Public and private management of renewable resources: Who gains, who loses?☆

Martin F. Quaas[a,], Max T. Stöven[a]

[a]*Department of Economics, University of Kiel, Wilhelm-Seelig-Platz 1, 24118 Kiel, Germany.*

Abstract

Renewable resources provide society with resource rent and surpluses for resource users (the processing industry, consumers) and owners of production factors (capital and labor employed in resource harvesting). We show that resource users and factor owners may favor inefficiently high harvest rates up to open-access levels. This may explain why public resource management is often very inefficient. We further show that privatizing inefficiently managed resources would cause losses for resource users and factor owners, unless (a) the stock is severely depleted and (b) the discount rate is low. We quantify our results for the Northeast Arctic Cod fishery.

Keywords: resource rent, consumer surplus, worker surplus, distribution, political economy

JEL: Q28, D33, D72, Q57

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Email addresses: quaas@economics.uni-kiel.de (Martin F. Quaas), stoeven@economics.uni-kiel.de (Max T. Stöven)

Wasteful overuse of natural resources, including fisheries, rangelands, and forests, is a world-wide problem of serious concern (Stavins, 2011; Millennium Ecosystem Assessment, 2005; TEEB, 2010). The persistence of this problem is puzzling, as the economic theory of common property resources has established a clear diagnosis long ago (Gordon, 1954). Since then, it became a commonplace among economists that efficient resource use requires the granting of private use rights (Scott, 1955; Grafton et al., 2005) or public management. There is a large body of literature characterizing efficient public management for various resources (Wilen, 2000). This paper is motivated by the question why these insights have failed to improve resource management in so many cases.

Studying the political economy of renewable resource management, particularly the question who gains and who loses from better resource management (Hilborn, 2007), may help explain why inefficiency persists. The first aim of this paper is to determine conditions under which stakeholder interests in public resource management diverge. If public resource management fails, privatization might be an option to implement efficiency. The second aim of this paper is to determine the conditions under which privatization of renewable resources increases or decreases (a) surplus of the resource processing industry and consumers of resource products (*user surplus*) and (b) surplus for capital owners and workers employed in resource harvesting (*factor surplus*).

The literature comes to mixed conclusions. Focusing on labor input, Samuelson (1974) and Weitzman (1974) find that wages are higher under open access to a natural resource compared to a situation in which the resource is privately owned. Later, Meza and Gould (1987), Brito et al. (1997), and Baland and Bjorvatn (2013) show that workers may be better off in consequence of privatization. Olson (2011) summarizes the empirical evidence for ten fisheries that have been privatized and finds examples for both increases and decreases in crew income and employment. Looking at consumption in steady state, Copes (1972) finds that consumer surplus may increase or decrease under efficient management, but without identifying clear conditions for either case. Turvey (1964) and Anderson (1980) state that whether a shift from open access to efficient management increases or decreases consumer surplus and intramarginal rent to resource workers cannot be determined a priori. Hannesson

(2010) argues that increases in resource rent may over- or understate the societal benefits of efficient resource management.

In contrast to most of the literature, we consider a dynamic setting, taking into account the effects of transitional dynamics and discounting. Based on the canonical model of renewable resource economics (Gordon, 1954; Clark, 1991), we study the harvesting decisions of three stakeholder groups (Turvey, 1964; Copes, 1972; Anderson, 1980): (i) Owners of fishing firms whose profit from resource harvesting equals *resource rent*. We refer to this group as *producers*. (ii) Commercial or private consumers who buy harvest for processing or final consumption. We refer to this group as *resource users* and to the aggregate of their profits and consumer surplus as *user surplus*. (iii) The owners of factor inputs such as capital and labor whose renumeration may be above opportunity costs. We refer to this group as *factor owners* and to the aggregate surplus of capital and labor employment in resource harvesting as *factor surplus*.

We analyze the distributional effects of resource management in two steps, structured according to the two aims of the paper. First, we focus on public resource management and conduct a thought experiment with three scenarios. In each scenario, open access is stopped and one of the interest groups gets the exclusive, non-transferable right to set harvest rates according to their interests. The aim of this thought experiment is to study under which conditions stakeholder interests in resource management diverge. Second, we consider privatization (i.e., the scenario of resource management by producers) and study how the present values of user and factor surpluses increase or decrease under privatization compared to the status quo.

We show that the mixed conclusions in the literature about who gains and who loses from privatization can be traced back to different assumptions about the 'stock effect'. The 'stock effect' captures how harvesting productivity depends on the size of the resource stock (Clark and Munro, 1975). Typically harvesting becomes more productive the larger the stock size is, for example because search costs for a dispersed resource decrease. We show that producers would always choose the socially efficient harvesting plan, whereas users and factor owners would do so only in absence of a stock effect. If there is a stock effect, the preferred harvesting rates of the three groups diverge: Users prefer higher harvest rates than producers, and factor owners prefer even higher harvest rates than users. Both resource users and factor owners would implement open-access conditions already for finite discount rates. These findings may explain why many renewable resources continue to be managed inefficiently by public authorities. In such cases, the persistence of rent dissipation and resource depletion may reflect that the processing industry, capital owners, and workers have enough political influence to implement their preferred harvest rates.

Privatizing renewable resources could be seen as a way to weaken the political influence of stakeholders arguing for inefficiently high harvest rates. We show however, that resource users and factor owners lose from privatization, unless (a) the stock is severely depleted and (b) the discount rate is low. These results highlight the central role of transition dynamics and discounting that cannot be found in a static analysis.

In quantitative terms, the losses of resources users and factor owners may be substantial, as the case study of the North East Artic cod fishery demonstrates. Compared to a status quo at the stock size of 2008, an efficient management of the North East Artic cod stock would have increased the present value of resource rent by 6.2 billion USD since 2008 (at a discount rate of 1%), while the present value of user surplus would have decreased by 2.2 billion USD.

The rest of the paper is organized as follows. Section 1 introduces the model on which we build our analysis. In Section 2, we analyze the interests of producers, resource users and factor owners in public resource management. In Section 3, we study the distributive effects of privatization. Section 4 contains the quantitative application to the Northeast Arctic cod fishery. Section 5 concludes.

1. Dynamic model of renewable resource use

Our model builds on the canonical Gordon-Clark model of renewable resource economics (Gordon, 1954; Clark, 1991). For the bio-economic part we use the standard textbook model of a dynamic renewable natural resource. Only with regard to input and output markets we generalize the textbook model to some degree.

The resource stock x grows according to[1]

$$\dot{x} = g(x) - h, \tag{1}$$

where $\dot{x} \equiv dx/dt$ is the net growth of the resource stock and $h \geq 0$ is the harvest rate. The biological growth function $g(x)$ is assumed to be strictly concave with $g(0) = 0$, $g(K) = 0$ for some constant $K > 0$, and $g(x) > 0$ for $x \in (0, K)$.[2] This implies that there is a unique stock size x_{MSY} with $0 < x_{\text{MSY}} < K$ that generates the maximum sustainable yield (MSY), i.e. the maximal harvest rate that could be taken from the stock in the long run.

The harvesting technology is described by a generalized Gordon-Schaefer harvesting function (Gordon, 1954; Schaefer, 1957; Clark, 1991) with effort $e(l, k)$ being an intermediate input (Hannesson, 1983), which itself is produced by labor l and capital k under constant returns to scale, and stock size x affecting harvesting productivity,[3]

$$h = q(x)\, e(l, k), \tag{2}$$

with $q'(x) \geq 0$ and $q''(x) \leq 0$, which means that harvest weakly increases with stock size at any given level of labor input, and that $q(x)$ is a concave function of x. The function $q(x)$ captures the 'stock effect' if $q'(x) > 0$ (Clark and Munro, 1975). In steady state, we have $h = g(x)$ and steady-state effort equals $g(x)/q(x)$. We assume that $g(x)/q(x)$ is strictly quasi-concave in x on $[0, K]$. Thus, there exists a unique stock size $x_{\text{MSE}} \geq 0$ that generates the 'maximum sustainable effort' (MSE), or 'maximum sustainable employment' (Hilborn, 2007). It is easy to verify that the resource stock that allows MSE is smaller than the MSY

[1] We omit the time (t) argument for variables, unless needed for clarification.

[2] A minimum viable stock $x_{\min} > 0$ below which extinction becomes inevitable could be incorporated into the model without changing results if $x_0 > x_{\min}$ and $g(x)$ remains strictly concave between $g(x_{\min}) = 0$ and $g(K) = 0$.

[3] There are two classes of externalities in the use of common property resources (Munro and Scott, 1985). Class I refers to rent dissipation through depletion of the resource, while Class II refers to rent dissipation through crowding or congestion due to the excessive use of production inputs. We exclude Class II externalities by assuming constant returns to scale in effort production, and focus on Class I externalities in a dynamic analysis. Adding a Class II static crowding externality would reduce the dynamic stock externality by impairing harvesting efficiency at high effort levels.

resource stock, $x_{\text{MSE}} \leq x_{\text{MSY}}$.

Assuming that resource harvesters minimize cost while taking factor prices as given, the cost function for producing effort follows as $C(e, w, r) = \hat{c}(w, r)\, e$, where w is the wage rate and r the rental rate of capital. Because of constant returns to scale, the cost function is linear in effort.

We assume that a local labor market offers alternative income opportunities to labor employed in resource harvesting, l.[4] As harvesting skills may be of little value in alternative employment, the availability and desirability of such alternative employment will typically differ among potential resource workers, such that the marginal opportunity costs of employment in resource harvesting increase (Copes, 1972). We capture this by a monotonically increasing inverse supply function for labor, $w(l)$, with $w(0) \geq 0$ and $w'(\cdot) > 0$.

Also capital employed in resource harvesting is often not perfectly malleable. A simple way to model this is to consider an imperfectly elastic inverse supply function for capital, $r(k)$ with $r(0) \geq 0$ and $r'(\cdot) > 0$. Using the factor allocation for labor $\hat{l}(e)$ and capital $\hat{k}(e)$ in equilibrium on factor markets for an effort level e, we obtain the inverse effort supply function $c(e) = \hat{c}(w(\hat{l}(e)), r(\hat{k}(e)))$. Because of the imperfectly elastic supply of production factors in resource harvesting, this inverse effort supply function is increasing, $c'(\cdot) > 0$. Thus, there is a factor surplus

$$\text{FS}(e) = c(e)\, e - \int_0^e c(\tilde{e})\, d\tilde{e} > 0, \tag{3a}$$

which is the sum of worker and capital owner surplus in resource harvesting (cf. area FS in Figure 1).

The resource consumption good y (e.g. processed fish, or a timber product) is produced

[4]The assumption of a local labor market is not critical for any results on optimal producer and consumer decisions. Assuming an exogenous wage rate would only remove worker interests in resource management from our model. One could also strengthen the assumption of a local labor market by assuming a fixed total labor supply that is allocated between harvesting and other production sectors, such as in the harvesting-manufacturing model of Brander and Taylor (1997). Following this interpretation, the marginal costs of increasing employment in resource harvesting would equal the value of the resulting marginal decrease in alternative production.

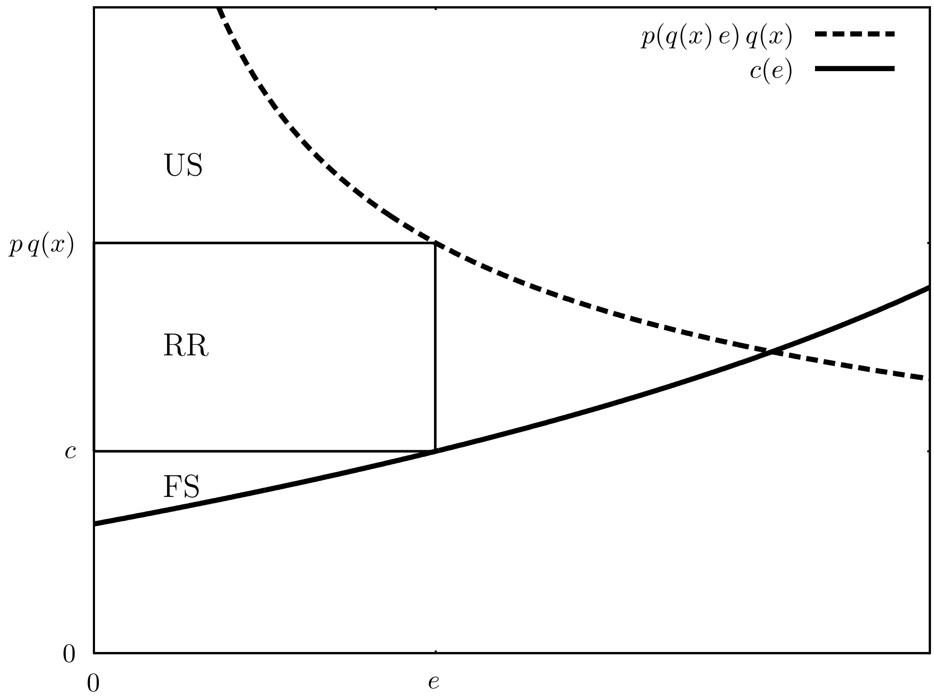

Figure 1: Instantaneous user surplus (US), resource rent (RR) and factor surplus (FS). Stock dynamics would shift the marginal utility of effort function $p(q(x)\,e)\,q(x)$. With adjusted effort e, this would affect all rent categories.

by using resource harvest h as input, according to a production technology described by $y = f(h)$, where $f'(h) > 0$ and $f''(h) \leq 0$. Using $\pi(y)$ to denote the inverse demand function for the resource consumption good, and p to denote the market price for harvest h, profit maximization in resource processing yields the inverse demand function for resource harvest $p(h) = \pi(f(h))\,f'(h)$, where $p'(h) = \pi'(f(h))\,(f'(h))^2 + \pi(f(h))\,f''(h) < 0$. User surplus,

$$\text{US}(h) = \int_0^h p(\tilde{h})\,d\tilde{h} - p(h)\,h, \tag{3b}$$

is the sum of rents in the resource processing industry and consumer surplus from the resource consumption good. It is depicted as area US in Figure 1).

Resource rent is equal to the profits in resource harvesting, i.e. the difference between the revenue from selling resource harvest at market price p and expenses for effort used at marginal cost c (cf. area RR in Figure 1).

$$\mathrm{RR}(h,e) = p\,h - c\,e. \tag{3c}$$

The sum of resource rent, user surplus, and factor surplus, is the social surplus of utilizing the resource,

$$\mathrm{RR}(h,e) + \mathrm{US}(h) + \mathrm{FS}(e) = \int_0^h p(\tilde{h})\,d\tilde{h} - \int_0^e c(\tilde{e})\,d\tilde{e}, \tag{3d}$$

which is equal to the utility derived from resource use net of the opportunity costs of the factors used in resource harvesting. The social surplus corresponds to the union of areas US, RR and FS in Figure 1.

To summarize the model set up, the exogenous parts of the model are the inverse supply functions for labor and capital, $w(l)$ and $r(k)$, which are summarized in the inverse supply function for effort, $c(e)$, the biomass growth function of the resource $g(x)$, the harvesting function $h = q(x)\,e(k,l)$, the production function of resource processing $y = f(h)$, and the inverse demand function for the resource consumption good, $\pi(y)$. Endogenously determined are the time paths of effort e, harvest h, the resource stock x and the time paths of the market prices c (for inputs) and p (for harvest). Resource rent reflects the real scarcity of a renewable resource (Gordon, 1954). To separate resource rent from artificial scarcity rents (monopoly and monopsony rents), we assume that all agents behave as price-takers.

For answering the question who gains and who loses from privatization of the resource, we have to compare the privatization scenario to some baseline. Of all possible harvest and stock trajectories starting at the initial stock $x_0 > 0$, conserving the 'status quo' at x_0 seems to be the most natural choice for the reference case. There is a tradition in the literature following Samuelson (1974) and Weitzman (1974) to use the open-access steady state $x_0 = x_{\mathrm{OA}}$ as the reference case for studying the distributive effects of implementing efficiency. Here we generalize this type of analysis by allowing the initial stock size x_0 to differ from x_{OA}. This means that the 'status quo' may result from open-access harvesting (which is, of course, a particularly relevant case) or harvesting under some form of inefficient public resource management. Harvest in the status-quo steady state is $g(x_0)$ and effort is $g(x_0)/q(x_0)$.

The change in the present value (at a discount rate $\rho > 0$) of resource rent from privatizing the renewable resource compared to the steady state at x_0 is

$$\Delta\mathrm{RR}(x_0, \{h_t, e_t\}) = \int_0^\infty \mathrm{RR}(h_t, e_t)\, e^{-\rho t}\, dt - \frac{1}{\rho}\,\mathrm{RR}(g(x_0), g(x_0)/q(x_0)), \tag{4a}$$

and the change in the present value of resource user surplus is

$$\Delta\mathrm{US}(x_0, \{h_t\}) = \int_0^\infty \mathrm{US}(h_t(x_0))\, e^{-\rho t}\, dt - \frac{1}{\rho}\,\mathrm{US}(g(x_0)), \tag{4b}$$

and the change in the present value of factor surplus is

$$\Delta\mathrm{FS}(x_0, \{e_t\}) = \int_0^\infty \mathrm{FS}(e_t(x_0))\, e^{-\rho t}\, dt - \frac{1}{\rho}\,\mathrm{FS}(g(x_0)/q(x_0)). \tag{4c}$$

In the following, we will consider three interest groups: Interest group P (for producers) consists of those individuals who receive resource rent RR; interest group U are all individuals deriving user surplus US from buying resource harvest for processing and consumption; and interest group F are the owners of production factors employed in resource harvesting, thus this group's surplus is FS. Considering these interest groups abstracts from real-world complexities in the following respects: First, the distinction is between three different forms of rent, so there may be individuals who are employed in resource harvesting (and thus members of F), and receive resource rent at the same time. Second, we disregard any coordination problems within the interest groups and consider a representative agent who pursues the common interest of the respective group. Finally, we assume that all agents in the model apply the same discount rate.

To understand the distributive effects of efficient resource management, we proceed in two steps. In the first step (Section 2), we consider three scenarios where the groups P, U, and F choose their optimal harvesting trajectories. This means that in each of these scenarios, one interest group (P, U, or F) is given the exclusive and permanent, but non-transferable right to set harvest rates.

In the second step (Section 3), we study under which conditions the harvesting path h_{Pt} chosen by producers, together with the associated path of harvesting effort e_{Pt}, increases or decreases the present value of resource user surplus and factor surplus compared to the status quo, i.e. under which conditions $\Delta\text{US}(x_0, \{h_{Pt}\})$ and $\Delta\text{FS}(x_0, \{e_{Pt}\})$ are positive or negative.

2. Stakeholder interests in public resource management

We begin by introducing the reference cases of socially efficient harvesting and open access. The social planner maximizes social surplus (3d) subject to the equation of motion (1). The current-value Hamiltonian for the social planner follows as $H = \int_0^h p(\tilde{h}) - \int_0^{h/q(x)} c(\tilde{e})\, d\tilde{e} + \mu\, (g(x) - h)$. The necessary and sufficient conditions for socially efficient harvesting can be written as

$$p(h) = \frac{c(e)}{q(x)} + \mu, \tag{5a}$$

$$\rho = \frac{\dot{\mu}}{\mu} + g'(x) + \frac{p(h) - \mu}{\mu}\, q'(x)\, e, \tag{5b}$$

with $h \geq 0$, $\mu \geq 0$, initial stock x_0 given, and transversality condition $e^{-\rho T}\, \mu(T)\, x(T) \xrightarrow{T \to \infty} 0$. Condition (5a) states that along the optimal harvesting path, the resource price $p(h)$ equals marginal costs, which are comprised of marginal harvesting costs $c(e)/q(x)$ and the marginal opportunity costs of reducing the stock, μ. Condition (5b) essentially states the familiar condition that the own rate of interest when marginally increasing the stock should equal the discount rate ρ (Clark and Munro, 1975). The term $g'(x)$ captures the value of a marginal increase in biological productivity, while the term $((p - \mu)/\mu)\, q'(x)\, e$ captures the 'stock effect', i.e. the value of a marginal increase in harvesting productivity.

Open access can be defined as the absence of any use rights for the resource. All resource rent is dissipated, such that price equals marginal harvesting costs, $p(h) = c(e)/q(x)$. We use $h_{\mathrm{OA}}(x)$ to denote the open-access harvest rate at a given stock size x, and $x_{\mathrm{OA}} \geq 0$ to denote the open-access steady-state stock size.

The following propositions contain the main results of this section, which we shall first state and then study in detail to prove the results. In these propositions, we use $h_i(x)$ to denote the optimal harvest of interest group $i = P, H, F$ at a current stock size x, i.e. the optimal feedback policy for the respective interest group. The socially efficient harvest rate at a given stock size x is $h^*(x)$.

The first proposition shows that the stock effect determines whether stakeholder interests in resource management diverge. Appendix B contains the proof, which makes use of the conditions for optimal management for the three interest groups derived below.

Proposition 1. *1a) If there is no stock effect, $q'(\cdot) \equiv 0$, all interest groups choose efficient harvest rates,*

$$q'(\cdot) \equiv 0 \quad \Rightarrow \quad h_F(x) = h_U(x) = h_P(x) = h^*(x) \quad \textit{for all } x > 0. \tag{6}$$

1b) If there is a stock effect, $q'(\cdot) > 0$, only group P chooses efficient harvest rates. At any given stock size $x > 0$, interest group U prefers a strictly higher harvest rate than socially efficient, and interest group F prefers a weakly higher harvest rate than group U:

$$q'(\cdot) > 0 \quad \Rightarrow \quad h_F(x) \geq h_U(x) > h_P(x) = h^*(x) \quad \textit{for all } x > 0 \tag{7}$$

Not surprisingly, we find that a competitive private owner maximizing profits will choose the socially efficient harvesting path, irrespective of the stock effect. This is the very reason why resource economists propose rights-based management as the preferred way of regulating the use of common-pool resources (Levhari et al., 1981). Proposition (1) highlights the importance of the stock effect. Only in absence of a stock effect, resource users and factor owners choose the efficient harvesting path. If there is a stock effect, these two interest groups would choose strictly higher harvest rates than efficient.

The second proposition shows that the discount rate ρ has an important influence on the optimal harvesting plans.

Proposition 2. *Assume $q'(\cdot) > 0$.*

2a) If $\rho \geq \rho_U \equiv g'(x_{OA})$, the optimal management by interest group U is the same as under open access,

$$\rho \geq \rho_U \quad \Rightarrow \quad h_U(x) = h_{OA}(x) \quad \text{for all } x > 0. \tag{8}$$

2b) If $\rho < \rho_U$, $h_U(x) < h_F(x)$ for all $x > 0$.

2c) If $\rho \geq \rho_F \equiv g'(x_{OA}) - g(x_{OA})\, q'(x_{OA})/q(x_{OA}) < \rho_U$, the optimal management by interest group F is the same as under open access,

$$\rho \geq \rho_F \quad \Rightarrow \quad h_F(x) = h_{OA}(x) \quad \text{for all } x > 0. \tag{9}$$

Proof. See appendix C. □

Assuming that there is a stock effect, $q'(\cdot) > 0$, Proposition 2 provides an explanation as to why there is over-harvesting in common-pool resources that are publicly managed: Users and factor owners favor inefficiently high harvest rates and may have sufficient influence over the political process. If their discount rate is above a finite threshold ρ_U, open access is the preferred harvesting strategy for the resource processing industry and consumers. The corresponding threshold for interest group F is strictly lower, $\rho_F < \rho_U$. Finite thresholds for ρ above which the sole owner of a renewable resource favors open access are a new result. For producers, such finite thresholds do not exist (Clark, 1991).

If the discount rate of group F is below ρ_U, the harvest rates for the three interest groups can be unambiguously ordered, with factor owners preferring the highest and producers preferring the lowest rate, $h_F(x) > h_U(x) > h_P(x)$. This result is illustrated in Figure 2. The economic intuition for the different harvest strategies is given in the following subsections.

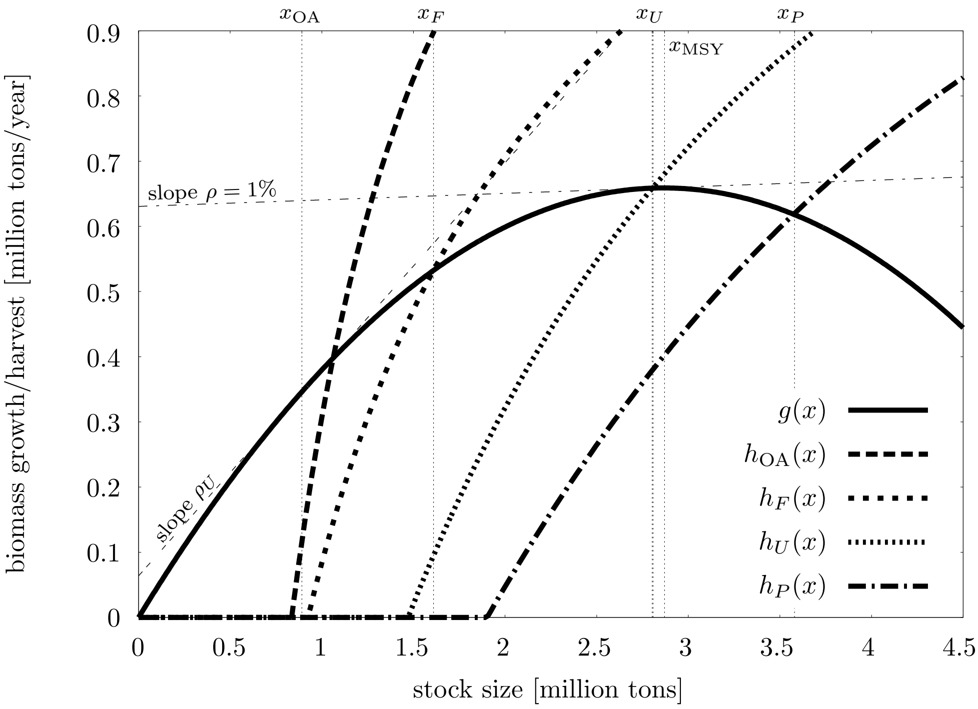

Figure 2: Phase diagram illustrating optimal harvest rates for the different interest groups as functions of stock sizes ($h_F(x)$, $h_U(x)$, $h_P(x)$); and open-access harvest $h_{\mathrm{OA}}(x)$, as well as steady-states, using the example of the Northeast Arctic cod fishery (see Section 4).

2.1. Resource management by producers

The representative producer maximizes the present value of profits from resource harvesting while taking the time paths of harvest price p and marginal effort costs c as given. With current-value shadow price μ_P for constraint (1) and using (2), the current-value Hamiltonian is $H_P = p\,h - c\,h/q(x) + \mu_P\,(g(x) - h)$. The necessary and sufficient conditions for interest group P's optimal harvesting plan can be written as

$$p = \frac{c}{q(x)} + \mu_P, \tag{10a}$$

$$\rho = \frac{\dot{\mu}_P}{\mu_P} + g'(x) + \frac{p - \mu_P}{\mu_P}\,q'(x)\,e, \tag{10b}$$

together with (1), a given initial stock size x_0, the conditions $l \geq 0$, $\mu_P \geq 0$, and the transversality condition $e^{-\rho T}\,\mu_P(T)\,x(T) \xrightarrow{T\to\infty} 0$.

As the conditions for the producers' optimal harvesting and the conditions for socially efficient harvesting (5) are identical, it is obvious that producers would choose efficient harvesting rates, $h_P(x) = h^*(x)$ for all $x > 0$. An implicit equation for the socially efficient steady-state stock size $x^* = x_P$ is given in Appendix A.

2.2. Resource management by resource users

When maximizing (4b), the representative user of resource products takes the producer price p_P of harvest as given. With current-value shadow price μ_U for constraint (1), the current-value Hamiltonian is $H_U = \int_0^h p(\tilde{h})\, d\tilde{h} - p_P\, h + \mu_c\, (g(x) - h)$. After inserting (2), the conditions for the optimal harvesting plan can be written as

$$p(h) = p_P + \mu_U = \frac{c(e)}{q(x)} + \mu_U \tag{11a}$$

$$\rho = \frac{\dot{\mu}_U}{\mu_U} + g'(x), \tag{11b}$$

together with (1), the initial stock x_0, the conditions $h \geq 0$, $\mu_U \geq 0$, and the transversality condition $e^{-\rho T}\, \mu_U(T)\, x(T) \xrightarrow{T\to\infty} 0$.

Because they do not have the use rights in this scenario, resource harvesting firms do not face an intertemporal optimization problem, i.e. they maximize static profit. For this reason, their marginal opportunity costs of current stock reductions are zero and firms equate price with marginal harvesting costs, $p_P = c/q(x)$. We have used this to obtain (11a).

Condition (11a) states that the marginal benefit of using the resource equals marginal costs, which consist of the pecuniary unit costs paid to producers and the marginal opportunity costs of current consumption μ_U. These marginal opportunity costs μ_U capture the marginal decrease in present value user surplus that results from the stock decrease for current consumption. The non-negative difference between the harvest price $p(h)$ and marginal harvesting costs is marginal resource rent μ_U. This rent is incidentally received by resource users who take into account stock dynamics and hence may limit harvest below the amount at which the harvest price equals marginal harvesting costs.

The formal structure of (11a) is identical to the corresponding condition under socially efficient privatization (10a). At each point in time interest group U equates their marginal utility of consuming the resource with the sum of the marginal harvesting costs plus the marginal costs of reducing the stock. The difference to the efficient harvesting plan originates from resource users disregarding the effect of stock abundance on harvesting productivity in their calculation of marginal stock value. Accordingly, the efficiency of group U's harvesting plan depends on the presence of this link between stock abundance and harvesting productivity. Condition (11b) again states that the own rate of interest when marginally increasing the stock should equal the discount rate. Interest group U, however, only takes into account the marginal increase in biological productivity of the resource. Under price-taking behavior, it is rational for resource users to disregard the effect of stock abundance on harvesting productivity. User surplus solely depends on the harvest quantity h whose equilibrium price equals total marginal costs of harvest. The relative shares of harvesting costs $c/q(x)$ and marginal opportunity costs μ_U in total marginal costs of harvest do not affect resource user surplus.

Intuition might suggest that x_{MSY} is the preferred steady state for resource users, as it yields the maximum harvest level and hence maximizes steady-state user surplus. However, resource users prefer a steady-state stock size below x_{MSY}, if this is feasible, i.e. $x_{\mathrm{OA}} < x_{\mathrm{MSY}}$:

$$x_U = \max(\hat{x}_U, x_{\mathrm{OA}}), \tag{12}$$

with $g'(\hat{x}_U) = \rho$, cf. Appendix A. This is because increased short-run consumption during the disinvestment phase from x_{MSY} to x_U plus a subsequent long-run consumption of $g(x_U)$ yields a higher user surplus in net present value terms than a continued consumption of $g(x_{\mathrm{MSY}})$. Complete rent dissipation equivalent to open-access conditions is the preferred outcome for resource users if the discount rate is above the finite threshold level $\rho_U = g'(x_{\mathrm{OA}})$. Thus, as opposed to socially efficient resource management, maximization of consumer surplus fully aware of stock dynamics aligns with myopic profit maximization under open access already for finite discount rates (Proposition 2a)). This is illustrated for two different discount rates in Figure 2: For $\rho = 1\%$, the optimal steady state for resource users is only slightly below the maximum-sustainable-yield stock x_{MSY}. With increasing discount rate, the optimal steady-state stock for resource users decreases. For $\rho = \rho_U$, it is equal to the open-access steady state. For a still higher discount rate, resource users would prefer an even lower $x_\rho < x_{\mathrm{OA}}$, but this is infeasible with non-negative profits for the fishing industry, hence $x_U = \max(x_\rho, x_{\mathrm{OA}})$.

2.3. Resource management by factor owners

The representative factor owner maximizes (4c) while taking as given the marginal costs of effort c_P paid by resource harvesting firms. With the current-value shadow price μ_F for constraint (1) and inserting (2), the current-value Hamiltonian follows as $H_F = c_P\, e - \int_0^e c(\tilde{e})\, d\tilde{e} + \mu_F\, (g(x) - q(x)\, e)$. The conditions for the optimal harvesting plan can be written as

$$\frac{c_P}{q(x)} = \frac{c(e)}{q(x)} + \mu_F. \tag{13a}$$

$$\rho = \frac{\dot{\mu}_F}{\mu_F} + g'(x) - q'(x)\, e, \tag{13b}$$

together with the equation of motion (1), given initial stock size x_0, the conditions $l \geq 0$, $\mu_F \geq 0$, and transversality condition $e^{-\rho T}\, \mu_F(T)\, x(T) \xrightarrow{T \to \infty} 0$.

Resource harvesting firms maximize static profit by setting harvest price equal to marginal harvesting costs, $p = c_P/q(x)$, such that effort is paid the value of its marginal product in resource harvesting. Using this, condition (13a) has the same formal structure as (10a) and (11a), and hence a similar interpretation. Condition (13b) determines marginal stock value, requiring that the own rate of interest when marginally increasing the stock must equal the discount rate. Note that the marginal stock effect, captured by the term $-q'(x)\, e$, is taken into account by group F. However, interest group F perceives harvesting productivity being sensitive to stock size as competition by a rival production input. This is why the stock effect enters with a negative sign in (13b). As long as it is economically feasible, i.e. as long as profits for harvesting firms are non-negative, factor owners prefer a lower steady-state stock size than resource users,

$$x_F = \max(\hat{x}_F, x_{\text{OA}}) \tag{14}$$

with $\hat{x}_F < \hat{x}_U$, cf. Appendix A. For discount rates above $\rho_F \equiv g'(x_{\text{OA}}) - g(x_{\text{OA}})\, q'(x_{\text{OA}})/q(x_{\text{OA}})$, factor owners favor open access and complete rent dissipation $\mu_F = 0$ occurs for all t.

It follows as a corollary to Proposition 2 that the preferred steady-state stock sizes can be ordered as $x_F \leq x_U < x_P = x^*$ if there is a stock effect, $q'(\cdot) > 0$.

3. Who gains, who loses? – The distributional effects of privatization

Proposition 1 shows that privatization, i.e. management by interest group P, would lead to socially efficient management (given the assumptions of the model considered here, in particular price-taking behavior and identical discount rates for all agents). In this section, we analyze how socially efficient harvesting would affect surpluses of resource users and factor owners compared to the status quo steady state at the initial stock size x_0. We focus on initial stock sizes below the efficient steady-state stock level, $x_0 < x^*$.[5]

The changes in the present values of user and factor surpluses under privatization, $\Delta\text{US}(x_0, \{h_t^*\})$ given by (4b) and $\Delta\text{FS}(x_0, \{e_t^*\})$ given by(4c), can thought of as consisting of two parts. The first part is the difference in steady-state user and factor surplus at the initial stock size x_0 and at the final stock size x^* under privatization. As harvest and effort levels might be lower or higher in the efficient steady state than in the status quo, this long-run effect is ambiguous. The second part is the transition phase during which harvest and effort will initially be below the status-quo levels, as otherwise the stock would not increase to $x^* > x_0$. Thus, the transition effect is always negative.

The lower x_0, the longer the transition phase, which tends to increase costs of privatization to resource users and factor owners. On the other hand, the lower x_0, the higher

[5]For $x_0 > x*$, disinvestment in the stock causes a temporary increase in harvest and effort while it also moves the steady-state stock closer to the steady-state levels preferred by resource users and factor owners. Thus, $\Delta\text{US}(x_0, \{h_t^*\}) > 0$ and $\Delta\text{FS}(x_0, \{e_t^*\}) > 0$ for all $x_0 \in (x^*, K]$. If the initial stock size equals the efficient stock size, there are no transitional effects, hence $\Delta\text{US}(x^*, \{h_t^*\}) = 0$ and $\Delta\text{FS}(x^*, \{e_t^*\}) = 0$.

may be the benefit for users and factor owners in the long-run steady-state compared to the status quo. The following proposition shows that the transition costs dominate the long-run benefits for high initial stock sizes, i.e. initial stock sizes above some threshold values. Recall that we use $\hat{x}_U$ ($\hat{x}_F$) to denote the optimal steady state stock size for management by resource users (factor owners).

Proposition 3. *Assume $q'(\cdot) > 0$.*

3a) There exists a $\underline{x}_U$ with $0 \leq \underline{x}_U < \hat{x}_U$ such that

$$\Delta\, US(x_0, \{h_t^*\}) < 0 \quad \textit{for all } x_0 \in (\underline{x}_U, x^*). \tag{15a}$$

3b) There exists a $\underline{x}_F$ with $0 \leq \underline{x}_F < \hat{x}_F$ such that

$$\Delta FS(x_0, \{e_t^*\}) < 0 \quad \textit{for all } x_0 \in (\underline{x}_F, x^*). \tag{15b}$$

Proof. See appendix D. □

With $\underline{x}_F < \hat{x}_U$ ($\underline{x}_F < \hat{x}_F$), resource users (factor owners) lose from socially efficient harvesting for a large interval of initial stock sizes. However, for a very small initial resource stock, and if the discount rate is sufficiently low, resource users and even factor owners may benefit from privatization, as the following result shows.

Proposition 4. *Assume $q'(\cdot) > 0$.*

4a) There exists a discount rate $\overline{\rho}_U > 0$ such that for all $\rho \leq \overline{\rho}_U$ there exists a stock size $\overline{x}_U > 0$ such that

$$\Delta\, US(x_0, \{h_t^*\}) > 0 \quad \forall\, x_0 \in (0, \overline{x}_U). \tag{16a}$$

4a) If $x_{MSE} > 0$, there exists a discount rate $\overline{\rho}_F > 0$ such that for all $\rho \leq \overline{\rho}_F$ there exists a stock size $\overline{x}_F > 0$ such that

$$\Delta FS(x_0, \{e_t^*\}) > 0 \quad \forall\, x_0 \in (0, \overline{x}_F). \tag{16b}$$

Proof. See appendix E. □

Focusing on the comparison of open access with socially efficient management starting at $x_0 = x_{\text{OA}}$, Proposition 4 shows that serious biological overfishing under open access ($x_{\text{OA}} < \overline{x}_U$ resp. $x_{\text{OA}} < \overline{x}_F$), is a necessary condition for resource users (factor owners) to gain from efficient management. We have shown that the stock effect drives a wedge between the harvesting plans preferred by producers, resource users and factor owners. A weak stock effect enables producers to fish down the stock to very low stock sizes under open access. A weak stock effect also brings user and factor owner interests closer to the harvesting plan implemented by a socially efficient private owner. Thus, these interest groups potentially gain a lot from privatization – provided the discount is sufficiently small.

Because of it's prominent role in the literature, we shall briefly study the case of the classical Gordon-Schaefer model (Gordon, 1954; Schaefer, 1957), which specifies $q(x) = q_0\, x$ and $g(x) = r\, x\, \left(1 - \frac{x}{K}\right)$. In this case, $g(x)/q(x) = (r/q_0)\, \left(1 - \frac{x}{K}\right)$ is linear and factor owners prefer any inefficient status quo over privatization, irrespective of their discount rate ($\underline{x}_F = 0$ for all $\rho \geq 0$). For this special case, our model becomes a variant of the static models of Samuelson (1974) and Weitzman (1974). In line with them, we obtain the unambiguous result that workers are always better off under open access in this special case.

4. The Northeast Arctic cod fishery

To provide a quantitative example, we apply our analysis to the Northeast Arctic cod (NEAC) fishery. This fishery is based on a *Gadus morhua* cod stock in the Barents Sea and Svalbard waters north of Norway and Northeast Russia. With an estimated carrying capacity of 5.73 million tons (Kugarajh et al., 2006), the NEAC is potentially the largest stock of true cod in the world (Nakken, 1994). Although stock dynamics show significant inter-annual variations due to environmental factors (recruitment positively linked to water temperature) and stock interactions (cannibalism and abundance of main prey species capelin), declines in stock biomass were mainly caused by fishing (Nakken, 1994). Total stock biomass showed a negative trend from 4.2 million tons in 1946 to a low of 0.7 million tons in 1983 (cf. Figure 3).

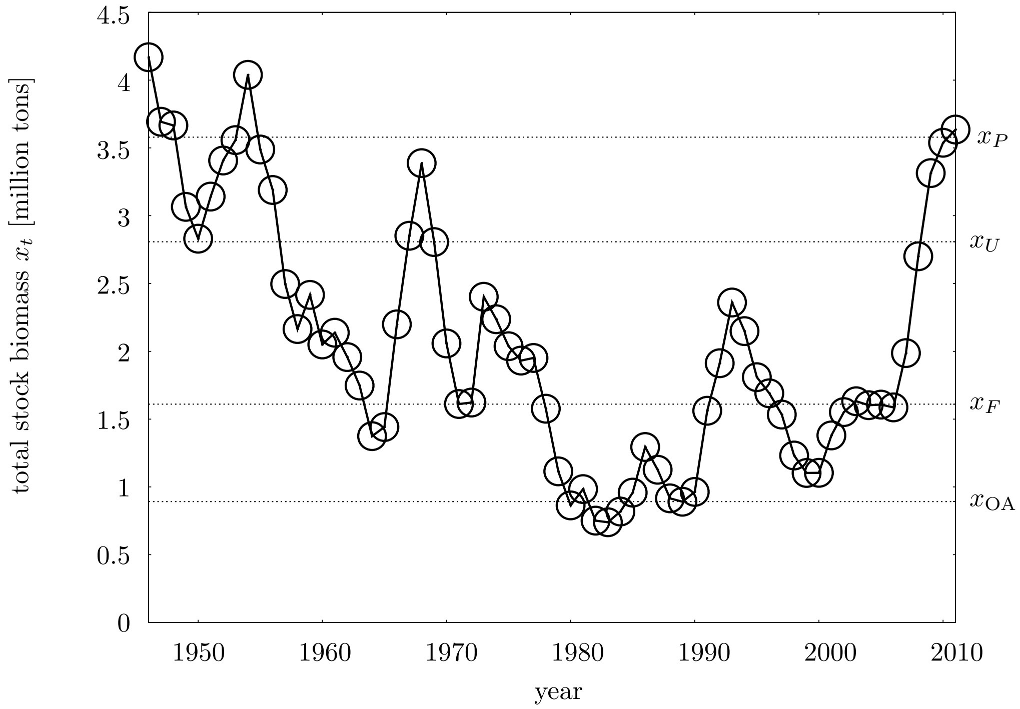

Figure 3: The development of the Northeast Arctic cod stock in 1946–2011 according to ICES (2012) stock assessment.

During that period, annual landings exceeded a million tons five times (ICES, 2012). After quotas were introduced for the trawler fleets in 1978 and for the coastal fleets in 1989, a series of low annual fishing mortalities allowed the stock to recover (ICES, 2012).

To study the distributive consequences of a continued stock rebuilding, we use specifications of the inverse demand, biomass growth and cost functions from the literature. From the inverse demand function estimated by Kugarajh et al. (2006), we obtain[6]

$$p(h) = 1.4 - 0.79\ h, \tag{17}$$

where the price is measured in billions of USD in 1998 prices, and harvest is measured in

[6]Norwegian Krone in 1998 prices is converted to USD in 1998 prices using an exchange rate of 7.5451 Norwegian Krone per USD (OECD, 2010).

million tons. The biomass growth function adopted from Kugarajh et al. (2006) is

$$g(x) = 0.46\, x \left(1 - \frac{x}{5.73}\right), \tag{18}$$

where stock sizes are measured in million tons. Accordingly, the MSY-stock is $x_{\text{MSY}} = 2.87$ million tons.

Cost functions for the Northeast Arctic cod fishery have been estimated by Kugarajh et al. (2006), Sumaila and Armstrong (2006), and Richter et al. (2011); also used by Eikeset et al. (2013). Kugarajh et al. (2006) and Sumaila and Armstrong (2006) assume $q(x) = q_0\, x$, which implies that workers always lose from privatization (cf. Section 3). Richter et al. (2011) assume $q(x) = q_0\, x^{\chi}$ and estimate a stock elasticity of harvest of $\chi = 0.58$. For the overall fishing cost function, Richter et al. (2011) estimate $c(e)/q(x) = 1.06\, x^{-0.58}$. This cost function is independent of the effort level, because Richter et al. (2011) impose the assumption that marginal costs of increasing the number of vessels are independent of total effort in the fishery. This assumption implies that there is no surplus for owners of factors employed in the fishery. Here we follow Sumaila and Armstrong (2006) instead, who use an increasing marginal effort cost function $c(e) = c_0\, e^{\beta}$ with $\beta = 0.01$, such that $c(e) \approx c_0\,(1 - \beta + \beta\, e)$. In the following we use $c_0 = 1.06$ from Richter et al. (2011) and $\beta = 0.01$ from Sumaila and Armstrong (2006). Thus, the cost function we use is[7]

$$\frac{c(e)}{q(x)} = \frac{1.05 + 0.01\, e}{x^{0.58}}. \tag{19}$$

The open-access harvest rate thus is $h_{\text{OA}}(x) = \max\left\{(a - c_0\, x^{-\chi})/(b + c_1\, x^{-2\chi}), 0\right\}$, as shown in the phase diagram in Figure 2. The resulting open-access steady-state stock size is $x_{\text{OA}} = 0.89$ million tons, which is about the minimum of historically observed stock sizes (see Figure 3).

Proposition 2 states that there exist threshold values for the discount rates of resource users and factor owners above which these interest groups would prefer open-access harvest-

[7]For effort levels $e \in [0, 2]$, the difference between the cost function (19) and the estimate by Richter et al. (2011) is less than 1%.

ing over any other harvesting plan. For users of Northeast Arctic cod, this threshold value is $\rho_U = r\ (1 - 2\, x_{\mathrm{OA}}/K) = 0.32$. This is a high figure, so it seems safe to conclude that users of Northeast Arctic cod do not favor open access. For owners of capital and labor employed in the fishery, the threshold value is much lower at $\rho_F = r\ (1 - 2\, x_{\mathrm{OA}}/K) - \chi\, r\ (1 - x_{\mathrm{OA}}/K) = 0.09$. Experimental evidence suggests that there may well be individuals discounting at rates higher than 9% per year (Andersen et al., 2008).

To determine the optimal harvesting plans, we use an annual discount rate $\rho = 0.01$. The steady-state stock sizes resulting in the three scenarios are $x_F = 1.61$ million tons, $x_U = 2.81$ million tons, and $x_P = x^* = 3.58$ million tons. The optimal stock size exceeds $x_{\mathrm{MSY}} = 2.87$ million tons because of the stock effect.

Figure 3 shows that the stock was close to x_F between 2002 and 2006. Starting from 2006 there was a period of stock rebuilding, passing x_U in 2008, and approaching levels close to x_P in 2011.

Figure 4 shows the difference in the present values between a steady state at an initial stock size x_0 and the efficient harvesting path starting at x_0 for (a) user surplus, $\Delta\mathrm{US}(x_0, \{h_t^*\})$, (b) factor surplus, $\Delta\mathrm{FS}(x_0, \{e_t^*\})$, (c) resource rent, $\Delta\mathrm{RR}(x_0, \{h_t^*, e_t^*\})$, and (d) social surplus, which is the sum of the first three surpluses.

As stated in Proposition 4, users may gain from rebuilding severely over-fished stocks, $\Delta\mathrm{US}(x_0, \{h_t^*\}) > 0$ for x_0 below $\underline{x}_U$. Such an interval of depleted stock sizes x_0, for which user would gain from privatization, exists for all discount rates below $\overline{\rho}_U = 0.84$. For the discount rate used here, we find $\underline{x}_U = 2.05$ million tons. Since 2008, the NEAC stock has passed that threshold.

The gain or loss $\Delta\mathrm{FS}(x_0, \{e_t^*\})$ of factor owners from privatization compared to a status quo at x_0 is shown in Figure 4 (b). Note that the y-axis here is in millions rather than in billions of USD, which is due to the small effect of fishing effort on the cost function (19). Factor owners are better off in the status quo than under privatization for initial stock sizes above $\underline{x}_F = 0.28$ million tons (and below x_P). This value is far below the open-access steady-state stock size. There is no possible gain from privatization at low stock sizes for factor owners if their discount rate exceeds the threshold value $\overline{\rho}_F = 0.29$.

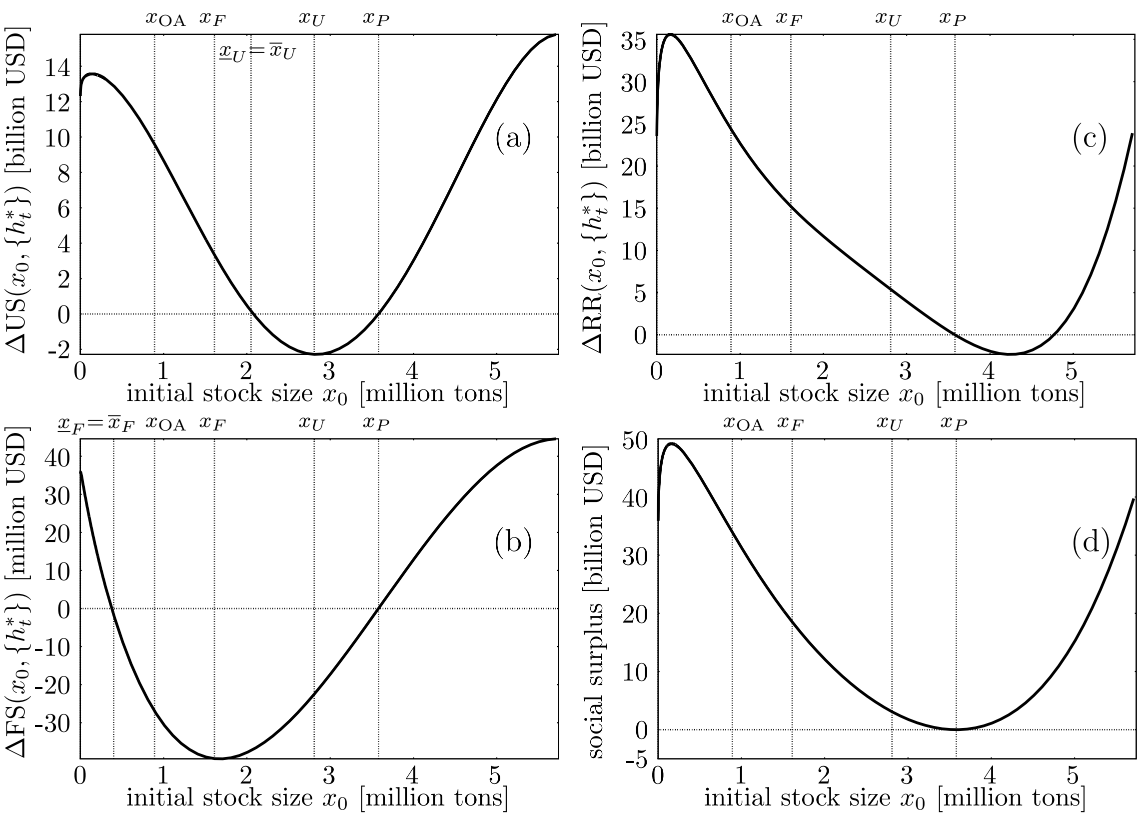

Figure 4: Differences in present values of (a) user surplus, (b) factor surplus, (c) resource rent, and (d) social surplus, between the options of maintaining a steady state at x_0 or efficient management of the Northeast Artic cod fishery.

The minimum of the aggregate social gain from privatization is at x_P, as shown in Figure 4 (d). This reflects the finding that privatization is socially efficient, cf. Proposition 1, with considerable aggregate benefits. Figure 4 (c) shows that producers would be even better off for somewhat larger stock sizes, i.e. the minimum of $\Delta\text{RR}(x_0, \{h_t^*\})$ is obtained at a stock size $x_0 > x_P$. This follows from the artificial scarcity rents a producer could earn in addition to resource rent. A producer who also maximizes monopoly rent on the product market and monopsony rent on the factor market along with resource rent would increase the steady-state stock size and lower production output and factor inputs relative to the social optimum. We have excluded artificial scarcity rents from our analysis by assuming a price-taking producer.

But even with price-taking behavior, resource rent exceeds the social surplus of harvesting for initial stock sizes above $\overline{x}_U$. For example, if we compare an efficient management starting in 2008 to a steady-state at that year's stock size, the gain in the present value of resource rent is $\Delta\text{RR}(x_{2008}, \{h_t^*\}) = 6.208$ billion USD, but this comes at a loss in surplus for factor owners of $\Delta\text{FS}(x_{2008}, \{h_t^*\}) = -0.025$ billion USD and a loss in surplus of users of Northeast Arctic cod of $\Delta\text{US}(x_{2008}, \{h_t^*\}) = -2.214$ billion USD. The net social gain is only 3.969 billion USD. About a third of the gain in resource rent would come from a transfer of benefit from factor owners and resource users. Recovering the sunken billions of resource rent (World Bank, 2008) may require the sinking of other rent categories.

5. Discussion and Conclusions

While traditional bio-economics focuses on the maximization of resource rent, we consider two additional interest groups that may have an impact on resource management: Resource users, who derive surplus from buying harvest for processing and consumption, and owners of production factors employed in resource harvesting, i.e. capital owners and workers. By identifying conditions that determine whether resource users and factor owners gain or lose from better resource management in a dynamic model, our results shed a new light on the well-known efficiency results obtained in traditional renewable resource economics.

We have shown that only in absence of a stock effect, all stakeholder groups would unanimously prefer socially efficient resource management. If there is a stock effect, only producers would favor socially efficient harvesting rates. Because resource users care only about harvest quantities and not about (stock-dependent) harvesting costs, they would choose inefficiently high harvest rates. Factor factor owners prefer still higher harvesting rates, because this increases demand for production factors and, hence, factor surplus. We have further shown that resource users and factor owners prefer open access over any other form of management if their discount rates exceed certain finite thresholds.

These results may provide an explanation as to why common-pool resource stocks continue to be governed inefficiently even in countries and regions that have the knowledge and capabilities to improve management. If processors, consumers, capital owners and workers employed in resource harvesting have enough political influence to implement their preferred harvest rates, public resource management may fail to be efficient. Harvest rates close to open-access conditions under public resource management have been observed in the past, for example in European fisheries (Quaas et al., 2012).

Privatizing a renewable resource may be seen as a way to weaken the influence of stakeholders arguing for inefficiency. In the second part of our analysis, we studied the distributive consequences of privatization, assuming that there is a stock effect of harvesting. We have found that resource users and factor owners lose from privatization, unless (a) the stock is severely depleted and (b) the discount rate is low.

Such distributive effects raise the question of compensation. Because privatization is socially efficient, auctioning off harvesting rights or implementing royalty schemes could raise funds that could fully compensate resource users and factor owners who lose from privatization. Such a compensation seems difficult in practice. Obviously, any direct price instrument would have distortive effects. Lump-sum transfers, by contrast, may easily be too small to fully compensate those individuals that lose most from privatization. It might thus be impossible to implement privatizations as pure Pareto-improvements. Resource users and factor owners are particularly likely to lose from privatization if harvesting costs are large (due to a high stock effect) and the discount rate is high. These are conditions that typically hold in developing countries.

With technical progress, the stock effect of harvesting becomes less and less important. Our analysis suggests that as a consequence, the objectives of factor owners and resource users become more aligned with efficient management. Recent improvements in fisheries management in the United States and other more developed regions of the world may indicate that such processes already have a positive effect on the political economy of renewable resource management.

Appendix

A. Steady-state stock sizes

In steady state, harvest equals biomass growth, $h = g(x)$, effort equals $e = h/q(x) = g(x)/q(x)$, and the shadow price μ is constant.

The condition determining the socially efficient steady-state stock size $x^* = x_P$ is obtained by using these conditions in (5),

$$g'(x^*) = \rho - \frac{c\,(g(x^*)/q(x^*))\;q'(x^*)\,g(x^*)/q(x^*)}{p(g(x^*))\,q(x^*) - c\,(g(x^*)/q(x^*))}. \tag{20}$$

It is straightforward to show that x^* is decreasing with the discount rate, $dx^*/d\rho < 0$, with $x^* \xrightarrow{\rho\to\infty} x_{OA}$ (the proof can be obtained from the authors upon request).

For interest group U, the optimal steady-state stock size $\hat{x}_U$ for $\mu > 0$ is obtained by using $\dot{x} = 0$ and $\dot{\mu} = 0$ in (11). This leads to the condition

$$g'(\hat{x}_U) = \rho. \tag{21}$$

As $g'(\cdot)$ is monotonically decreasing and the right-hand side of (21) is smaller than the right-hand side of (20) for $q'(\cdot) > 0$, it follows that $\hat{x}_U < x^*$ for $q'(\cdot) > 0$ (Clark and Munro, 1975).

For interest group F, the optimal steady-state stock size $\hat{x}_F$ for $\mu > 0$ is obtained by using $\dot{x} = 0$ and $\dot{\mu} = 0$ in (13). This leads to the condition

$$g'(\hat{x}_F) = \rho + g(\hat{x}_F)\,\frac{q'(\hat{x}_F)}{q(\hat{x}_F)}. \tag{22}$$

As $g'(\cdot)$ is monotonically decreasing and as the right-hand side of (22) is smaller than the right-hand side of (21) for $q'(\cdot) > 0$, it follows that $\hat{x}_F < \hat{x}_U$ for $q'(\cdot) > 0$.

Thus, if $q'(\cdot) > 0$, we have $\hat{x}_F < \hat{x}_U < x_P = x^*$.

B. Proof of Proposition 1

For all scenarios, it follows that (Acemoglu, 2008)

$$h'_P(x) > 0, \quad h'_U(x) > 0 \quad \text{and} \quad h'_F(x) > 0, \tag{23}$$

as $p'(h) < 0$, $c'(e) > 0$, and $q(x)$ is concave. We thus have $g(x) - h_i(x) > 0$ for all $x < x_i$ and $g(x) - h_i(x) < 0$ for all $x > x_i$, where x_i denotes the optimal steady-state stock size for interest group $i = P, U, F$.

Proof of 1a). For the stock size x at which the harvest rates for interest groups U and P are compared, we consider three cases, (i) $x_U \leq x \leq x^*$, (ii) $x < x_U$, and (iii) $x > x^*$.

(i) $x_U \leq x \leq x^*$. In this case, $h_U(x) \geq g(x) \geq h_P(x)$ with $g(x) > h_P(x)$ for $x = x_U$ and $h_U(x) > g(x)$ for $x = x^*$.

(ii) $x < x_U$. Differentiating (10a) with respect to time, we obtain

$$\dot{\mu}_P = \left(\left[p'(h_P(x)) - \frac{c'\left(h_P(x)/q(x)\right)}{q(x)^2}\right] h'_P(x) + \frac{c'\left(h_P(x)/q(x)\right)\, h_P(x) + c\left(h_P(x)/q(x)\right)\, q(x)}{q(x)^2}\, \frac{q'(x)}{q(x)}\right) (g(x) - h_P(x)) \quad (24)$$

Using this in (10b), we obtain

$$\left(\rho - g'(x)\right) \left(p(h_P(x)) - \frac{c(h_P(x)/q(x))}{q(x)}\right) - \frac{c'\left(h_P(x)/q(x)\right)\, h_P(x) + c\left(h_P(x)/q(x)\right)\, q(x)}{q(x)^2}\, \frac{q'(x)}{q(x)}\, (g(x) - h_P(x)) - \left[p'(h_P(x)) - \frac{c'\left(h_P(x)/q(x)\right)}{q(x)^2}\right] (g(x) - h_P(x))\, h'_P(x) = c(h_P(x)/q(x))\, \frac{q'(x)\, h_P(x)}{q(x)^2} \quad (25)$$

Similarly, differentiating (11a) with respect to time yields

$$\dot{\mu}_U = \left(\left[p'(h_U(x)) - \frac{c'\left(h_U(x)/q(x)\right)}{q(x)^2}\right] h'_U(x) + \frac{c'\left(h_U(x)/q(x)\right)\, h_U(x) + c\left(h_U(x)/q(x)\right)\, q(x)}{q(x)^2}\, \frac{q'(x)}{q(x)}\right) (g(x) - h_U(x)) \quad (26)$$

Using this in (11b), we obtain

$$\left(\rho - g'(x)\right) \left(p(h_U(x)) - \frac{f(h_U(x)/q(x))}{q(x)}\right) - \frac{c'\left(h_U(x)/q(x)\right)\, h_U(x) + c\left(h_U(x)/q(x)\right)\, q(x)}{q(x)^2}\, \frac{q'(x)}{q(x)}\, (g(x) - h_U(x)) - \left[p'(h_U(x)) - \frac{f'\left(h_U(x)/q(x)\right)}{q(x)^2}\right] (g(x) - h_U(x))\, h'_U(x) = 0 \quad (27)$$

Now assume that there exists some stock size $\hat{x} < x_U$ such that $h_U(\hat{x}) = h_P(\hat{x})$. Comparing (25) and (27), the first and second terms on the left hand sides are the same. Also the factors in front of $h_i'(\hat{x})$ are the same. The terms in square brackets are negative, as $p'(\cdot) < 0$, $f'(\cdot) > 0$, and $g(\hat{x}) - h_i(\hat{x}) > 0$ for $\hat{x} < x_U$. The right hand side of (25) is larger than the right hand side of (27). Thus, we must have $h_U'(\hat{x}) < h_P'(\hat{x})$.

Since $h_U(x_U) = g(x_U) > h_P(x_U)$, however, it must hold that $h_U'(\tilde{x}) > h_P'(\tilde{x})$ for the largest $\tilde{x}$ where $h_U(\tilde{x}) = h_P(\tilde{x})$. This is a contradiction to the result derived above that $h_U'(\hat{x}) < h_P'(\hat{x})$ for any $\hat{x}$ where $h_U(\hat{x}) = h_P(\hat{x})$. Thus, we conclude that such a value $\hat{x} < x_U$ does not exist. Hence, $h_U(x) > h_P(x)$ for all $x < x_U$.

(iii) $x > x^*$. Comparing (25) and (27) similar as in case (ii), but now with $g(\hat{x}) - h_i(\hat{x}) < 0$, we find that for any $\hat{x} > x^*$ where $h_U(\hat{x}) = h_P(\hat{x})$, we must have $h_U'(\hat{x}) > h_P'(\hat{x})$. Since $h_U(x^*) > g(x^*) = h_P(x^*)$, we again have a contradiction and conclude that such a value $\hat{x} > x^*$ does not exist. Hence, $h_U(x) > h_P(x)$ for all $x > x^*$.

Proof of 1b). For the stock size x at which the harvest rates for interest groups U and P are compared, we consider three cases, (i) $x_F \leq x \leq x_U$, (ii) $x < x_F$, and (iii) $x > x_U$.

(i) $x_F \leq x \leq x_U$. In this case, $h_F(x) \geq g(x) \geq h_U(x)$ with $g(x) > h_U(x)$ for $x = x_F$ and $h_F(x) > g(x)$ for $x = x_U$.

(ii) $x < x_F$. Differentiating (13a) with respect to time yields

$$\dot{\mu}_F = \left(\left[p'(h_F(x)) - \frac{c'\left(h_F(x)/q(x)\right)}{q(x)^2} \right] h_F'(x) + \frac{c'\left(h_F(x)/q(x)\right) h_F(x) + f\left(h_F(x)/q(x)\right) q(x)}{q(x)^2} \frac{q'(x)}{q(x)} \right) (g(x) - h_F(x)) \quad (28)$$

Using this in (13b), we obtain

$$(\rho - g'(x)) \left([p(h_F(x)) - \frac{c(h_F(x)/q(x))}{q(x)} \right) - \frac{c'\left(h_F(x)/q(x)\right) h_F(x) + c\left(h_F(x)/q(x)\right) q(x)}{q(x)^2} \frac{q'(x)}{q(x)} (g(x) - h_F(x)) - \left(p'(h_F(x)) - \frac{c'\left(h_F(x)/q(x)\right)}{q(x)^2} \right) (g(x) - h_F(x)) \, h_F'(x) = -h_F(x) \frac{q'(x)}{q(x)} \left(p(h_F(x)) - \frac{c(h_F(x)/q(x))}{q(x)} \right) \quad (29)$$

Assume that there exists some stock size $\hat{x} < x_F$ such that $h_F(\hat{x}) = h_U(\hat{x})$. Comparing (27) and

(29), the first and second terms on the left hand sides are the same. Also the factors in front of $h_i'(\hat{x})$ are the same. The terms in square brackets are negative, as $p'(\cdot) < 0$, $c'(\cdot) > 0$, and $g(\hat{x}) - h_i(\hat{x}) > 0$ for $\hat{x} < x_F$. The right hand side of (27) is larger than the right hand side of (29) if $\mu_F > 0$, i.e. if the optimal steady-state stock size for group F exceeds the open-access steady-state stock size. Thus, we must have $h_F'(\hat{x}) < h_U'(\hat{x})$ in this case and $h_F'(\hat{x}) = h_U'(\hat{x})$ if $\mu_F = 0$.

Since $h_F(x_F) = g(x_F) > h_U(x_F)$, if $\mu_U > 0$, however, it must hold that $h_F'(\tilde{x}) > h_U'(\tilde{x})$ for the largest $\tilde{x}$ where $h_F(\tilde{x}) = h_U(\tilde{x})$. This is a contradiction to the result derived above that $h_F'(\hat{x}) \leq h_U'(\hat{x})$ for any $\hat{x}$ where $h_F(\hat{x}) = h_U(\hat{x})$. Thus, we conclude that such a value $\hat{x} < x_F$ does not exist. Hence, $h_F(x) > h_U(x)$ for all $x < x_F$. If, however, $\mu_U = 0$, and, hence, $\mu_F = 0$, we have $h_F(x) = h_U(x)$ for all x.

(iii) $x > x_U$. Comparing (27) and (29) for $\mu_U > 0$, similar as in case (ii), but now with $g(\hat{x}) - h_i(\hat{x}) < 0$, we find that for any $\hat{x} > x_U$ where $h_F(\hat{x}) = h_U(\hat{x})$, we must have $h_F'(\hat{x}) > h_U'(\hat{x})$. Since $h_F(x_U) > g(x_U) = h_U(x_U)$, we again have a contradiction and conclude that such a value $\hat{x} > x_U$ does not exist. Hence, $h_F(x) > h_U(x)$ for all $x > x_U$. Similarly, we have $h_F(x) = h_U(x)$ if $\mu_U = 0$.

C. *Proof of Proposition 2*

2a). If $x_{\text{OA}} \geq x_{\text{MSY}}$, it follows that $x_U = x_{\text{OA}}$ for all $\rho \geq 0$. If $x_{\text{OA}} < x_{\text{MSY}}$, $x_U = x_{\text{MSY}}$ for $\rho = 0$. Because $\partial x_\rho / \partial \rho < 0$, $x_\rho \xrightarrow{\rho \to \infty} 0$, and $\partial x_{OA} / \partial \rho = 0$, a $\rho_U > 0$ must exist such that $x_U = x_{\text{OA}}$. In steady state with $x_U = x_{\text{OA}}$ we have $\mu_U = 0$. Condition (11b) implies that $\mu_U = 0$ also during the transition dynamics to the steady state.

2b). $h_U(x) = h_F(x)$ holds only if $h_U(x) = h_F(x) = h_{\text{OA}}(x)$. If $\rho < \rho_U$, it follows from the proof of Proposition (1) that $h_U(x) < h_F(x) \leq h_{\text{OA}}$.

2c). For the steady state, this follows from the proof of Proposition 3 and the fact that $\hat{x}_F < \hat{x}_U$ if $q'(\cdot) > 0$. In steady state with $x_F = x_{\text{OA}}$ we have $\mu_F = 0$. Condition (11b) implies that $\mu_F = 0$ also during the transition dynamics to the steady state.

D. *Proof of Proposition 3*

Proof of 3a). We distinguish two cases. The first is that the discount rate is small enough such that $g(\hat{x}_U) \geq g(x^*)$. Hence, $g(x_0) \geq g(x^*)$ and because of transition effects

$$\Delta \text{US}(x_0, \{h_t^*\}) < \frac{1}{\rho}\,\text{US}(g(x^*)) - \frac{1}{\rho}\,\text{US}(g(x_0)) < 0$$

for all $x_0 \in [\hat{x}_U, x^*)$.

In the second, more difficult case, the discount rate ρ is so high that $g(\hat{x}_U) < g(x^*)$. If $x^* > x_{\mathrm{MSY}}$ there exists a stock size x_u with $g(x_u) = g(x^*)$ and $x_u < x^*$. Let $\underline{x}_u = \min\{x_u, x^*\}$. If $\underline{x}_u = x_u$, then $\Delta\mathrm{US}(x_0, \{h_t^*\}) < 0$ for all $x_0 \in [x_u, x^*)$. With the same reasoning as in the first case we conclude that $\Delta\mathrm{US}(x_0, \{h_t^*\}) < 0$. Now consider $x_0 \in (\hat{x}_U, \underline{x}_u)$, such that $g(x_0) < g(x^*)$. It exists a ρ' such that $\hat{x}_U(\rho') = x_0$. For that discount rate ρ' with $\rho' < \rho$, the steady state at x_0 optimizes the present value of user surplus. Thus,

$$\int_0^\infty \left(\mathrm{US}(h_t^*(x_0)) - \mathrm{US}(g(x_0))\right) e^{-\rho' t}\, dt < 0$$

The hypothetical constant instantaneous user surplus that would lead to the same present value of user surplus (at some discount rate ρ'') as the dynamic path under the given optimal harvesting path $h_t^*(x_0)$, is defined as

$$\mathrm{US}^*_{\rho''}(x_0) \equiv \rho'' \int_0^\infty \mathrm{US}(h_t^*(x_0))\, e^{-\rho'' t}\, dt$$

This value decreases with ρ'', because

$$\frac{d\mathrm{US}^*_{\rho''}(x_0)}{d\rho''} = \int_0^\infty (1-\rho'' t)\, \mathrm{US}(h_t^*(x_0))\, e^{-\rho'' t}\, dt = \int_0^{1/\rho''} \underbrace{(1-\rho'' t)}_{>0} \underbrace{\mathrm{US}(h_t^*(x_0))}_{<\mathrm{US}(h^*_{1/\rho''}(x_0)) \text{ for } t<1/\rho''} e^{-\rho'' t}\, dt$$
$$+ \int_{1/\rho''}^\infty \underbrace{(1-\rho'' t)}_{<0} \underbrace{\mathrm{US}(h_t^*(x_0))}_{>\mathrm{US}(h^*_{1/\rho''}(x_0)) \text{ for } t>1/\rho''} e^{-\rho'' t}\, dt < \mathrm{US}(h^*_{1/\rho''}(x_0)) \int_0^\infty (1-\rho'' t)\, e^{-\rho'' t}\, dt = 0,$$

which holds because the user surplus under socially efficient harvesting monotonically increases in the transition towards the steady state, as $dh^*(x)/dx > 0$ (23) and hence, $dh_t^*(x_0)/dt > 0$.

We have shown before that $\mathrm{US}^*_{\rho'}(x_0) < \mathrm{US}(g(x_0))$ for the discount rate $\rho' < \rho$ where $\hat{x}_U(\rho') = x_0$. As $\mathrm{US}(g(x_0))$ is independent of ρ'', and $\mathrm{US}^*_{\rho''}(x_0)$ monotonically decreases with ρ'', the inequality $\mathrm{US}^*_\rho(x_0) < \mathrm{US}(g(x_0))$ must also hold for the actual discount rate ρ, which concludes the proof for all $x_0 \in (\hat{x}_U, \underline{x}_u)$.

So far we have shown that $\Delta\mathrm{US}(x_0, \{h_t^*\}) < 0$ for all $x_0 \in (\hat{x}_U, x^*)$. A steady state at $x_0 = \hat{x}_U$, however, is the optimum for resource users, such that $\Delta\text{US}(\hat{x}_U, \{h_t^*\})$ is negative (probably by a large amount). By continuity of $\Delta\text{US}(\hat{x}_U, \{h_t^*\})$, we conclude that it exists an $\underline{x}_U$ with $0 \leq \underline{x}_U < \hat{x}_U$ such that $\Delta\text{US}(x_0, \{h_t^*\}) < 0$ for all $x_0 \in (\underline{x}_U, x^*)$.

Proof of 3b). We use $\bar{e}(x) = \frac{g(x)}{q(x)}$ to denote steady-state effort at stock size x. The term $e_t^*(x_0)$ remains effort at $t \geq 0$ under the efficient harvesting plan starting at x_0. Because of transition effects it follows

$$\Delta\text{FS}(x_0, \{h_t^*\}) < \frac{1}{\rho}\,\text{FS}(\bar{e}(x^*)) - \frac{1}{\rho}\,\text{FS}(\bar{e}(x_0)) \tag{30}$$

for all $x_0 < x^*$. We have that $\Delta\text{FS}(x_0, \{e_t^*\}) < 0$ for all $x_0 < x^*$ with $\bar{e}(x_0) \geq \bar{e}(x^*)$. Because of the strict quasi-concavity of $\bar{e}(x)$, $\bar{e}(x_0^{'}) \geq \bar{e}(x^*)$ implies $\bar{e}(x_0) \geq \bar{e}(x^*)$ and hence $\Delta\text{FS}(x_0, \{e_t^*\}) < 0$ for all $x_0 \in [x_0^{'}, x^*]$.

In case $e(\hat{x}_F) \geq e(x^*)$, we directly conclude that $\Delta\text{FS}(x_0, \{e_t^*\}) < 0$ for all $x_0 \in [\hat{x}_F, x^*]$. Particularly if $x_{\text{MSE}} = 0$, it follows $\Delta\text{FS}(x_0, \{e_t^*\}) < 0$ for all $x_0 \in (0, x^*)$.

In the more difficult case $\bar{e}(\hat{x}_F) < \bar{e}(x^*)$, there exists a stock size x_f with $\bar{e}(x_f) = \bar{e}(x^*)$. Let $\underline{x}_f = \min\{x_f, x^*\}$. If $\underline{x}_f = x_f$, then $\Delta\text{FS}(x_0, \{e_t^*\}) < 0$ for all $x_0 \in [x_f, x^*)$. It remains to show that $\Delta\text{FS}(x_0, \{e_t^*\}) < 0$ for all $x_0 \in (\hat{x}_F, \underline{x}_f)$. For each $x_0 \in (\hat{x}_F, \underline{x}_f)$, it exists a $\rho^{'}$ such that $\hat{x}_F(\rho^{'}) = x_0$. For this discount rate $\rho^{'}$ with $\rho^{'} < \rho$, the steady state x_0 optimizes present value of factor surplus. Thus,

$$\int_0^\infty \left(\text{FS}(e_t^*(x_0)) - \text{FS}(\bar{e}(x_0))\right)\, e^{-\rho'\, t}\, dt < 0$$

The hypothetical constant instantaneous factor surplus that would lead to the same present value of factor surplus (at some discount rate ρ'') as the effort path under efficient resource management, is defined as

$$\text{fs}^*_{\rho''}(x_0) \equiv \rho'' \int_0^\infty \text{FS}(e_t^*(x_0))\, e^{-\rho''\, t}\, dt.$$

Using that $e_t^*(x_0) = h_t^*(x_0)/q(x_0)$ for $t = 0$, $e_t^*(x_0) < h_t^*(x_0)/q(x_0)$ for $t > 0$ and $d(h_t^*(x_0)/q(x_0))/dt >$

0, it follows that $\text{fs}^*_{\rho''}(x_0)$ decreases with ρ'':

$$\frac{d\text{fs}^*_{\rho''}(x_0)}{d\rho''} = \int_0^\infty (1-\rho''\,t)\,\text{FS}(l_t^*(x_0))\,e^{-\rho''\,t}\,dt < \int_0^\infty (1-\rho''\,t)\,\text{FS}(h_t^*(x_0)/q(x_0))\,e^{-\rho''\,t}\,dt$$

$$\begin{aligned}
&\int_0^\infty (1-\rho''\,t)\,\text{FS}(e_t^*(x_0)/q(x_0))\,e^{-\rho''\,t}\,dt\\
&= \int_0^{1/\rho''} \underbrace{(1-\rho''\,t)}_{>0} \underbrace{\text{FS}(e_t^*(x_0)/q(x_0))}_{<\text{FS}(e^*_{1/\rho''}(x_0)/q(x_0)) \text{ for } t<1/\rho''} e^{-\rho''\,t}\,dt\\
&+ \int_0^{1/\rho''} \underbrace{(1-\rho''\,t)}_{<0} \underbrace{\text{FS}(e_t^*(x_0)/q(x_0))}_{>\text{FS}(e^*_{1/\rho''}(x_0)/q(x_0)) \text{ for } t>1/\rho''} e^{-\rho''\,t}\,dt\\
&\qquad < \text{FS}(e^*_{1/\rho''}(x_0)/q(x_0)) \int_0^\infty (1-\rho''\,t)\,e^{-\rho''\,t}\,dt = 0.
\end{aligned}$$

We have shown before that $\text{fs}^*_{\rho'}(x_0) < \text{FS}(\bar{e}(x_0))$ for the discount rate $\rho' < \rho$ where $x_F(\rho') = x_0$. As $\text{FS}(\bar{e}(x_0))$ is independent of ρ'', and $\text{fs}^*_{\rho''}(x_0)$ monotonically decreases with ρ'', the inequality $\text{fs}^*_{\rho}(x_0) < \text{FS}(\bar{e}(x_0))$ must also hold for the actual discount rate ρ, which concludes the proof for all $x_0 \in (\hat{x}_F, \underline{x}^*)$.

So far we have shown that $\Delta\text{FS}(x_0, \{e_t^*\}) < 0$ for all $x_0 \in (\hat{x}_F, x^*)$. A steady state at $x_0 = \hat{x}_F$, however, is the optimum for factor owners, such that $\Delta\text{FS}(\hat{x}_F, \{e_t^*\})$ is negative (probably by a large amount). By continuity of $\Delta\text{FS}(x_0, \{e_t^*\})$, we conclude that it exists an $\underline{x}_F$ with $0 \leq \underline{x}_F < \hat{x}_F$ such that $\Delta\text{US}(x_0, \{e_t^*\}) < 0$ for all $x_0 \in (\underline{x}_F, x^*)$.

E. Proof of Proposition 4

Proof of 4a). For $\rho = 0$, there exists a stock size $\overline{x}_U$ with $g(\overline{x}_U) = g(x^*)$ and $\overline{x}_U < x^*$. Given $\rho = 0$, transitional costs do not outweigh steady-state benefits for all $x_0 < \overline{x}_U$, hence $\Delta\text{US}(x_0, \{e_t^*\}) > 0 \quad \forall\, x_0 \in (0, \overline{x}_U)$. By continuity of (4b), this also holds for some positive discount rates $\rho \leq \overline{\rho}_U$.

Proof of 4b). If $x_{\text{MSE}} > 0$, there also exists a $\overline{x}_F$ with $\frac{g(\overline{x}_F)}{q(\overline{x}_F)} = \frac{g(x^*)}{q(x^*)}$ and $\frac{g(x_0)}{q(x_0)} > \frac{g(x^*)}{q(x^*)}\,\forall x_0 < \overline{x}_F$. Because of $\rho = 0$, transitional costs do not outweigh steady-state benefits $\forall x_0 < \overline{x}_F$, hence

$\Delta\mathrm{FS}(x_0, \{h_t^*\}) > 0 \, \forall \, x_0 \in (0, \overline{x}_F)$. By continuity of (4c), this also holds for some positive discount rates $\rho \leq \overline{\rho}_F$.

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