from harvesting the resource in period T below the sustainability goal s^* is to pay a refund $R(s_T)$ contingent on the escapement level in period T

$$R(s_T) = \begin{cases} r & \text{if } s_T \geq s^* \\ 0 & \text{if } s_T < s^* \end{cases}. \quad (10)$$

Now we can define the auctioning-refunding allocation mechanism under constant prices.

Definition 1 (Auctioning-refunding mechanism under constant price level)

Under the assumption of constant prices $p_t = p$, $\forall t$, we define an auctioning-refunding mechanism $ARMC(T, b_{min}, r)$ by the following sequence of events:

1. *The regulator announces the tenure of the concession T , a minimum bid b_{min} and a refund r .*
2. *Bidders submit sealed bids b_i where b_i denotes the bid of resource manager i .*
3. *All bids with $b_i < b_{min}$ are removed.*
4. *If there are no bids left, the resource remains unsold. Otherwise, the resource manager with the highest bid wins the auction. If more than one resource managers submit the highest bid the winner is determined by a lottery among them. The winner pays the highest non-winning bid if it exists, and b_{min} otherwise. She is granted exclusive use rights over the natural resource for tenure length T .*
5. *At the end of the concession period the regulator pays a refund $R(s_T)$, as given by condition (10), to the resource user.*

The auctioning-refunding mechanism $ARMC(T, b_{min}, r)$ is essentially a second-price sealed-bid auction with a lower bound for bids. We show that it ensures the regulator's sustainability goal if the concession tenure T , the minimum bid b_{min} and the refund r are set appropriately. Defining

$$T_{min} = \min_T \{x_T \geq s^* | x_{t+1} = \underline{z}f(x_t)\} , \quad (11a)$$

$$b^* = EPV(\delta^*, T) + \delta^{*T} \epsilon , \quad (11b)$$

$$r^* = \pi(s^*, s_\infty, p) + \epsilon , \quad (11c)$$

$$\epsilon > 0, \quad \text{arbitrarily small} , \quad (11d)$$

the following propositions summarize the characteristics of the auctioning-refunding mechanism under constant prices.

Proposition 1 (ARMC ensures sustainability goal)

The auctioning-refunding mechanism $ARMC(T \geq T_{min}, b^, r^*)$ ensures that the sustainability goal is attained in minimal time and always supported thereafter for the tenure of the concession if $\bar{\delta} \geq \delta^*$. Otherwise, the concession remains unsold.*

The proof is given in the appendix.

The intuition for the result is as follows. First, the concession tenure of at least T_{min} ensures that the sustainability goal is attainable within a time horizon of T . Second, due to the second-price sealed-bid auction all private resource managers bid the expected net present value of holding the concession if it is at least as high as the minimum bid b^* . Third, the refund compensates the resource managers for not harvesting below the escapement level s^* . In fact, if the stock in period T is at least as high as the escapement level s^* not harvesting below s^* yields an expected net present value of profits of $EPV(\delta_i, T) + \delta_i^T \epsilon$ which is higher than the corresponding value $EPV(\delta_i, T)$ for harvesting to the open-access escapement level s_∞ .

Now, by virtue of Lemmata 1 and 2 both the expected present value of profits from resource management over a concession tenure of T , $EPV(\delta_i, T)$, and the optimal escapement level s_i^* are increasing in the discount factor δ_i . This ensures that only resource managers with a discount factor $\delta_i \geq \delta^*$ and an optimal escapement level $s_i^* \geq s^*$ exhibit an expected net present value of holding the concession at least as high as the minimum bid b^* . According to condition (7), these resource managers harvest only if $x_t \geq s_i^* \geq s^*$ except for the last period T . This implies that the sustainability goal is attained in minimum time if $s_0 < s^*$ and that escapement in each period is at least as high as the

sustainability goal. As this also implies that $x_T > s^*$ these resource managers maximize profits restricting harvest in period T to the escapement level s^* and, thus, being eligible for the refund r^* .

In addition, the ARMC is efficient as the following proposition states:

Proposition 2 (Efficiency of the ARMC)

The auctioning-refunding mechanism $ARMC(T \geq T_{min}, b^, r^*)$ is efficient in the sense that the concession is given to the resource manager with the highest expected net present value if $\bar{\delta} \geq \delta^*$.*

Proof: If $\bar{\delta} \geq \delta^*$ resource managers exhibiting the discount factor $\bar{\delta}$ submit the bid $\bar{b} = EPV(\bar{\delta}, T) + \bar{\delta}^T \epsilon$, and one of them wins the auction. By virtue of Lemma 1 $EPV(\bar{\delta}, T) + \bar{\delta}^T \epsilon > EPV(\delta_i, T) + \delta_i^T \epsilon, \forall \delta_i < \bar{\delta}$. \square

Proposition 2 says that the resource manager who values the resource most gets the exclusive right to manage it. Thus, the $ARMC(T \geq T^*, b^*, r^*)$ maximizes the sum of seller and buyer surplus. The division of the total surplus depends on the highest non-winning bid due to the second-price auction design. The regulator gets paid at least the minimum bid b^* (if the second highest bid is less or equal to b^*) and at most $EPV(\bar{\delta})$ if more than one resource manager exhibit a discount factor $\bar{\delta}$. However, the regulator has to pay the refund r in period T . Nevertheless, the ARMC is self-financing, as the following proposition states:

Proposition 3 (ARMC is self-financing)

1. *If the discount factor of the regulator $0 < \delta^R < 1$ is lower than or equal to δ^* , $ARMC(T \geq T_{min}, b^*, r^*)$ is self-financing.*
2. *If $\delta^R > \delta^*$ and $ARMC(T \geq T_{min}, b^*, r^*)$ is not self-financing, then there exists a concession tenure T^* such that $ARMC(T \geq T^*, b^*, r^*)$ is self-financing.*

Proof: The net present value of the refund equals $(\delta^R)^T [\pi(s^*, s_\infty, p) + \epsilon]$. The regulator is paid at least b^* which can be written as

$$b^* = \max_{\{s_t\}_{t=1}^T} \mathbb{E} \left[\sum_{t=1}^{T-1} (\delta^*)^t \pi(x_t, s_t, p_t) + (\delta^*)^T \pi(x_T, s^*, p) \right] + (\delta^*)^T [\pi(s^*, s_\infty, p) + \epsilon]. \quad (12)$$

Thus, for all $\delta^R \leq \delta^*$ b^* is at least as high as the net present value of the refund.

For $\delta^R > \delta^*$ note that $\lim_{T \rightarrow \infty} (\delta^R)^T [\pi(s^*, s_\infty, p) + \epsilon] = 0$ and $\partial b^* / \partial T > 0$. Thus, there exists a $T_{sf} = \min_T \{ (\delta^R)^T [\pi(s^*, s_\infty, p) + \epsilon] \geq b^* \}$. Setting $T^* = \max [T_{min}, T_{sf}]$ yields

the minimal T for which the auctioning-refunding mechanism exhibits the properties laid out in Propositions 1 and 2, and is also self-financing. \square

Proposition 3 says that the auctioning-refunding mechanism is self-financing if the tenure period is sufficiently long. In fact, in the model setting of constant price levels it is not clear, why the regulator should hesitate to surrender the use rights for the natural resource for good. Selling the resource in a second-price auction with a minimum bid of $b^* = EPV(\delta^*, \infty)$ ensures that the resource is sold to a resource manager who exhibits an optimal escapement level at least as high as the sustainability goal. The problem of exploiting the resource at the end of the tenure period would not arise. Limited tenure concessions, however, are one of the predominant institutional setting for the private management of natural resources in the property of the regulator. We shall see in the next section that stochastic prices render a rationale for this common practice.

3.2 Stochastic prices

We now drop the assumption of constant prices. Instead, the price follows a random walk without drift, as defined in equation (3). First, we outline why the auctioning-refunding mechanism introduced by Definition 1 may fail to ensure the sustainability goal under these circumstances. Then, we introduce a more encompassing auctioning-refunding mechanism ensuring the sustainability goal in case of stochastic prices. We shall see that the maximal tenure length is now endogenous and may be finite.

Suppose a regulator who wants to ensure a sustainability goal s^* (implying a discount factor δ^*) auctions a limited tenure use right by means of $ARMC(T \geq T_{min}, b^*, r^*)$ in case of stochastic prices. As the a priori expectation of the resource price equals the resource price in period zero, p , risk neutral resource managers submit the same bids as in case of constant prices. Thus, if $\bar{\delta} > \delta^*$ the concession is sold to a resource manager exhibiting a discount factor $\bar{\delta}$.

With stochastic prices, however, optimal escapement $s_{i,t}^*$ of resource manager i is not constant but depends on the stochastic price in period t . In fact, optimal escapement in period t is obtained by a similar rule as in the case of constant prices (see Appendix A.3)

$$\frac{1}{\delta_i} = f'(s_{i,t}^*) \frac{p_t - E_z [zc(z f(s_{i,t}^*))]}{p_t - c(s_{i,t}^*)}. \quad (13)$$

Comparing equation (13) with its counterpart (8) under constant prices reveals that the constant price p in equation (8) is simply replaced by the actual price p_t . It is straight forward to show that Lemma 2 also holds in the case of stochastic prices. In addition, the following lemma holds:

Lemma 3 ($s_{i,t}^*$ is strictly decreasing in p_t)

The optimal escapement level $s_{i,t}^$ is a strictly decreasing function with respect to the resource price p_t .*

The proof is given in the appendix.

Lemma 3 implies that $ARMC(T \geq T_{min}, b^*, r^*)$ may fail to prevent the resource manager from harvesting below the sustainability goal s^* in period T , as $\pi(s^*, s_\infty, p) < \pi(s^*, s_\infty(p_T), p_T)$ for $p_T > p$. We can remedy this problem by paying a refund $R(s_T, p_T)$ contingent on the escapement level and the price in period T

$$R(s_T, p_T) = \begin{cases} r(p_T) & \text{if } s_T \geq s^* \\ 0 & \text{if } s_T < s^* \end{cases} . \quad (14)$$

Moreover $ARMC(T \geq T_{min}, b^*, r^*)$ may also fail to ensure the sustainability goal in periods $t < T$. To see this, note that by virtue of equation (3) the highest possible price in period t is given by:

$$p_t^{max} = p\bar{\eta}^t . \quad (15)$$

Thus, for each discount factor δ_i , there is a minimal optimal escapement level $s_{i,t}^{min}$ given by the solution of the implicit equation

$$\frac{1}{\delta_i} = f'(s_{i,t}^{min}) \frac{p_t^{max} - \mathbb{E}_z [zc(z f(s_{i,t}^*))]}{p_t^{max} - c(s_{i,t}^*)} . \quad (16)$$

From Lemma 3 follows directly that minimal optimal escapement $s_{i,t}^{min}$ is decreasing over time. Moreover, for t to infinity the limit $s_{i,\infty}^{min}$ is given by:

$$\frac{1}{\delta_i} = f'(s_{i,\infty}^{min}) . \quad (17)$$

Denoting the minimal optimal escapement $s_{i,t}^{min}$ for the resource user with $\delta_i = \bar{\delta}$ by \bar{s}_t^{min} the following lemma holds:

Lemma 4 (Maximal sustainable tenure length T_{max})

If $\bar{s}_\infty^{min} < s^*$ then there exists T_{max} such that $\bar{s}_t^{min} < s^*$ for all $t > T_{max}$.

The proof follows directly from Lemma 3.

Lemma 4 implies that $ARMC(T \geq T_{min}, b^*, r^*)$ may fail to ensure the sustainability goal if $T > T_{max}$. This also gives a rationale for the common practice of limited-tenure use rights for the management of natural resources. In the following, we define an adapted auctioning-refunding mechanism endogenously determining the maximal tenure length T_{max} .

Definition 2 (Auctioning-refunding mechanism under stochastic prices)

We define an auctioning-refunding mechanism with stochastic prices $ARMS(T_{min}, \mathbf{b}_{min}, r(p_T))$, by the following sequence of events:

1. The regulator announces a minimum tenure length T_{min} , a vector of minimum bids $\mathbf{b}_{min} = (b_{min}(T_{min}), \dots, b_{min}(\infty))$ and a refund $r(p_T)$. $b_{min}(T)$ is the lower bound for bids for a concession of tenure length T .
2. Bidders submit sealed bids (b_i, T_i) where b_i denotes the bid of resource manager i for a concession of tenure length T_i .
3. All bids with either $T_i < T_{min}$ or $b_i(T_i) < b_{min}(T_i)$ 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 bid for tenure length T_{max} wins the auction. If more than one resource managers submit the highest bid for 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 $b_{min}(T_{max})$ otherwise. She 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 (14), to the resource user at the end of the concession period.

To show that the auctioning-refunding mechanism $ARMS(T_{min}, \mathbf{b}_{min}, r(p_T))$ ensures the sustainability goal s^* if the parameters T_{min} , \mathbf{b}_{min} and $r(p_T)$ are set accordingly, we define the the ‘‘sustainable discount rate’’ $\delta^*(T)$ as a function of tenure length T

$$\delta^*(T) = \left[f'(s^*) \frac{\bar{\eta}^T p_1 - \mathbb{E}_z [zc(zf(s^*))]}{\bar{\eta}^T p_1 - c(s^*)} \right]^{-1}. \quad (18)$$

for which the following lemma holds.

Lemma 5 ($\delta^*(T)$ is strictly decreasing in T)

The sustainable discount rate $\delta^(T)$ is strictly decreasing in the tenure length T .*

The proof is given in the Appendix.

For all $\delta^i \geq \delta^*(T)$ it holds that $s_{i,t}^{min} \geq s^*$ for all $t \leq T$. Thus, a resource manager exhibiting a discount factor larger than the sustainable discount factor $\delta^*(T)$ will not harvest below the sustainability goal s^* over the tenure length T (apart from the last period unless she is compensated).

Defining the following parameters

$$T_{min}^* = \min_T \{x_T \geq s^* | x_{t+1} = z f(x_t)\} , \quad (19a)$$

$$\mathbf{b}_{min}^* = (b^*(T_{min}), \dots, b^*(\infty)) \quad \text{with} \quad b^*(t) = EPV(\delta^*(t), t) + \delta^*(t)^t \epsilon , \quad (19b)$$

$$r^*(p_T) = \pi(s^*, s_\infty(p_T), p_T) + \epsilon , \quad (19c)$$

$$\epsilon > 0, \quad \text{arbitrarily small} , \quad (19d)$$

the auctioning-refunding mechanism $ARMS(T_{min}^*, \mathbf{b}_{min}^*, r^*(p_T))$ satisfies the following propositions.

Proposition 4 (ARMS ensures sustainability goal)

The auctioning-refunding mechanism $ARMS(T_{min}^, \mathbf{b}_{min}^*, r^*)$ ensures that the sustainability goal is attained in minimal time and always supported thereafter for the tenure of the concession if $\bar{\delta} \geq \delta^*(T_{min}^*)$. Otherwise, the concession remains unsold.*

The proof is given in the appendix.

Proposition 4 is the straight forward generalization of Proposition 1. Again, the minimal concession tenure T_{min}^* ensures that the sustainability goal is attainable. All private resource managers bid the expected net present value of holding the concession for the highest tenure length T_i for which this bid is at least as high as the minimum bid $b^*(T_i)$. The refund compensates the resource managers for not harvesting below the escapement level s^* at the end of the concession tenure. As the price is stochastic, the refund has to be contingent on the resource price in the final period.

We know from Lemmata 1 and 2 that both the expected present value of profits from resource management over a given concession tenure of T , $EPV(\delta_i, T)$, and the optimal escapement level s_i^* are increasing in the discount factor δ_i . Thus, resource managers with

a discount factor $\delta_i = \bar{\delta}$ exhibit the highest expected present value for a given concession tenure. By virtue of Lemma 5 the sustainable discount factor $\delta^*(T)$ is increasing with concession tenure T . As $\delta^*(T)$ is the lower bound for the discount factor a resource manager has to exhibit so that the expected present value of the concession exceeds the minimum bid $b_{min}^*(T)$, there is, according to Lemma 4 a maximum tenure length T_{max} resource managers with discount factor $\bar{\delta}$ can offer if $\bar{s}_{\infty}^{min} < s^*$. In this case, the mechanism endogenously determines the maximal tenure length T_{max} , otherwise the tenure length $T_{max} = \infty$. Of course, T_{max} has to exceed T_{min}^* , as there are no valid bids otherwise.

Again, the auctioning-refunding mechanism ensures that a resource manager exhibiting a discount factor of $\bar{\delta}$ gets the concession, if it is sold at all. Thus, analogously to Proposition 2, $ARMS(T_{min}^*, \mathbf{b}_{min}^*, r^*)$ is efficient.

Proposition 5 (Efficiency of the ARMS)

The auctioning-refunding mechanism $ARMS(T_{min}^, \mathbf{b}_{min}^*, r^*)$ is efficient in the sense that the concession is given to the resource manager with the highest expected net present value if $\bar{\delta} \geq \delta^*$.*

The proof is analogous to the proof of Proposition 2.

Thus, like $ARMC(T \geq T^*, b^*, r^*)$ in the case of constant prices, $ARMS(T_{min}^*, \mathbf{b}_{min}^*, r^*)$ maximizes the sum of seller and buyer surplus. Again, the division of the total surplus depends on the highest non-winning bid.

In case of constant prices, the auctioning-refunding mechanism could always be designed in such that it was self-financing (Proposition 3). This does not necessarily hold for the case of stochastic prices.

Proposition 6 (ARMS may not be self-financing)

1. *If $T_{max} = \infty$, $ARMS(T_{min}^*, \mathbf{b}_{min}^*, r^*)$ is always self financing.*
2. *For $T_{max} < \infty$, $ARMS(T_{min}^*, \mathbf{b}_{min}^*, r^*)$ is self-financing in expectation if the discount factor of the regulator $0 < \delta^R < 1$ is lower than or equal to $\delta^*(T_{max})$. If $\delta^R > \delta^*(T_{max})$, $ARMS(T_{min}^*, \mathbf{b}_{min}^*, r^*)$ may not be self-financing.*

Proof: If $T_{max} = \infty$ there is no final period and no refund, thus $ARMS(T_{min}^*, \mathbf{b}_{min}^*, r^*)$ is always self financing. If $T_{max} < \infty$, the expected present value of the refund equals $(\delta^R)^{T_{max}} [\pi(s^*, s_{\infty}, p) + \epsilon]$. The regulator is paid at least $b_{min}^*(T_{max})$ which can be written

as

$$b^*(T_{max}) = \max_{\{s_t\}_{t=1}^{T_{max}}} \mathbb{E} \left[\sum_{t=1}^{T_{max}-1} (\delta^*)^t \pi(x_t, s_t, p_t) + (\delta^*)^{T_{max}} \pi(x_{T_{max}}, s^*, p) \right] + (\delta^*)^{T_{max}} [\pi(s^*, s_\infty, p) + \epsilon] . \quad (20)$$

Thus, for all $\delta^R \leq \delta^*(T_{max})$ $b^*(T_{max})$ is at least as high as the expected present value of the refund. However, this need not be true for $\delta^R > \delta^*(T_{max})$. \square

Proposition 6 says that questions of self-financing only occur if the concession tenure is finite, as only then a refund has to be paid. Moreover, in expectation the auctioning-refunding mechanism $ARMS(T_{min}^*, \mathbf{b}_{min}^*, r^*)$ is self-financing if the regulator exhibits a discount rate not higher than the sustainable discount rate $\delta^*(T_{max})$. Note, however, that the mechanism may not be self-financing ex post, as the refund is contingent on the resource price $p_{T_{max}}$, the upper bound of which is given by $p_{T_{max}}^{max}$ and may well exceed the expected price p . Thus, the refund may be more expensive than expected (it may also be cheaper, of course). This poses no problem if the regulator is able to hedge this risk either by financial instruments or by diversifying in different resource concessions. However, the auctioning-refunding mechanism $ARMS(T_{min}^*, \mathbf{b}_{min}^*, r^*)$ cannot ensure to be self-financing, not even in expectation, if the regulator's discount rate exceeds the sustainable discount rate $\delta^*(T_{max})$. The remedy, which was possible in cases of constant prices, to increase the concession tenure unless the mechanism is self-financing, fails, as the sustainability goal cannot be ensured for concession tenures higher than T_{max} .

4 Numerical Illustration: Northwestern Hawaiian Islands Lobster Fishery

In this section we illustrate our general results by studying the example of the Northwestern Hawaiian Islands Lobster fishery. We have chosen this example for two reasons: First, the lobster is a relatively stationary marine resource. Thus, it makes sense to grant concessions for its exclusive use. Second, this fishery is well documented with calibrated bioeconomic models available. Clarke et al. (1992) estimated the following Fox (1970) population model

$$f(s_t) = s_t + r s_t \ln(K/s_t) , \quad (21)$$

with $r = 0.4$ and $K = 6$ million individuals. The biomass allowing to harvest the maximum sustainable yield would, thus, equal to $s_{\text{msy}} = K/\exp(1) = 2.2$ million individuals. We consider this value to be the regulator's sustainability goal, i.e., we set $s^* = 2.2$ million individuals. Furthermore, Clarke et al. (1992) estimated a cost function

$$c(x_t) = 6.4 \$ x_t^{-1} , \quad (22)$$

implying $\theta = 1$. As a consequence, environmental uncertainty does not effect the optimal escapement level (see appendix). As the upper limit for the price stochasticity we used the maximum factor of price increase of spiny lobster in the period 1984 to 1999, as reported in Townsend et al. (2003). We, thus, obtain a value of $\bar{\eta} = 1.4$. Furthermore, we use the price of 1984, $p = 3.7$ \$ per spiny lobster, for the following calculations of the sustainable discount rate an the minimum bid. Figure 1 shows the resulting sustainable discount factor as a function of tenure length T . It is monotonically increasing from a value of 73% for a one-year tenure length (corresponding to a discount rate of 36%) to virtually one for a tenure length of ten years.

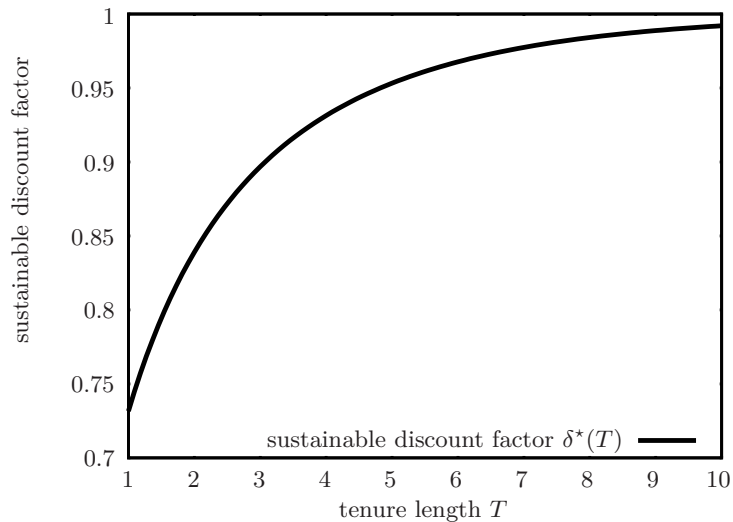


Figure 1: Sustainable discount factor as a function of tenure length T .

No stock data are reported for the Hawaiian lobster, so no estimate for T_{min} is possible. To illustrate the effect of time on the minimum bid in the simplest way, we assume an initial stock $s_0 = s^*$. The annual expected profit is then constant for all years, and equal

to

$$\pi(f(s^*), s^*, p) = p(f(s^*) - s^*) + c \ln(s^*/f(s^*)) - c E[\ln(z)] = 1.11 \text{million } \$ - c E[\ln(z)], \quad (23)$$

In the following, we neglect the risk-premium term on the far left, as no estimates for the probability distribution of z are available. The minimum bid as a function of tenure length is then given by $b_{min}^*(T) = \delta^*(T) \frac{1 - (\delta^*(T))^{T+1}}{1 - \delta^*(T)} \pi(f(s^*), s^*, p_1)$. The minimum bids are shown in Figure 2. The minimum bid is increasing slightly convex from 1.4 million \$ for a one-year tenure length to 11.6 million \$ for a tenure length of ten years.

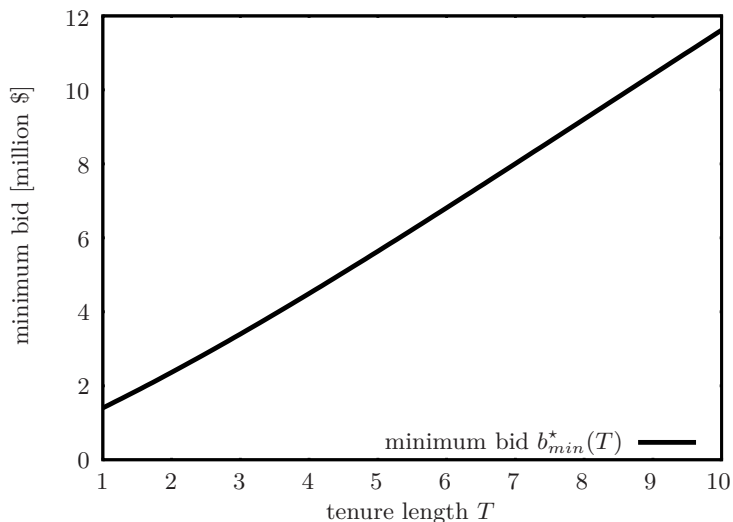


Figure 2: Minimum bid as a function of tenure length T .

5 Discussion

The auctioning-refunding mechanism introduced in Section 3 ensures that a given sustainability target is reached in the most efficient way. However, depending on the sustainability target and the distribution of discount factors across potential resource managers, the auctioning-refunding mechanism may fail to allocate the concession. In fact, this happens if no valid bid is submitted. In this case, the sustainability goal is not compatible with the private management of the resource, given the discount factors of the potential resource managers. This indicates that either the sustainability goal is too ambitious or

that the resource is better managed by the regulator itself and not rented out to private resource managers. If the resource is below the sustainability goal at the time of auctioning under stochastic prices, waiting until the resource level reaches the sustainability goal may be a remedy, as this reduces the minimal tenure length T_{min}^* .

Our results rely on some (although standard) assumptions, which we shall address in the following. First, the auctioning-refunding mechanism is designed such that it leads to the most sustainable resource use compatible with the sustainability goal. However, the mechanism requires large front-up payments by the auction-winning resource manager. This implies that resource managers either have to have sufficient funds or access to financial markets. Our model set-up, therefore, may better fit developed rather than developing countries.

Second, 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 would choose higher escapement levels (Reed 1979), 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.

Third, we assumed stochastic prices but constant (marginal) harvesting costs over time. As optimal escapement levels are determined by 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. We assume that resource prices have no trend, which implies that the resource neither becomes more or less scarce over time. The validity of this assumption strongly hinges upon the time horizon and the resource under consideration. With harvesting costs one would rather expect declining prices over time due to technological progress. The mechanism works well also if the resource price and/or the harvesting costs exhibit a trend, as long as this trend is common knowledge.

6 Conclusion

In this paper we have introduced an auctioning-refunding mechanism which reconciles a potential clash between efficiency and sustainability goals in the management of renewable natural resources. The mechanism is not only compatible with limited-tenure resource rights, but also offers a 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 maximizes resource rents and shares them among resource managers and the society. The mechanism is also self-financing in expectation (if the regulator is not more patient than the most patient resource manager). However, the mechanism requires resource managers to have sufficient start-up funds or access to financial markets in order to take part in the auction. The mechanism, thus, fits developed rather than developing countries. Overcoming this obstacle seems a fruitful agenda for future research.

Appendix

A.1 Proof of Lemma 2

The relationship between δ_i and s_i^* is given by equation (8). In the following, we show that

$$F(s) = f'(s) \frac{p - \mathbb{E}_z [zc(zf(s))]}{p - c(s)}, \quad (\text{A.1})$$

is a strictly decreasing function for all $s \in (s_\infty, \bar{s})$, which proves the proposition.

First, for $\theta = 0$ the proof is trivial. Second, for $\theta > 0$ $p = c(s_\infty)$ holds. Inserting $c(y) = \kappa y^{-\theta}$, the expectation with respect to z yields

$$\mathbb{E}_z [zc(zf(s))] = \mathbb{E}_z [z^{1-\theta} \kappa f(s)^{-\theta}] = \kappa f(s)^{-\theta} \mathbb{E}_z [z^{1-\theta}] = \kappa \left[\mathbb{E}_z [z^{1-\theta}]^\theta f(s) \right]^{-\theta}. \quad (\text{A.2})$$

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

$$F = \hat{z}^{-\theta} \left[f'(s) \left(\frac{s}{f(s)} \right)^\theta \right] \left[\frac{[\hat{z}f(s)]^\theta - s_\infty^\theta}{s^\theta - s_\infty^\theta} \right]. \quad (\text{A.3})$$

Differentiating F with respect to s yields

$$\begin{aligned} \frac{\partial F}{\partial s} &= f'(s) \left(\frac{s}{f(s)} \right)^\theta \frac{\theta f(s)^\theta}{(s^\theta - s_\infty^\theta)^2} \left\{ s^{\theta-1} \left[\frac{s f'(s)}{f(s)} - 1 \right] - s_\infty^\theta \frac{f'(s)}{f(s)} \right\} \\ &\quad + \frac{[\hat{z}f(s)]^\theta - s_\infty^\theta}{s^\theta - s_\infty^\theta} \frac{\theta s^{\theta-1}}{[\hat{z}f(s)]^\theta} \left\{ \frac{s f''(s)}{\theta} + f'(s) \left[1 - \frac{s f'(s)}{f(s)} \right] \right\} \\ &= \frac{([\hat{z}f(s)]^\theta - s_\infty^\theta) s f''(s)}{(s^\theta - s_\infty^\theta) [\hat{z}f(s)]^\theta} - \frac{\theta}{(s^\theta - s_\infty^\theta)^2 [\hat{z}f(s)]^\theta} \left[s^\theta s_\infty^\theta [\hat{z}f(s)]^\theta \frac{f'(s)^2}{f(s)} \right. \\ &\quad \left. + s^{\theta-1} \left(s_\infty^\theta [\hat{z}f(s)]^\theta + s^\theta s_\infty^\theta - s_\infty^{2\theta} \right) \left\{ f'(s) \left[1 - \frac{s f'(s)}{f(s)} \right] \right\} \right] < 0. \end{aligned} \quad (\text{A.4})$$

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

A.2 Proof of Proposition 1

First, a concession tenure $T \geq T^*$ ensures that the sustainability goal is attainable within the duration of the concession. It also ensures that $EPV(\delta_i) > 0$ for all resource managers, as harvesting would be optimal at least in the last period. According to Lemma 1, $EPV(\delta_i) > 0$ implies that $EPV(\delta_i)$ is strictly increasing in δ_i .

Second, the net present value of holding the concession depends on whether resource managers comply with the sustainability constraint in period T and receive a refund. Of course, compliance is only possible, if $x_T \geq S^*$. In case of compliance, resource managers choose the escapement level $s_T = s^*$ yielding profits of $\pi(f(s_i^*), s^*, p)$ and receive the refund $\pi(s^*, s_\infty, p) + \epsilon$. Non-compliance yields profits $\pi(f(s_i^*), s_\infty, p)$ if $x_T \geq s_\infty$ and zero otherwise. As $\pi(f(s_i^*), s^*, p) + \pi(s^*, s_\infty, p) + \epsilon = \pi(f(s_i^*), s_\infty, p) + \epsilon$, profit maximizing resource managers comply with the sustainability constraint in period T if $x_T \geq S^*$. According to (7) and (8), resource managers follow a constant escapement rule for $0 < t < T$, and, thus, all resource managers with $s_i^* \geq s^*$ comply with the resource constraint in period T when holding the concession. Accordingly, their net present value of holding the concession equals $EPV(\delta_i, T) + \delta_i^T \epsilon$.

Third, due to the Vickrey auction design it is a dominant strategy for all resource managers to bid the net present value of holding the concession if it is at least as high as the minimum bid b^* (otherwise resource managers are indifferent between bidding the net present value of holding the concession and not bidding at all). By design, b^* equals the net present value of holding the concession of a resource manager who exhibits the discount factor $\delta_i = \delta^*$ implying the optimal escapement level $s_i^* = s^*$. According to Lemmata 1 and 2 for all resource managers with $\delta_i > \delta^*$ the net present value of holding the concession exceeds the minimum bid, the resource manager(s) with $\delta_i = \bar{\delta}$ exhibit the highest net present value of holding the concession, the optimal escapement level exceeds the sustainability goal $s_i^* > s^*$. Thus, all resource managers with $\delta_i \geq \delta^*$ will bid $b_i = EPV(\delta_i, T) + \delta_i^T \epsilon$. Thus, there are bids at least as high as the minimum bid b^* if and only if $\bar{\delta} \geq \delta^*$. If this holds, the concession is sold to a resource manager exhibiting a discount factor $\delta_i = \bar{\delta}$. \square

A.3 Optimal escapement with stochastic prices

We define

$$Q(x_t, p_t) = p_t (x_t - s_\infty) - \int_{s_\infty}^{x_t} c(y) dy \quad (\text{A.5})$$

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

$$\max_{\{s_t\}_{t=1}^T} E_\eta E_z \left[\sum_{t=1}^T \delta_i^t [Q(x_t, p_t) - Q(s_t, p_t)] \right] \quad (\text{A.6})$$

Consider period T . The optimization problem is

$$\max_{s_T} Q(x_T, p_T) - Q(s_T, p_T) \quad (\text{A.7})$$

The optimal solution is to choose $s_T = s_\infty$. Now consider period $T-1$. The optimization problem is

$$\max_{s_{T-1}} (Q(x_{T-1}) - Q(s_{T-1}) + \delta \mathbb{E}_\eta \mathbb{E}_z [Q(x_T) - Q(s_\infty)]) \quad (\text{A.8})$$

$$= -\delta \mathbb{E}_\eta [Q(s_\infty)] + Q(x_{T-1}) + \max_{s_{T-1}} (-Q(s_{T-1}) + \delta \mathbb{E}_\eta \mathbb{E}_z [Q(zf(s_{T-1}))]) \quad (\text{A.9})$$

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

$$p_{T-1} - c(s_{T-1}) = \delta f'(s_{T-1}) (E_\eta[\eta p_{T-1}] - E_z(zc(zf(s_{T-1})))) \quad (\text{A.10})$$

$$= \delta f'(s_{T-1}) (p_{T-1} - E_z(zc(zf(s_{T-1})))) \quad (\text{A.11})$$

By induction, the first-order condition for the optimal escapement in any period is given by (13).

A.4 Proof of Lemma 3

Re-arranging equation (13) yields:

$$G = p_t [1 - \delta_i f'(s_{i,t}^*)] - \{c(s_{i,t}^*) - \mathbb{E}_z [zc(zf(s_{i,t}^*))]\} \quad (\text{A.12})$$

$$= p_t [1 - \delta_i f'(s_{i,t}^*)] - \kappa [(s_{i,t}^*)^{-\theta} - (\hat{z}f(s_{i,t}^*))^{-\theta}] = 0 \quad (\text{A.13})$$

with $\hat{z} = \mathbb{E}_z [z^{1-\theta}]^\theta$ as defined in the proof of Lemma 2. By virtue of the implicit function theorem $ds_{i,t}^*/dp_t$ is given by:

$$\frac{ds_{i,t}^*}{dp_t} = -\frac{\partial G/\partial p}{\partial G/\partial s_{i,t}^*} \quad (\text{A.14})$$

$$= \frac{1 - \delta_i f'(s_{i,t}^*)}{\delta_i f''(s_{i,t}^*) - \frac{\theta \kappa}{s_{i,t}^*} \left[(s_{i,t}^*)^{-\theta} - \frac{s_{i,t}^*}{f(s_{i,t}^*)} (\hat{z}f(s_{i,t}^*))^{-\theta} \right]} < 0. \quad (\text{A.15})$$

$ds_{i,t}^*/dp_t < 0$, as $f''(s_{i,t}^*) < 0$ and $s_{i,t}^* f'(s_{i,t}^*)/f(s_{i,t}^*) \leq 1$ (f is concave). \square

A.5 Proof of Lemma 5

Differentiating $\delta^*(T)$ with respect to tenure length T yields:

$$\frac{\partial \delta^*(T)}{\partial T} = \frac{c(s^*) - \mathbb{E}_z [zc(f(s^*))]}{\left\{ f'(s^*) \left(p\bar{\eta}^T - \mathbb{E}_z [zc(f(s^*))] \right) \right\}^2 p\bar{\eta}^T \ln[\eta]}. \quad (\text{A.16})$$

From the proof of Lemma 2 follows that $\mathbb{E}_z [zc(f(s^*))] = c(\hat{z}f(s^*))$ with $\bar{z} > \hat{z} > \underline{z}$. Thus, $\hat{z}f(s^*) > s^*$ as $s^* < \underline{z}$. As $c(s)$ is strictly decreasing in s , $\partial \delta^*(T)/\partial T > 0$. \square

A.6 Proof of Proposition 4

Like in the case of constant prices, the minimal concession tenure T_{min}^* ensures that the sustainability goal is attainable within the duration of the concession and that $EPV(\delta_i) > 0$ for all resource managers, as harvesting would be optimal at least in the last period. Lemma 1 implies that $EPV(\delta_i)$ is strictly increasing in δ_i . Moreover, the refund is such that resource managers holding the concession comply with the sustainability goal s^* in the final period T_{max} , if $T_{max} < \infty$. Of course, if $T_{max} = \infty$ there is no last period and the problem of exploiting the resource in the last period does not arise.

Again, the second price auction design ensures that it is a dominant strategy for all resource managers to reveal the true valuation of holding the concession. As among all valid bids, the bid with the highest concession tenure wins, resource managers bid the concession tenure T_i , for which the expected net present value of holding the concession is at least as high as the minimum bid $b^*(T_i)$. Thus, they bid $(EPV(\delta_i, T_i) + \delta_i^{T_i}, T_i)$. From Lemmata 2 and 4 it follows that resource managers with the highest discount factor $\delta_i = \bar{\delta}$ offer the highest tenure length T_{max} , which is finite if $\bar{s}_\infty^* < s^*$ and infinite otherwise. Lemma 1 also implies that, for any given tenure length T , these resource users exhibit the highest expected present value of holding the concession. Of course, the resource remains unsold, if $T_{max} < T_{min}^*$, which is the case if $\bar{\delta} < \delta^*(T_{min}^*)$, as is obvious from equation 1 and Lemma 5.

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