Demand for renewable resources

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In the beginning of 2008, Prof. Dr. Till Requate informed me that the economics department had recently recruited a new Professor for Resource and Environmental Economics with a focus on fisheries. At that time I had already organized a stay at the Fisheries Centre of the UBC Vancouver. With my studies in economics nearly finished, my plan was get to know the field of fisheries economics. Prof. Dr. Martin F. Quaas recruited me as a PhD student and allowed me to spend the two terms at UBC as a visiting PhD student. After searching for positions in fisheries economics abroad, my home university suddenly gave me the opportunity to work in the field I was interested in.

The time as a PhD student was always pleasant. When stuck in research questions, one could simply go to Martin's office and discuss the questions immediately. Comments on draft papers were returned by Martin within a week. The direct and quick contact to my supervisor was a great luxury. Another luxury was the possibility to attend many motivating conferences.

I would like to thank Martin for these exceptional working conditions. I would also like to thank Prof. Dr. Till Requate for establishing the contact and the feedback on Martin's and my paper. Rüdiger Voss and Jörn Schmidt were always great discussion partners, especially at the IIFET conference in Montpellier 2010. I enjoyed working with many interesting and kind PhD colleagues. To avoid an incomplete list, I better not start one here. I would also like to thank Rashid Sumaila for supervising me at UBC and the German Academic Exchange Service for financing the stay there. I would also like to give thanks to the organizers and participants of the EAERE-FEEM-VIU European Summer School in Venice 2011 and the Kiel-Kyoto exchange 2010.

Contents

Introduction 1

Enjoying catch and fishing effort:
The effort effect in recreational fisheries 5

Public and private management of renewable resources:
Who gains, who loses? 27

New trade in renewable resources and consumer preferences
for diversity 64

Eidesstattliche Erklärung 84

Lebenslauf 85

Introduction

Economic theory about the demand for renewable resources usually focuses on one good and one goal: Biomass harvested from a resource stock and its socially efficient production. The aim of the dissertation at hand is to broaden this perspective on renewable resources in three respects.

The first paper entitled "Enjoying catch and fishing effort: The effort effect in recreational fisheries" argues that recreational fishermen derive utility not only from their catch. While fishing effort is a costly input to harvest production for both recreational and commercial fishermen, anglers value fishing effort also by itself. If welfare is generated not only by harvest, but also by harvesting effort, three key results follow. First, a density-dependent "effort effect" emerges that holds under first-best management as well as under open access: The higher the importance of fishing effort relative to catch in an representative agent's utility function, the lower are actual catches at high stock sizes and the higher are actual catches at low stock sizes. Second, the effort effect under first-best management lowers the bar for optimal extinction. In a standard commercial fisheries model without harvesting costs, extinction becomes optimal if the discount rate exceeds the maximum growth rate of the stock (Clark, 1991). With the direct benefits of harvesting effort incorporated, extinction already becomes optimal if the discount rate exceeds the maximum growth rate of the stock times the relative importance of catch for fisherman utility. Third, the effort effect under open access adds an interesting insight to the discussion about the potential of recreational fishing to cause stock depletion. In mixed commercial-recreational fisheries, recreational fishing might in fact be a negligible source of fishing mortality at high stock sizes. Once commercial fishing has reduced the stock, rising unit fishing costs limit commercial catches under open access. Recreational fishing, being less dependent on catches due to the effort effect, might then realize higher actual catches than commercial fishing at low stock sizes. If the importance of catch is below a certain threshold, recreational fishing may continue overexploitation until stock collapse. The article has been accepted for publication in Environmental and Resource Economics (Stoeven, 2013).

The second paper "Public and private management of renewable resources: Who gains, who loses?" is joint work with my supervisor Martin F. Quaas. Our paper is motivated by the question why many renewable resources on land or within Exclusive Economic Zones continue to be managed inefficiently. This is an interesting question because the economic theory of common property resources provides policy advice to resolve inefficiency under various forms of management from pure open access to public management with insufficient input or output controls. To understand why insights from resource economics are not adopted, we start our paper with a thought experiment and study how producers (the owners of fishing firms who receive resource rent from producing resource harvest), resource users (buyers of resource harvest for processing or final consumption who receive consumer surplus) and factors owners (owner of capital and labor who receive factor surplus from employment in resource harvesting over the best remuneration in alternative employment) would manage a renewable resource if they became the sole owner of the resource use rights. We show that both resource users and factor owners have an interest in inefficiency if the harvesting costs are stock-dependent and that both interest groups prefer open access over any other form of management for discount rates above certain finite thresholds. It is a well-known result in the literature that price-taking resource management maximizing resource rent can only align with open access for an infinite discount rate (Clark, 1991). Our paper shows that price-taking sole owners (maximizing consumer surplus or factor surplus) may want to introduce open-access conditions already for finite discount rates. The intuition for consumers is that their expenditures for harvest equals the sum of harvesting costs and resource rent, such that they do not necessarily benefit if resource management improves and the share of resource rent in consumer expenditures increases. The intuition for factor owners is that they understand the resource stock as a rivaling input to harvest production if the marginal productivity of effort is stock-dependent. If such interest groups benefiting from inefficiently high harvest rates have sufficient political influence, public resource management may fail. If public resource management suffers from stakeholders lobbying for inefficiency, privatizing use rights may be seen as a way to weaken such influences. We show that privatization is the likelier the lower the current stock size and the lower the discount rate. This is because resource users and factor owners are the likelier to gain from leaving the status quo the more depleted the resource stock and the lower the discount rate is.

My contribution to the paper includes the initial model setup for analyzing the consumer benefits of improving resource management in a dynamic model. Prof. Dr. Martin F. Quaas enlarged the model setup to include factor owners and processors as well. To avoid mistakes, both Prof. Dr. Martin F. Quaas and myself calculated the dynamic harvesting plans of the three interest groups separately. The economic rationale for resource users and factor owners to prefer inefficiency despite being sole owners was written by me. Prof. Dr. Martin F. Quaas realized the critical role of the stock effect and provided most of the proofs in the appendix.

The third paper "New trade in renewable resources and consumer preferences for diversity" is joint work with my supervisor Martin F. Quaas. It is an extension of Quaas and Requate (2013) to trade with varying consumer expenses. The literature about trade in renewable resources makes the implicit assumption that the traded resources are perfect substitutes. If the harvesting cost structure of open-access resources is comparable, trade liberalization has the effect to relieve the more depleted resource stock by redirecting demand towards the more abundant one. The literature on trade in renewable resources thus uses a modeling framework that makes trade-induced stock collapses improbable as it works towards balanced stock sizes. Our paper is motivated by lifting this assumption. Using a CES utility function to model the preferences for two types of harvest, we show that decreasing the elasticity of substitution from the standard case of perfect substitutes towards the second limit case of Cobb-Douglas preferences decreases the equilibrium stock size of the stock with the smaller intrinsic growth rate. In the limit case of Cobb-Douglas preferences, trade liberalization may result in the collapse of one or the sequential collapse of both resource stocks. The intuition for this result is that increasing the consumers' love of variety weakens the link between resource scarcity and demand. Concerning the welfare effects of trade liberalization, trade in perfect substitutes bar any general equilibrium feedbacks has a winner and a loser as the resulting equilibrium price lies between the former autarky prices. We show that a love of variety effect may compensate trade-induced increases or decreases in domestic consumption, making the total welfare effect of trade more ambiguous.

My contribution to the paper includes the literature review, most of the writing and the model setup in the two-species-two-country case. The basic model setup builds on Quaas and Requate (2013). I developed the trade model in $x_1 - x_2$ space to make it as comprehensible as possible. Prof. Dr. Martin F. Quaas developed the model about trade between a species-rich and a species-poor country.

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Enjoying catch and fishing effort: The effort effect in recreational fisheries[☆]

May 26, 2013

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Abstract

Recreational fishermen derive utility from catch and fishing effort. Building our analysis on the Gordon-Clark model for renewable resources, we show that a lower importance of catch may result in higher catches. While this effect also holds under first-best management, it may destabilize open-access recreational fisheries to the point of stock collapse. Technical progress in recreational fisheries may mask such dynamics as it enables unaltered angler behavior and constant catches during stock declines.

Keywords: recreational fishing, angling, importance of catch, collapse, overfishing

JEL: Q22, Q26

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Recreational fishing is the most important source of fishing mortality in many inland and coastal waters (Lewin et al., 2006; Ihde et al., 2011). Prominent examples include four Canadian freshwater species whose collapse is attributed to recreational fishing (Post et al., 2002) and several saltwater species in the U.S. for which recreational exceed commercial landings (NMFS, 2011; Coleman et al., 2004). The mere number of recreational fishermen, e.g. 11 million anglers compared to 0.11 million commercial harvesters in U.S. marine fisheries (NMFS, 2010) illustrates why contrasting a single angler with rod and reel to a commercial trawler is an increasingly misleading image (Cooke and Cowx, 2006).

Recreational fishing differs from commercial fishing by the perception of fishing effort. While fishing effort is a costly production input for both types of fisheries, recreational fishermen also value fishing effort by itself[1]. The importance of catch relative to the importance of fishing effort (which represents non-catch benefits such as being outdoors) varies significantly between angler subgroups (Fedler and Ditton, 1986; Arlinghaus, 2006). We show that the intuitive result that a lower importance of catch results in anglers catching fewer fish only holds for high stock sizes. At low stock sizes however, a lower importance of catch increases actual catches. While this effect also holds under first-best management, it may destabilize open-access recreational fisheries to the point of stock collapse. This result is especially relevant for mixed commercial-recreational fisheries in which recreational fishing becomes more important, e.g. for 71 fisheries in the U.S. (Ihde et al., 2011). While recreational fishing may indeed be a negligible source of fishing mortality for abundant stocks, it may endanger smaller fish stocks including those that experienced severe commercial overexploitation in the past.

As the large number of recreational fishermen prevents the enforcement of quota schemes while attempts to limit total fishing effort often receive bitter opposition (Walters and Cox, 1999), recreational fisheries usually have restrictions for single fishing days only, leaving total seasonal fishing effort and catch unregulated. It is the aim of this paper to analyze how angler preferences for fishing effort and catch affect recreational fisheries under such de-facto open access.

This study builds on three strands of the multi-disciplinary literature on recreational fisheries (Fenichel et al., 2012). A first strand of literature studies angler motivation (Fedler and Ditton, 1986, 1994; Arlinghaus, 2006) and shows that the motives to go fishing and hence fishing effort vary significantly between angler subpopulations. A second strand of literature are resource economics models that inter alia address the commercial-recreational allocation problem (McConnell and Sutinen, 1979; Bishop and Samples, 1980), reaction to stock enhancement activities (Anderson, 1983) and endogenous retention decisions (Anderson, 1993). A third strand of literature are studies mainly from fisheries science that apply parameterized effort response functions to specific recreational fisheries. The functional form of the effort response function is either chosen according to empirical model selection criteria, simply postulated, or deduced from ecological predator-prey theory. Most studies known to the author use linear (Scott R. Milliman et al., 1992; Johnson and Carpenter, 1994; Beard et al., 2003; Cox et al., 2002; Post et al., 2008) or sigmoidal effort responses (Schuhmann and Easley, 2000; Post et al., 2003; Carpenter et al., 1994). In the third strand of literature, most effort response functions lack a microeconomic foundation.

We are not aware of any work that modeled catch-fishing effort bundles with a constant elasticity of substitution (CES) utility function. While the existing literature (McConnell and Sutinen, 1979; Bishop and Samples, 1980; Anderson, 1983, 1993) uses more general utility functions, having a distinct parameter for catch orientation yields interesting results concerning its effect on angler-fish dynamics. Extending the canonical Gordon-Clark model from renewable resource economics (Gordon, 1954; Clark, 1990) by a CES utility function for catch-fishing effort bundles, we derive a micro-founded effort response function that could be used in applied fisheries science, while model predictions align with results from the angler motivation literature.

The remainder of this paper is structured as follows. The first section introduces the model on which we build our analysis. The second section analyzes how the preferences for catch and fishing effort affect open-access recreational fisheries. The third section studies the hypothetical case of socially optimal fisheries management to give a reference case for discussions about overfishing and collapses in recreational fisheries. The fourth section concludes.

1 The model

We consider a representative recreational fisherman with fishing effort f and catch h. Besides fishing, the agent derives utility from other activities that are summed up in the composite numeraire good z. The recreational fisherman's present value of utility at $t = 0$ is

$$\int_0^\infty \left(u\left(h,f\right)+z\right)e^{-\rho t}dt. \tag{1}$$

The integrand $u\left(h,f\right)+z$ is instantaneous utility at time $t \geq 0$, the parameter $\rho \geq 0$ is the discount rate for the numeraire and $u\left(h,f\right)$ captures the benefits derived from recreational fishing (McConnell and Sutinen, 1979; Bishop and Samples, 1980; Anderson, 1983, 1993). In order to study how changing the relative importance of catch affects recreational fisheries dynamics, we assume that angler preferences for catch and effort can be represented by a constant elasticity of substitution utility function,

$$u(h,f) = \frac{1}{\beta}\left(\alpha\, h^\theta + (1-\alpha)\, f^\theta\right)^{\frac{\beta}{\theta}}. \tag{2}$$

Using catch h rather than landings in (2) has the advantage that the reason why catch is important to the recreational fisherman need not be specified. This keeps the utility function applicable to all consumptive orientations (Fedler and Ditton, 1986) from catch-and-release fishing to retention of all fish caught. The parameter $\beta \in (0,1)$ denotes the elasticity of instantaneous utility with respect to fishing benefits. The parameter $\alpha \in [0,1]$ is the relative utility weight on catch within the fishing utility function. The limit case $\alpha = 0$ represents a recreational fisherman who only cares about the time spent fishing, i.e. for whom catch is an incidental neutral good. The second limit case $\alpha = 1$ represents a recreational fisherman who sees effort solely as a necessity to produce catch. In this case, the model aligns with the classical bio-economic model for commercial fishing in which fishing effort is a costly production input only and $u(h,f)\big|_{\alpha=1} = \frac{1}{\beta}\, h^{\beta}$ is consumer welfare from fish consumption.

The elasticity of substitution between catch and effort is $\frac{1}{1-\theta}$. We assume that catch and effort are imperfect complements ($\theta < 0$) including the limit case of Cobb-Douglas preferences ($\theta = 0$).[2] A high elasticity of substitution ($\theta > 0$) would allow recreational fishermen to substitute decreasing catches so easily by effort that extinct open-access stocks would be still fished, $\lim_{x\to 0} f > 0$ for $\theta > 0$. Compared to other recreationists such as canoeists, recreational fishermen need a positive probability to catch a fish in order to enjoy the effort of trying to do so, such that no fish should imply no fishing utility and hence no fishing.

The harvesting function that gives catch h as a function of stock size x and fishing effort f is a modified Schaefer equation

$$h = q\, x^{\varphi}\, f, \tag{3}$$

where $q \in (0, \bar{q}]$ is the catchability coefficient and $\bar{q}$ is the catchability coefficient of the most effective fishing technique. The artificially low catchability $q < \bar{q}$ in many recreational fisheries emerge from fishing ethics or ideas of sportsmanship. For example, fly-fishing for trout is less effective than bait-fishing with earthworms, but the latter is commonly regarded as not sportsmanlike. The parameter $\varphi \geq 0$ can be interpreted as a concentration profile parameter of the fish stock (Clark, 1990). Fish populations with varying densities in their habitat will first be fished at the high density areas. If a fish population does not show range contracting behavior towards these high density areas, the catch-per-unit-effort (CPUE),

$$\text{CPUE} = q\, x^{\varphi}, \tag{4}$$

will initially decline more rapidly than total abundance. This CPUE effect is also known as "hyperdepletion" (Walters and Martell, 2004; Harley et al., 2001) and can be modeled by $\varphi > 1$ (c.f. Figure 1). Some sedentary species might show this concentration profile. If a fish population does show range-contracting or schooling behavior, CPUE may remain constant while stock abundance declines (except for very low stock sizes). This case of "hyper-stability" (Walters and Martell, 2004; Harley et al., 2001) is modeled by $\varphi < 1$ (c.f. Figure 1). Hyperstability seems to be widespread in commercial fisheries (Harley et al., 2001). Many fish species targeted by recreational fishermen show range-contracting behavior around structure such as reefs, weed beds or wrecks. As the CPUE of anglers targeting such "hot spots" often remains constant while stocks decline, hyperstability should be common in recreational fisheries as well. The limiting case between hyperdepletion and hyperstability is $\varphi = 1$, for which CPUE would react proportionally to changes in total abundance (c.f. Figure 1). Diffusive fish species are thought to fall into this category.

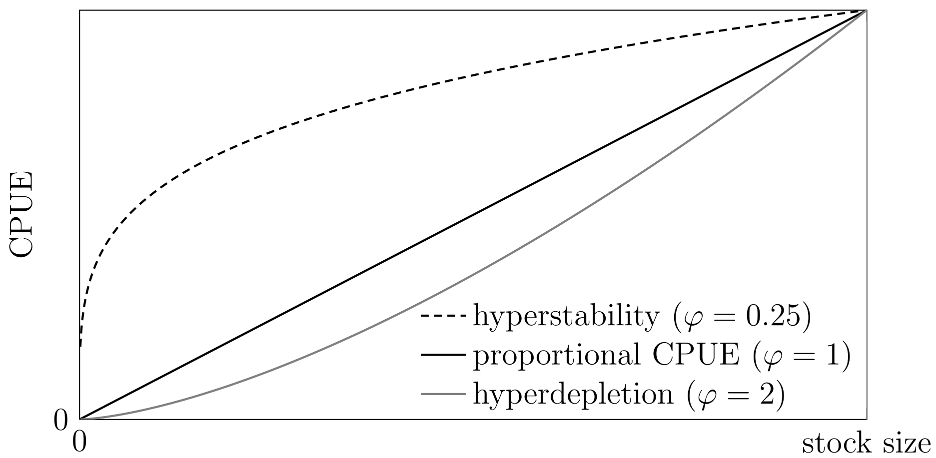

Figure 1: CPUE $q\,x^{\varphi}$ as a function of stock size x.

We assume that the total mortality rate for caught fish is $k \in (0, 1]$. Under pure catch-and-release fishing, k represents post-release mortality. The remaining fraction $1 - k$ are those fish that are caught, survive the release and recruit back into the stock. Net growth of the resource stock $\dot{x} \equiv dx/dt$ is

$$\dot{x} = g(x) - k\,h. \tag{5}$$

The biological growth function $g(x)$ is assumed to be strictly concave with

$g(0) = 0$ and $g(K) = 0$ for some $K > 0$. This implies that there is a unique stock size x_{MSY} with $0 < x_{\text{MSY}} < K$ that generates the maximum sustainable yield (MSY). We further use x_ρ to denote the stock size at which the marginal biological productivity equals the discount rate ρ, i.e. $g'(x_\rho) = \rho$. The stock size that generates maximum sustainable fishing effort (MSE) is denoted x_{MSE}. Note that as the maximization of steady-state fishing effort requires $g'(x_{\text{MSE}}) \geq 0$, it holds that $x_{\text{MSE}} \leq x_{\text{MSY}}$.

To close the model, we introduce a monetary budget constraint

$$m = w\,f + c\,\mathbf{I}_{f>0} + z \tag{6}$$

with exogenous income m and numeraire z. Recreational fishing induces marginal costs of effort w, e.g. foregone wages or monetary benefits of other leisure activities as opportunity costs, and effort-independent costs c. As there seems to be no distinct relationship between the catchability and the costs of a specific fishing technique in recreational fishing, we model the choice of the catchability coefficient without costs.

Travel expenses, license costs and expenses for fishing and boating equipment that are independent of the actual level of effort f (for example independent of the hours fished for a given fishing trip) are summarized in the costs c. In case these effort-independent costs c are not sunk, i.e. the angler decides if he wants to pay c in order to go fishing, the decision problem of the representative recreational fisherman becomes a two-step process. In a first step, the agent has to decide whether or not to fish, that is whether or not to pay c in order to go fishing (participation decision or decision about the extensive margin (Fenichel et al., 2012)). Given that he decides to become an active angler, a second step is to adjust fishing effort f to fishing quality (activity level decision or decision about the intensive margin (Fenichel et al., 2012)). The two-step decision problem is solved backwards in the following section.

2 Open-access recreational fishing

In a specific recreational fishery, the maximum number of participants that would become active at high stock abundance is typically unknown. For each active angler, gear restrictions, bag limits and minimum sizes usually regulate a fishing trip, but not the number of trips per season. Against this background, the term "open access" refers to a situation in which the aggregate fishing effort f directed at stock size x can be freely chosen.

Under open access, unilateral investments in the fish stock - by means of voluntary catch reductions - do not pay off. For this reason, recreational fishermen choose maximum catchability ($q = \bar{q}$) and ignore future stock dynamics (5) when choosing f. After inserting (2), the harvesting function (3) as well as the rearranged budget constraint (6), $z = m - c - w\,f$, instantaneous utility can be expressed as $\frac{1}{\beta}\left(\alpha\,(q\,x^{\varphi}\,f)^{\theta} + (1-\alpha)\,f^{\theta}\right)^{\frac{\beta}{\theta}} + m - w\,f - c$. The problem to maximize instantaneous utility under open access follows as

$$\max_{f}\ \frac{1}{\beta}\left(\alpha\,(\bar{q}\,x^{\varphi}\,f)^{\theta} + (1-\alpha)\,f^{\theta}\right)^{\frac{\beta}{\theta}} + m - w\,f - c. \tag{7}$$

From (7) follows the first-order condition that marginal utility of fishing effort equals its marginal costs,

$$\Big(\alpha\ (\bar{q}\,x^{\varphi})^{\theta} + 1 - \alpha\Big)^{\frac{\beta}{\theta}}\ f^{\beta-1} = w. \tag{8}$$

Solving (8) for f yields open-access fishing effort as

$$f^{o}(x) = w^{\frac{1}{\beta-1}}\ \left(\alpha\,(\bar{q}\,x^{\varphi})^{\theta} + 1 - \alpha\right)^{\frac{\beta}{\theta(1-\beta)}}. \tag{9}$$

Understood as a function of the stock size x, we refer to $f^{o}(x)$ as the open-access effort response function. There are many examples of other effort response functions in the literature (Scott R. Milliman et al., 1992; Johnson and Carpenter, 1994; Beard et al., 2003; Cox et al., 2002; Post et al., 2008; Schuhmann and Easley, 2000; Post et al., 2003; Carpenter et al., 1994). Many of these effort response functions are motivated by predator-prey theory, especially by their classification into linear Holling-Type I, concave Holling-Type

II and sigmoidal Holling Type III responses (Holling, 1959b,a) . As their function properties crucially affect fisheries dynamics, we briefly list the limit behavior and curvature properties of (9) in the following two propositions:

Proposition 1. *The elasticity of substitution between catch and effort within the fishing utility function determines the limit behavior of the effort response as follows:*

$$\lim_{x \to 0} f^o(x) = 0 \quad \text{for } \theta \leq 0 \quad \lim_{x \to +\infty} f^o(x) = \begin{cases} w^{\frac{1}{\beta-1}} (1-\alpha)^{\frac{\beta}{\theta(1-\beta)}} & \text{for } \theta < 0 \\ +\infty & \text{for } \theta = 0 \end{cases} \tag{10}$$

The limit behavior for $x \to +\infty$ shows that recreational fishing effort is bounded above if catch and fishing effort are complements.

Proposition 2. *2a) For $\theta < 0$, a concave effort response results for $\beta \leq \frac{1}{1+\varphi}$ and a sigmoidal effort response results for $\beta > \frac{1}{1+\varphi}$.*

2b) For $\theta = 0$, a concave effort response results for $\beta < \frac{1}{1+\alpha\varphi}$, a linear effort response results for $\beta = \frac{1}{1+\alpha\varphi}$ and a convex effort response results for $\beta > \frac{1}{1+\alpha\varphi}$.

For $\theta < 0$, the parameter β describing the marginal utility of the whole fishing experience and the parameter φ describing the concentration profile of the fish stock determine the curvature properties of the effort response. Both concave Holling-Type II and sigmoidal Holling-Type III responses are possible. For the limit case of Cobb-Douglas preferences ($\theta = 0$), the curvature properties also depend on the utility weight on catch.[3]

For a given elasticity β of overall utility with respect to fishing utility, a concave effort response function becomes the more likely the more the targeted fish stock tends to form aggregations, as both thresholds in Proposition 2a,b decrease in φ. In the Cobb-Douglas case, a concave effort response function also becomes the more likely the lower the utility weight on catch α. The parameter condition in Proposition 2b can also be interpreted as a threshold for the utility weight on catch, $\bar{\alpha}_0 = \frac{1-\beta}{\beta}\frac{1}{\varphi}$. Weak preferences for catch ($\alpha < \bar{\alpha}_0$) lead to concave effort response functions. All other parameters being equal, a low importance of catch for fishing utility (low α), a low importance of recreational fishing for overall utility (low β) and a fish stock that tends to form aggregations (low φ) increase the likeliness of concave effort response functions. This result is important for the discussion of stock collapses (cf. Proposition 4).

The utility weight on catch α does neither influence the limit behavior of the effort response nor its curvature properties in the general CES case. It does, however, have a twofold effect onto effort intensity and thus biomass removal by recreational fishermen:

Proposition 3. *The effect of increasing the utility weight on catch onto open-access fishing effort is stock-dependent. Denote by $\breve{x}$ the stock size at which catch-per-unit-effort equals one, $\breve{x} = \frac{1}{\bar{q}}^{\frac{1}{\varphi}}$. Then,*

$$\frac{\partial f^o(x)}{\partial \alpha} \begin{cases} > 0 & \textit{if } x > \breve{x} \\ = 0 & \textit{if } x = \breve{x} \\ < 0 & \textit{if } x < \breve{x} \end{cases} . \tag{11}$$

Within the expression for the marginal utility of fishing effort (cf. the LHS of (8)), the term $\alpha\ (\bar{q}\, x^{\varphi})^{\theta}$ represents the indirect link from fishing effort via catch to utility whereas $1 - \alpha$ represents the direct link from effort to utility. Increasing the weight α of the indirect link (i.e. a higher importance of catch) increases the marginal utility of fishing effort and hence open-access fishing effort only if the increase in the indirect link overcompensates the resulting decrease in the direct link, which is the case for a CPUE of $\bar{q}\, x^{\varphi} > 1$. Recreational fishermen becoming keener on catch thus only results in increased fishing effort if the fishery provides sufficiently high CPUE levels. The optimal response of recreational fishermen with a high weight on catch to fisheries with CPUE levels that do not meet their requirements is to spend more income on the numeraire. This interpretation is in line with the result that an increase in catchability $\bar{q}$ moves the threshold $\breve{x}$ to the left, as then recreational fishermen with a high weight on catch can meet their CPUE requirements at lower stock densities than before.

For low stocks, recreational fishermen becoming less keen on removing fish from the stock thus has the adverse effect of increased catches. Recreational fishermen who value the time spent fishing by itself so much that they keep fishing even at low stock densities with only incidental catches cause a higher fishing mortality for depleted stocks than more catch-orientated fishermen (who would extract more fish from the same stock at high stock densities). Given that most recreational fisheries are open access and tend to have low stock sizes, these theoretical findings are in line with the empirical finding of Fedler and Ditton (1986) that low-consumptive fishermen tend to fish more actively than those with a high catch orientation.

With the adverse effect at low stock sizes that lower preferences for catch lead to higher catches, one could ask if low utility weights on catch can cause unstable open-access equilibria below which stocks would be fished to local extinction. The emergence of such unstable open-access equilibria can most easily be illustrated for the limit case of Cobb-Douglas preferences:

Proposition 4. *Define* $\bar{\alpha}_1 = \frac{1-\beta}{\beta}\,\frac{1-\varphi}{\varphi}$*. For* $\theta = 0$*, utility weights on catch* $\alpha < \bar{\alpha}_1$ *enable unstable open-access equilibria. Stock sizes below such equilibria are fished to local extinction.*

Biomass removal by recreational fishing equals $l^o(x) = k\,\bar{q}\,x^{\varphi}\,f^o(x)$ and steady-state stocks are defined by $g(x) = l^o(x)$, cf. the stable equilibrium x_s in Figure 1. Strictly concave biomass removal functions $l^o(x)$ with $\alpha < \bar{\alpha}_1$ can result in a second unstable equilibrium x_u at low stock size, cf. Figure 1. If the stock is exogenously reduced below such an equilibrium x_u (via diseases, shifts in the ecosystem or commercial fishing), recreational fishermen with $\alpha < \bar{\alpha}_1$ value the time outdoors so much that they maintain a high fishing pressure even for low incidental catches until the stock fully collapses. As the strict concavity condition for the open-access effort response $f^o(x)$ is $\alpha < \bar{\alpha}_0$ with $\bar{\alpha}_0 > \bar{\alpha}_1$, a strictly concave effort response is a necessary condition for an unstable open-access equilibrium.

Note that a positive range $(0, \bar{\alpha}_1)$ for α-values that yield strictly concave biomass removal functions with their possibility of full stock collapses only

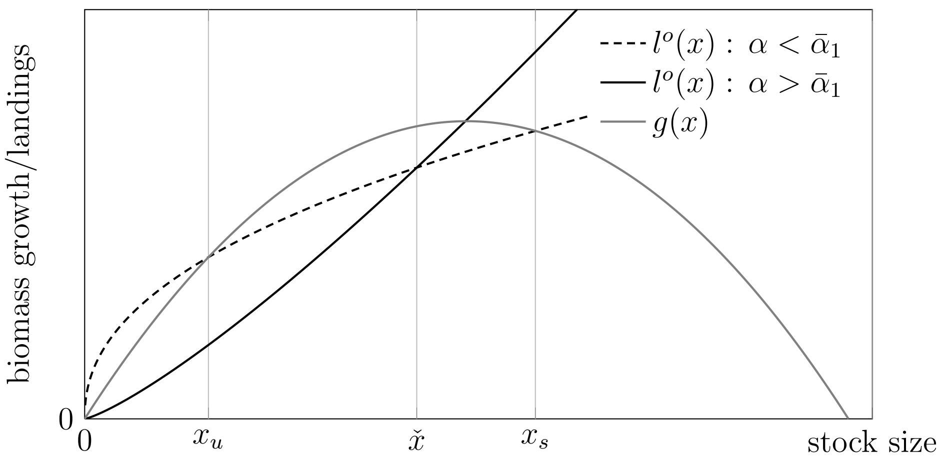

Figure 2: Fisheries dynamics with low (dashed) and high (solid) importance of catch.

exists for $\varphi < 1$. This is intuitive as only range-contracting or school forming species can be thought to be effectively fished down to stock collapse. Range-contracting or schooling behavior of game fish can be understood as a non-convexity in the ecosystem (Dasgupta and Mäler, 2003; Carpenter and Cottingham, 1997). If a perturbation has decreased the stock below x_u (c.f. Figure 2), management interventions are needed to prevent the system to flip from $x_s > 0$ to $x = 0$. This yields an important insight for the discussion about the impact of recreational fishing on marine fish stocks (Coleman et al., 2004; Nussman, 2005; Ihde et al., 2011): While recreational fishing may indeed be a negligible source of fishing mortality at high stock sizes, commercial overexploitation can give recreational fishing the potential to continue overexploitation up to stock collapse.

2.0.1 Participation decision

If the effort-independent costs c are sunk or zero, the effort response function (9) predicts positive effort levels for all stock sizes. In some cases, a continuous effort response can be a realistic model, in other cases it must be seen as an approximation to an effort response with a certain turning-on stock size $x_{\min}$, as we shall argue in the following.

If c is quasi-fixed, becoming an active recreational fisherman must yield non-negative net benefits (as otherwise utility from not fishing would be higher):

$$\frac{1}{\beta}\left(\alpha(\bar{q}\,x^{\varphi}\;(f^{o}(x))^{\theta}+(1-\alpha)\,(f^{o}(x))^{\theta}\right)^{\frac{\beta}{\theta}}-w\,f^{o}(x)-c\geq 0 \tag{12}$$

The participation condition (12) is fulfilled for open-access effort levels above

$$f_{\min}=\frac{\beta}{1-\beta}\frac{c}{w}. \tag{13}$$

This lower bound on open-access recreational fishing effort ensures that there is an open-access minimum stock or escapement

$$x_{\min}=\left(\frac{1}{\alpha}\left(\frac{\beta}{1-\beta}\,c\right)^{\frac{\theta(1-\beta)}{\beta}}w^{\theta}-\frac{1-\alpha}{\alpha}\right)^{\frac{1}{\theta\,\varphi}}\;\bar{x}. \tag{14}$$

Increasing the marginal costs of effort w or the quasi-fixed costs c (e.g. the price of a season license) increases the open-access minimum stock, $\frac{\partial x_{\min}}{\partial w}>0$, $\frac{\partial x_{\min}}{\partial c}>0$, while the effects on f_{min} differ, $\frac{\partial f_{\min}}{\partial w}<0$, $\frac{\partial f_{\min}}{\partial c}>0$. While varying c affects the point $(x_{\min}, f_{\min})$, varying w affects both the point $(x_{\min}, f_{\min})$ and the effort response $f^{o}(x)$ itself.

As a result, it is possible to implement a certain $x_{\min}$ stock size with different levels of $f_{\min}$ while the corresponding choice of w, c does not affect angler welfare at the escapement stock size. This might be interesting if open-access recreational fishing has more externalities than the stock externality, for example because angling damages habitat or disturbs endangered species. On the other hand, one might want to maximize f_{min} for given escapement $x_{\min}$ if the local economy depends on recreational fishing.

Advances in gear technology or angling skill increase the maximum catchability coefficient $\bar{q}$. This decreases the open-access minimum stock while the minimum effort level $f_{\min}$ remains unaffected, $\frac{\partial x_{\min}}{\partial \bar{q}}<0$, $\frac{\partial f_{\min}}{\partial \bar{q}}=0$. As CPUE (and hence catch) at the open-access minimum stock is not affected as well, $\frac{\partial \bar{q}\,x_{\min}^{\varphi}}{\partial \bar{q}}=0$, technical progress in recreational fisheries may cause a decrease of the open-access minimum stock that is masked by unaltered angler behavior and constant CPUE. Stock assessments in open-access recreational fisheries might thus be seriously misled by constant effort and catch levels.

3 A note on socially optimal recreational fishing

Whenever a fish stock is scarce, the opportunity costs of removing a fish from the stock (the marginal user costs) drive a wedge between open-access and socially optimal recreational fishing. As lack of information about stock sizes and angler characteristics prevents the calculation of individually optimal user costs, it seems unrealistic that first-best recreational fishing could be defined, let alone be enforced, in real-world recreational fisheries with their large number of participants. However, the notion of collapse and overfishing in recreational fisheries (Post et al., 2002; Coleman et al., 2004) raises the question about the socially optimal stock size that should function as the reference value for such discussions.

To calculate such a reference case, we use a hypothetical sole owner scenario, e.g. a private fishing club owning the exclusive and permanent right to manage a specific fish stock. In contrast to the open-access situation, the deliberate choice of $q < \bar{q}$ may pay off under sole ownership as it allows to enjoy increased effort levels in steady state. Social norms of sportsmanship in such a group of use rights-holders, i.e. to fly fish for trout instead of laying out earthworms, may secure the choice of $q < \bar{q}$ in real-world fisheries. The optimization problem of a private fishing club adopts a modified version of the objective function (7). In contrast to open-access, a private owner may choose $q < \bar{q}$ to enjoy more effort for a given stock size. Taking into account the stock dynamics (5) as well, the optimization problem follows as

$$\begin{aligned} &\max_{f,q,x} \int_0^\infty \left(\frac{1}{\beta} \left(\alpha \left(q\, x^\varphi\, f \right)^\theta + (1-\alpha)\, f^\theta \right)^{\frac{\beta}{\theta}} + m - c - w\, f \right) e^{-\rho t} \\ &\text{s.t. } \dot{x} = g(x) - k\, q\, x^\varphi\, f, \end{aligned} \tag{15}$$

where (6), (3) and (2) have been inserted into (1) to get the integrand in

(15). Evaluating changes in the stock x at its the current-value shadow price μ, the current-value Hamiltonian for this problem follows as

$$\max_{f,q,x} H = \frac{1}{\beta}\left(\alpha\,(q\,x^{\varphi}\,f)^{\theta} + (1-\alpha)\,f^{\theta}\right)^{\frac{\beta}{\theta}} + m - c - w\,f + \mu\,\left(g(x) - k\,q\,x^{\varphi}\,f\right). \tag{16}$$

The first-order conditions are

$$H_f = \left(\alpha\,\left(q\,x^{\varphi}\right)^{\theta} + 1 - \alpha\right)^{\frac{\beta}{\theta}}\,f^{\beta-1} - w - \mu\,k\,q\,x^{\varphi} = 0 \tag{17a}$$

$$H_q = \frac{1}{q}\,\left(\alpha\,\left(q\,x^{\varphi}\right)^{\theta} + 1 - \alpha\right)^{\frac{\beta}{\theta}-1}\,\alpha\,\left(q\,x^{\varphi}\right)^{\theta}\,f^{\beta} - \mu\,k\,x^{\varphi}\,f = 0 \tag{17b}$$

$$H_x = \frac{\varphi}{x}\,\left(\alpha\,\left(q\,x^{\varphi}\right)^{\theta} + 1 - \alpha\right)^{\frac{\beta}{\theta}-1}\,\alpha\,\left(q\,x^{\varphi}\right)^{\theta}\,f^{\beta} + \mu\,\left(g'(x) - \frac{\varphi}{x}\,k\,q\,x^{\varphi}\,f\right) = \mu\,\rho - \dot{\mu} \tag{17c}$$

together with (5). Inserting (17b) into (17a) yields

$$\left(\alpha\,\left(q\,x^{\varphi}\right)^{\theta} + 1 - \alpha\right)^{\frac{\beta}{\theta}}\,f^{\beta-1} - w - \frac{\alpha}{1-\alpha}\,w\,\left(q\,x^{\varphi}\right)^{\theta} = 0. \tag{18}$$

A marginal increase in f increases catch by $\left(q\,x^{\varphi}\right)^{\theta}$. This marginal catch is evaluated by its shadow price $\frac{\alpha}{1-\alpha}\,w$. The marginal user costs of the stock, $\frac{\alpha}{1-\alpha}\,w\,\left(q\,x^{\varphi}\right)^{\theta}$, differentiate (18) from the first-order condition (8) under open access. Because the cost difference depends positively on α, lowering the importance of catch brings the socially optimal fishing effort closer to open-access levels.

From (17b) and (17c) it furthermore follows that $\dot{\mu} = (\rho - g'(x))\,\mu$, such that the optimal steady-state stock size is

$$x^{*} = x_{\rho}. \tag{19}$$

Because q is an input with zero marginal costs, increasing it enables the recreational fisherman to decrease unit harvesting costs $\frac{w}{q\,x^{\varphi}}$. Going fishing with $q < \bar{q}$ can thus be interpreted as the deliberate choice to pay $w\,f^{*}$ while lower unit harvesting costs with $q = \bar{q}$ are possible. If q is unbounded, costless fishing would be possible. This makes (19) intuitive, as $x^* = x_\rho$ is the standard result in commercial fisheries models without harvesting costs (Clark, 1990).

In steady state, an implicit equation for f^* deduced from from (17a) and (17b) determines the share of f^* in $f^*\, q^*$,

$$f^* = \left(\frac{w}{1-\alpha}\right)^{\frac{1}{\beta-1}} \left(\alpha \left(\frac{g(x^*)}{k\, f^*}\right)^{\theta} + 1 - \alpha\right)^{\frac{\beta-\theta}{\theta(1-\beta)}}. \tag{20}$$

The effect of the importance of catch α onto f^* depends on the CPUE in the optimally managed fishery,

$$\frac{\partial f^*}{\partial \alpha} \begin{cases} > 0 & \text{if } q^*\, (x^*)^{\varphi} > \left(\frac{(1-\alpha)\,\beta}{(1-\alpha)\,\beta-\theta}\right)^{\frac{1}{\theta}} \\ = 0 & \text{if } q^*\, (x^*)^{\varphi} = \left(\frac{(1-\alpha)\,\beta}{(1-\alpha)\,\beta-\theta}\right)^{\frac{1}{\theta}} \\ < 0 & \text{if } q^*\, (x^*)^{\varphi} < \left(\frac{(1-\alpha)\,\beta}{(1-\alpha)\,\beta-\theta}\right)^{\frac{1}{\theta}} \end{cases} \tag{21}$$

Recreational fisherman becoming keener on catching fish thus prompts them to increase f only if CPUE is sufficiently high. This is related to the result from the open-access case in which the CPUE threshold is $q\, x^{\varphi} = 1$, cf. Proposition 3.

Comparison of the first-order conditions under first-best management (18) and open access (8) might lead to the conclusion that both align in the limit case of pure effort orientation, $\alpha = 0$. However, the stock can become scarce in this case as well, in which the socially optimal steady-state stock size x^* is implicitly given by

$$g'(x^*) = \rho + \varphi\, \frac{g(x^*)}{x^*}. \tag{22}$$

If catches do not matter for the representative angler, scarcity of the stock can still arise from the fact that stock decreases impair steady-state fishing effort. Following this explanation, intuition might suggest that the utility of an effort-enjoying recreational fisherman is maximized if he enjoys maximum sustainable effort in steady state, such that $x^* = x_{\mathrm{MSE}}$ (the stock size that generates maximum fishing effort in steady state). Comparing (22) with the condition for x_{MSE},

$$g'(x_{\mathrm{MSE}}) = \varphi \, \frac{g(x_{\mathrm{MSE}})}{x_{\mathrm{MSE}}}, \tag{23}$$

shows that this only holds for $\rho = 0$. For $\rho > 0$, the recreational fisherman deviates from x_{MSE} as this allows him to increase his fishing effort during the transition towards some lower $x^* < x_{\mathrm{MSE}}$. Note that as $x^* \leq x_{\mathrm{MSE}} < x_{\mathrm{MSY}}$, the social optimum in the limit case of pure effort orientation may imply very low stock levels. For example, the Schaefer model with $\varphi = 1$ implies $x_{\mathrm{MSE}} = 0$, such that fishing to local extinction would be socially optimal.

In case the catchability is fixed in a specific recreational fishery, the classical Schaefer model allows for a second interesting result on optimal local extinction in recreational fisheries. With the Schaefer harvesting equation, $w = 0$ and the logistic growth function $g(x) = rx\left(1 - \frac{x}{K}\right)$, the socially optimal stock size follows as

$$x^* = \frac{\alpha\, r - \rho}{(1+\alpha)\, r} K. \tag{24}$$

In the standard commercial fisheries model without harvesting costs, extinction would only be optimal if the discount rate exceeds the maximum growth rate of the stock, $\rho > r$ (Clark, 1990). Here, with the direct benefits of the harvesting process incorporated, extinction already becomes optimal for $\rho > \alpha\, r$. Fish stocks that are targeted by recreational fishermen thus have to meet higher intrinsic growth rates to not face optimal extinction than those targeted by commercial fishing.

4 Conclusion

Recreational fishermen value fishing effort directly and many commercial fishermen enjoy non-monetary benefits from fishing as well. If welfare is generated not only by harvest but also by harvesting effort, this additional "effort effect" implies that even local extinction may be socially optimal. Notions of collapse in recreational fisheries might thus not involve overfishing in economic terms. Fierce opposition to effort limitations programs by recreational fishermen (Walters and Cox, 1999) may thus simply reflect that anglers favor the "high effort - low catch" over the "low effort - high catch" bundle in their recreational fishery.

Although socially optimal fisheries management might entail very low stock sizes, it will usually differ from open access in most recreational fisheries. For angler-stock dynamics under open access, we have shown that a lower importance of catch decreases fishing effort at high stock sizes while it leads to more fishing intensity at low stock sizes. Although this effect also holds under first-best management with endogenous catchability, it may cause depleted recreational fisheries to collapse. In mixed commercial- recreational fisheries, sequential overexploitation by the two types of fisheries might threaten fish stocks: At high stock sizes, recreational fishing might be a negligible source of fishing mortality, while profitable commercial fishing reduces the stock. Once the stock is depleted, commercial fishing might cease, but recreational fishing, being less dependent on catches due to the effort effect, may continue overexploitation up to stock collapse. Technical progress may mask such collapses in recreational fisheries as it enables unaltered effort levels and constant catches during stock declines.

Notes

[1]This may hold for some commercial fishermen as well (Anderson, 1980).

[2]Excluding the case $\theta > 0$ shortens Propositions 1 and 2, but no result in this paper depends on the assumption $\theta \leq 0$.

[3]The result that the curvature properties in the Cobb-Douglas case depend on an additional parameter as compared to the general CES case are analogous to the case of a

non-renewable resource being essential or inessential for constant consumption (Dasgupta and Heal, 1979).

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

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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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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

[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.

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 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

[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.

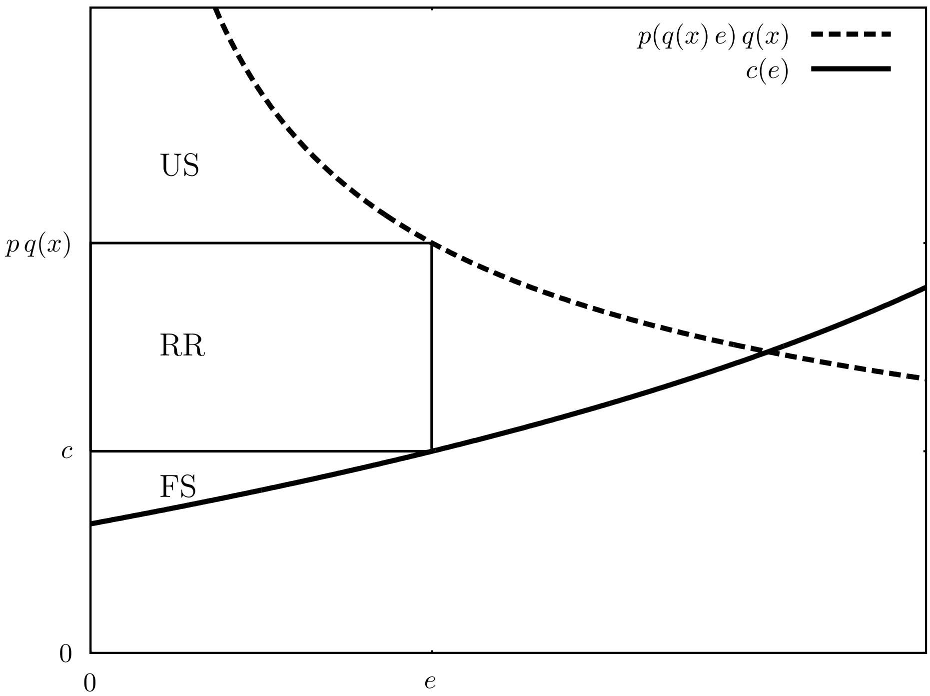

Figure 1: Instantaneous user surplus (US), resource rent (RR) and factor surplus (FS). Stock dynamics would shift the marginal utility of effort function $p(q(x)\,e)\,q(x)$. With adjusted effort e, this would affect all rent categories.

increasing, $c'(\cdot) > 0$. Thus, there is a factor surplus

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

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 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,

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

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 $x_0 = x_{\text{OA}}$ 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

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

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

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

and the change in the present value of factor surplus is

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

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 $\Delta\mathrm{US}(x_0, \{h_{Pt}\})$ and $\Delta\mathrm{FS}(x_0, \{e_{Pt}\})$ 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 $h_{\text{OA}}(x)$ to denote the open-access harvest rate at a given stock size x, and $x_{\text{OA}} \geq 0$ 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:*

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

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,*

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

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,*

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

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

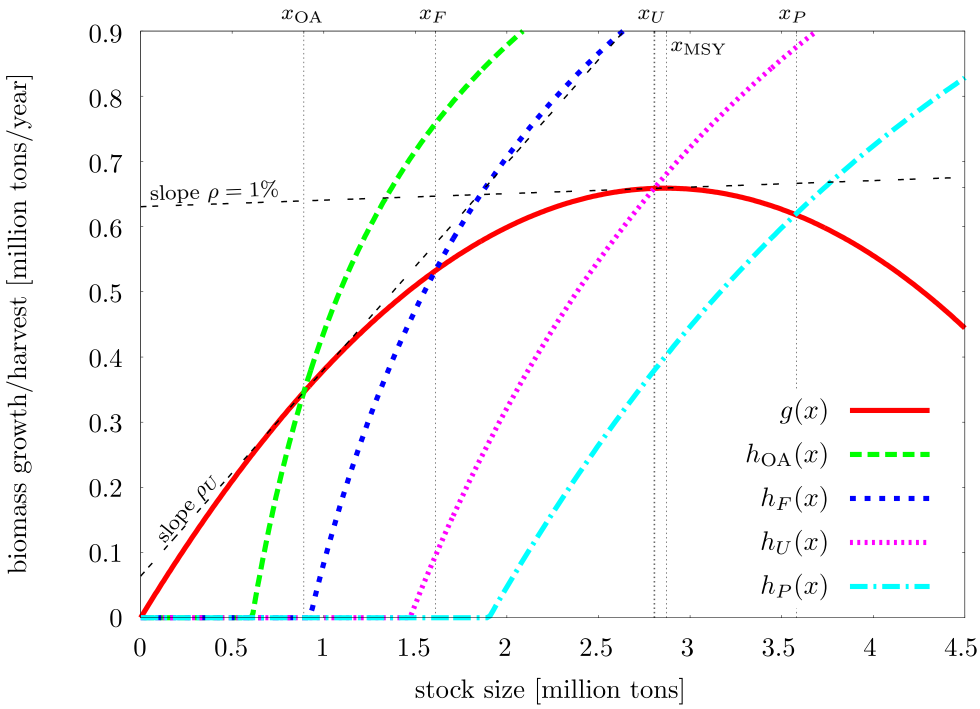

Figure 2: Phase diagram illustrating optimal harvest rates for the different interest groups as functions of stock sizes ($h_F(x)$, $h_U(x)$, $h_P(x)$); and open-access harvest $h_{\rm OA}(x)$, as well as steady-states, using the example of the Northeast Arctic cod fishery (see Section 4).

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.

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 $h \geq 0$, $\mu_P \geq 0$, 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 $e \geq 0$, $\mu_F \geq 0$, 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 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).

[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 $\Delta\text{FS}(x^*, \{e_t^*\}) = 0$.

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

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

4b) 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 $x_0 = x_{\mathrm{OA}}$, Proposition 4 shows that serious biological overfishing under open access ($x_{\mathrm{OA}} < \overline{x}_U$ resp. $x_{\mathrm{OA}} < \overline{x}_F$), 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). 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,

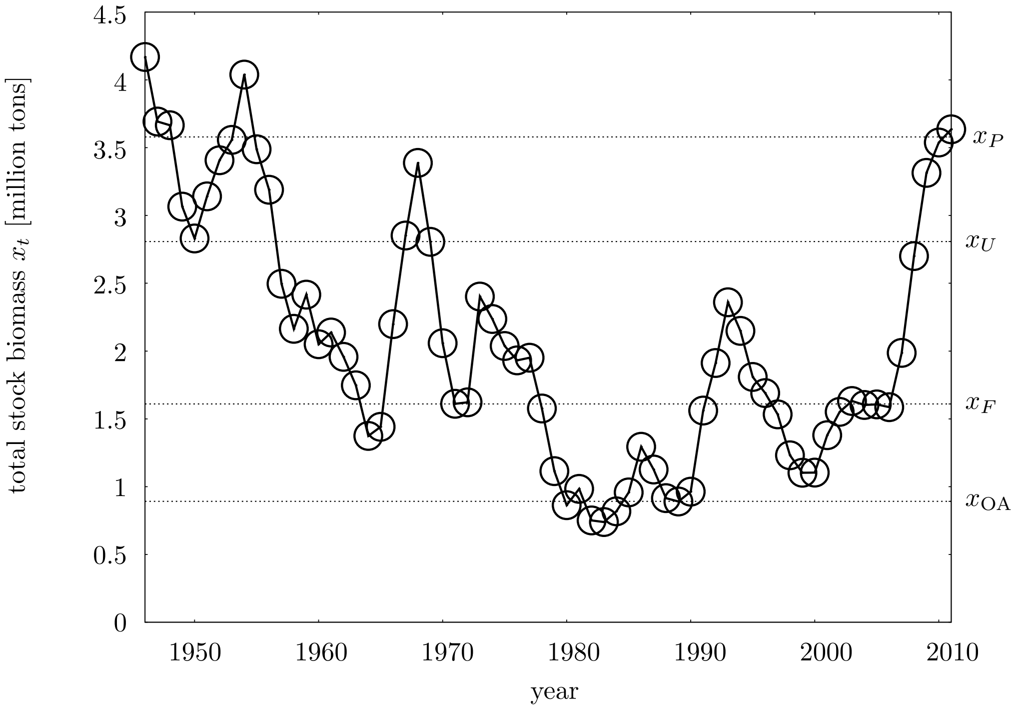

Figure 3: The development of the Northeast Arctic cod stock in 1946–2011 according to ICES (2012) stock assessment.

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 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

[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).

is $x_{\mathrm{MSY}} = 2.87$ 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 $h_{\mathrm{OA}}(x) = \max\big\{(a - c_0\, x^{-\chi})/(b + c_1\, x^{-2\chi}), 0\big\}$, as shown in the phase diagram in Figure 2. The resulting open-access steady-state stock size is $x_{\mathrm{OA}} = 0.89$ 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 harvesting 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

[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%.

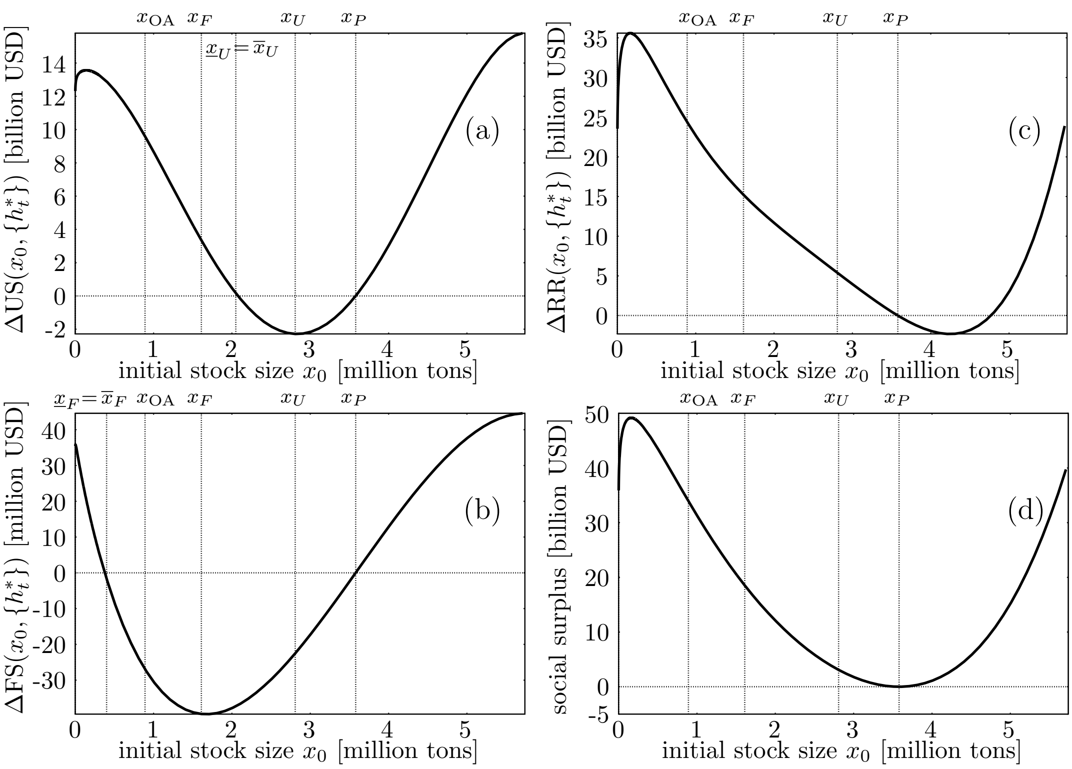

Figure 4: Differences in present values of (a) user surplus, (b) factor surplus, (c) resource rent, and (d) social surplus, between the options of maintaining a steady state at x_0 or efficient management of the Northeast Artic cod fishery.

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 $x_{\text{MSY}} = 2.87$ 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 overfished 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 $\overline{\rho}_F = 0.29$.

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 $\Delta\mathrm{RR}(x_0, \{h_t^*, e_t^*\})$ 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 $\Delta\mathrm{RR}(x_{2008}, \{h_t^*, e_t^*\}) =$

6.208 billion USD, but this comes at a loss in surplus for factor owners of $\Delta\text{FS}(x_{2008}, \{e_t^*\}) = -0.025$ 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),

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

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

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

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

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

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

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

Using this in (13b), we obtain

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

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 $x^* > x_{\text{MSY}}$ 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 $\Delta\text{US}(x_0, \{h_t^*\}) < 0$ for all $x_0 \in [x_u, x^*)$. With the same reasoning as in the first case we conclude that $\Delta\text{US}(x_0, \{h_t^*\}) < 0$. 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,

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

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

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

This value decreases with ρ'', because

$$\frac{d\mathrm{US}^*_{\rho''}(x_0)}{d\rho''} = \int\limits_0^\infty (1-\rho''\,t)\,\mathrm{US}(h^*_t(x_0))\,e^{-\rho''\,t}\,dt$$

$$= \int\limits_0^{1/\rho''} \underbrace{(1-\rho''\,t)}_{>0} \underbrace{\mathrm{US}(h^*_t(x_0))}_{<\mathrm{US}(h^*_{1/\rho''}(x_0))\text{ for } t<1/\rho''} e^{-\rho''\,t}\,dt$$

$$+ \int\limits_{1/\rho''}^\infty \underbrace{(1-\rho''\,t)}_{<0} \underbrace{\mathrm{US}(h^*_t(x_0))}_{>\mathrm{US}(h^*_{1/\rho''}(x_0))\text{ for } t>1/\rho''} e^{-\rho''\,t}\,dt$$

$$< \mathrm{US}(h^*_{1/\rho''}(x_0)) \int\limits_0^\infty (1-\rho''\,t)\,e^{-\rho''\,t}\,dt = 0,$$

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 $\Delta\mathrm{US}(\hat{x}_U, \{h^*_t\})$ is negative (probably by a large amount). By continuity of $\Delta\mathrm{US}(\hat{x}_U, \{h^*_t\})$, we conclude that it exists an $\underline{x}_U$ with $0 \leq \underline{x}_U < \hat{x}_U$ such that $\Delta\mathrm{US}(x_0, \{h^*_t\}) < 0$ 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

$$\Delta\mathrm{FS}(x_0, \{e^*_t\}) < \frac{1}{\rho}\,\mathrm{FS}(\bar{e}(x^*)) - \frac{1}{\rho}\,\mathrm{FS}(\bar{e}(x_0)) \qquad (30)$$

for all $x_0 < x^*$. We have that $\Delta\mathrm{FS}(x_0, \{e^*_t\}) < 0$ 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 $\Delta\mathrm{FS}(x_0, \{e^*_t\}) < 0$ 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'':

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

$$\int_0^\infty (1-\rho''\,t)\,\mathrm{FS}(e^*_t(x_0)/q(x_0))\,e^{-\rho''\,t}\,dt$$

$$= \int_0^{1/\rho''} \underbrace{(1-\rho''\,t)}_{>0} \underbrace{\mathrm{FS}(e^*_t(x_0)/q(x_0))}_{<\mathrm{FS}(e^*_{1/\rho''}(x_0)/q(x_0))\text{ for }t<1/\rho''} e^{-\rho''\,t}\,dt$$

$$+ \int_0^{1/\rho''} \underbrace{(1-\rho''\,t)}_{<0} \underbrace{\mathrm{FS}(e^*_t(x_0)/q(x_0))}_{>\mathrm{FS}(e^*_{1/\rho''}(x_0)/q(x_0))\text{ for }t>1/\rho''} e^{-\rho''\,t}\,dt$$

$$< \mathrm{FS}(e^*_{1/\rho''}(x_0)/q(x_0)) \int_0^\infty (1-\rho''\,t)\,e^{-\rho''\,t}\,dt = 0.$$

We have shown before that $\mathrm{fs}^*_{\rho'}(x_0) < \mathrm{FS}(\bar{e}(x_0))$ for the discount rate $\rho' < \rho$ where $x_F(\rho') = x_0$. As $\mathrm{FS}(\bar{e}(x_0))$ is independent of ρ'', and $\mathrm{fs}^*_{\rho''}(x_0)$ monotonically decreases with ρ'', the inequality $\mathrm{fs}^*_\rho(x_0) < \mathrm{FS}(\bar{e}(x_0))$ 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 $\Delta\mathrm{FS}(x_0, \{e^*_t\}) < 0$ 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 $\Delta\mathrm{FS}(\hat{x}_F, \{e^*_t\})$ is negative (probably by a large amount). By continuity of $\Delta\mathrm{FS}(x_0, \{e^*_t\})$, we conclude that it exists an $\underline{x}_F$ with $0 \leq \underline{x}_F < \hat{x}_F$ such that $\Delta\mathrm{US}(x_0, \{h^*_t\}) < 0$ 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 $\Delta\mathrm{US}(x_0, \{h^*_t\}) > 0 \quad \forall\, x_0 \in (0, \overline{x}_U)$. By continuity of (4b), this also holds for some positive discount rates $\rho \leq \overline{\rho}_U$.

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

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New trade in renewable resources and consumer preferences for diversity☆

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Abstract

The literature on trade in renewable resources implicitly assumes that the traded resources are perfect substitutes. We model trade in renewable resources as stipulated not only by autarky price differences, but also by consumers' love of variety. We show that the love-of-variety effect enables welfare gains from trade even if total consumption decreases. Total consumption may decrease because the love of variety weakens the link between resource scarcity and demand. If consumers are willing to pay the rising prices for harvests from increasingly depleted stocks, trade liberalization may end in stock collapse. The love of variety may thus threaten variety.

Keywords: trade, environment, renewable resources, open access, love of variety
JEL: Q21, Q22, Q23, Q27, F18

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The question if trade liberalization threatens or benefits renewable resources and their users is at the center of a lively scientific debate (Bulte and Barbier, 2005; Fischer, 2010). Whilst country differences that stipulate trade and feedbacks to other economic sectors are modeled in diverse ways, all models for trade in renewable resources known to the authors implicitly assume that the traded resources are perfect substitutes (Bulte and Barbier, 2005; Fischer, 2010).

At the core of these models, trade liberalization balances two former autarky prices for resource harvests. If the countries have comparable management regimes and harvesting costs, the prices for resource harvest reflect the biological abundance and economic scarcity of the underlying resources. By aligning prices, trade liberalization works in the direction of balanced stock sizes. Modeling trade effects under the assumption that the resources are perfect substitutes might thus underestimate the risk of severe overexploitation and stock collapse. It is the aim of this paper to study the consequences of departing from this assumption. The term 'New trade' is used in the sense that we look at consumer preferences for diversity. Starting from the reference case of perfect substitutes, we show that increasing the love for diversity under free trade might lead to increasingly skewed exploitation patterns up to stock collapse under open access. At the same time, increasing the love for variety increases the potential welfare gains from trade liberalization that may offset the price-quantity welfare effects known from the literature.

The literature on trade in renewable resources[1] can be classified according to the country differences that stipulate trade:

In North-South models differences in resource management create trade between two otherwise identical countries. Chichilnisky (1994) shows that the country with weaker resource management appears to have an "apparent comparative advantage" as it ignores the opportunity costs of current harvesting. As a result, South exports to the country with better resource management (the North). North increases its consumption by imports while South loses. Brander and Taylor (1997b) show that South's apparent advantage may become an apparent disadvantage if its harvesting sector has a

[1]See Bulte and Barbier (2005) for a comprehensive review of the literature.

backward-bending supply curve that enables severe over-harvesting at high autarky prices. In this case, South gains from trade as it becomes a resource importer. Karp et al. (2001) differentiate North and South more smoothly by varying the number of price-taking harvesters. Classified according to the intrinsic growth rate of the stocks, Karp et al. (2001) describe scenarios in which North drags down South (both lose) or North pulls up South (both gain). Copeland and Taylor (2009) assume that management efficiency is endogenously determined by resource prices.

A second class of models assumes that both countries have open-access regimes but differ in factor proportions: The home country is labor abundant while the foreign country is resource abundant. Brander and Taylor (1997a, 1998) show that a move from autarky to trade benefits the resource importing home country as trade eases the local open-access problem and releases labor for the manufactures sector. The foreign country can only gain from trade if it is able to specialize in resource harvesting at very high resource prices. Hannesson (2000) shows that a diversified resource exporter may also gain from trade if the manufactures sector has decreasing returns to scale. In this case, the benefits of importing manufactures may offset the resource exporter's deteriorating open-access problem. Emami and Johnston (2000) show that if one of two Brander and Taylor (1997a) countries improves its resource management from open access to price-taking sole ownership, both countries gain if world price drops. If world price rises, the country with improved management gains while the other loses. If demand for resources is higher in the country that improves its resource management, that country may lose as well if consumer welfare losses outweigh the newly collected resource rent.

The welfare results in the trade literature are diverse, which is in part due to differences in the general equilibrium framework of these models.[2] For this reason, we concentrate on resource economics in a partial equilibrium setting and disregard spillovers to other economic sectors. In a related work, Quaas and Requate (2013) study how consumer preferences for di-

[2] Cf. for example the contrasting results of Brander and Taylor (1998) and Hannesson (2000).

versity affect multi-species fishery management. The paper at hand can be interpreted as an extension of Quaas and Requate (2013) that focuses on trade-induced welfare effects in a two-country framework.

Trade liberalization can have two effects on renewable resources: First, opening up for trade increases the potential demand from domestic consumers to world demand. A second effect is that trade liberalization may enable demand to shift from depleted and hence expensive resources to more abundant and hence cheaper substitutes. The first effect is always present. While the literature assumes that the second effect works perfectly as well, we show that decreasing the elasticity of substitution weakens the demand reduction in reaction to increasing resource scarcity. In the limit, this may lead to a stock collapse or the sequential collapse of both stocks.

The rest of the paper is organized as follows. Section 1 presents the model. In Section 2, we study the move from autarky to free trade in a two country - two resources model. As trade liberalization always entails a positive diversity effect if there is only one resource under autarky, a model extension in Section 3 analyzes trade between a species-rich and a species-poor country. Section 4 concludes.

1 The model

We consider two countries, each with a representative consumer and a renewable natural resource that is harvested under conditions of open access. We will compare two scenarios: In the first scenario, each resource is consumed only domestically. We refer to this situation as the 'autarky' case, although there may be trade between the countries in goods other than the natural resources. We use a superscript a to the variables to indicate this scenario. In the other scenario, the countries freely trade harvests of the two resources and all other goods without any costs. We refer this scenario as the 'trade' scenario, and indicate this scenario by a superscript t to the variables.

The two countries may differ from each other in two respects: (i) The consumers may value resource consumption to a different degree, and (ii) the biological productivity of the two resources may differ. To allow for a closed form solution, we assume symmetry between the two countries in all other parts of the model.

The representative household in country $i = 1, 2$ has quasi-linear preferences over the consumption of a numeraire commodity (y_i) and consumption of natural resources (v_i) that are described by the utility function (Quaas and Requate, 2013)

$$u(v_i, y_i) = y_i + \gamma_i \ln v_i. \tag{1}$$

Due to unit elasticity of demand for resource products, the factor γ_i coincides with the expenditures on resources in country i. The sub-utility from resource consumption is described by a Dixit-Stiglitz utility function (Dixit and Stiglitz, 1977)

$$v_i = \left(\sum_{j \in \mathbb{S}_i} q_{ji}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \tag{2}$$

where q_{ji} is harvest produced in country j and consumed by the household in country i, and $\mathbb{S}_i$ is the set of species available for consumption in country i. Under autarky, this is equal to the species richness available domestically; under free trade, this is the number of all resource species harvested globally. The parameter $\sigma \geq 1$ measures the elasticity of substitution between different resources. The lower the value of σ, the stronger are the representative household's preferences for diversity. The budget constraint is

$$m_i = y_i + \sum_{j \in \mathbb{S}_i} p_j \, q_{ji} \tag{3}$$

with exogenous income m_i. We assume that $m_i > \gamma_i$ to assure an interior solution for the demand for natural resources.

In country $i = 1, 2$, the stock x_i grows according to the logistic function

$$g_i(x_i) = r_i \, x_i \, (1 - x_i) \tag{4}$$

with intrinsic growth rate r_i and carrying capacity normalized to one.

The representative resource harvester in country i has profits

$$\Pi_i = p_i\, h_i - \frac{c}{x_i}\, h_i = \left(p_i - \frac{c}{x_i}\right)\, h_i. \tag{5}$$

In (5) p_i denotes the price of harvest produced in country i. Under autarky, p_i is defined only for the domestic species. We assume that harvesting costs are the same for all resources, thus c carries no index. Everything that follows will depend on ratios of γ_i to the cost parameter c. To simplify notation, we normalize units of measurement for the numeraire commodity such that $c = 1$.

As resources are harvested under conditions of open access, resource rents are dissipated. Profits (5) are zero, and the price of species i is equal to marginal harvesting costs,

$$p_i = \frac{1}{x_i}. \tag{6}$$

Using the open-access condition (6), the price index for resource goods in country i, P_i, can be expressed as a function of resource stocks,

$$P_i = \left(\sum_{j\in\mathbb{S}_i} p_j^{1-\sigma}\right)^{\frac{1}{1-\sigma}} = \left(\sum_{j\in\mathbb{S}_i} x_j^{\sigma-1}\right)^{\frac{1}{1-\sigma}}. \tag{7}$$

The Marshallian demand of consumer i for resource type j is obtained from the first-order conditions of utility maximization, i.e. the maximization of (1) with (2) subject to the budget constraint (3),

$$q_{ji} = \gamma_i\, \frac{p_j^{-\sigma}}{\sum\limits_{j\in\mathbb{S}_i} p_j^{1-\sigma}} = \gamma_i\, \frac{p_j^{-\sigma}}{P_i^{1-\sigma}}. \tag{8}$$

2 The two-species-two-country case

We first consider the case where each country has one resource stock each. The two countries may differ in the biological productivity of their resource r_i and in the consumer expenses for resource harvests, γ_i. We start the analysis by considering the autarky scenario and then proceed to the scenario of free trade.

2.1 Autarky

Without any trade in resources, only one type of resource harvest is available in each country. This reduces the model to the textbook case of an open-access resource. In particular, the demand function (8) simplifies to $q_{ii} = \gamma_i / p_i$, and domestic demand must equal domestic supply, $q_{ii} = h_i$. Consumer expenses for resource harvest must equal revenues from harvesting the domestically available species in country i,

$$\gamma_i = p_i \, h_i. \tag{9}$$

Inserting (4) and (6) and solving yields the open-access steady-state stock of resource i,

$$x_i^a = 1 - \frac{\gamma_i}{r_i}. \tag{10}$$

The open-access stock decreases with the expenditures for resources. It increases with the intrinsic growth rate r_i and the harvesting cost parameter c.

To study the consequences of trade liberalization, we assume that domestic demand cannot cause stock collapse:

Assumption 1 (Positive autarky stocks)**.** *Neither of the two stocks collapses under autarky, $\gamma_i < r_i$, for both countries $i = 1, 2$.*

Without loss of generality, we furthermore assume that the autarky price in country 1 is higher than in country 2:

Assumption 2 (Ordered autarky prices)**.** *The ratio of consumer expenses to growth rate is higher in country 1 than in country 2,*

$$\frac{\gamma_1}{r_1} > \frac{\gamma_2}{r_2}. \tag{11}$$

This implies a higher autarky price and a lower autarky stock in country 1, $p_1^a > p_2^a$ and $x_1^a < x_2^a$.

For clarity of exposition, we treat the case $\frac{\gamma_1}{r_1} = \frac{\gamma_2}{r_2}$ separately: The condition implies $p_1^a = p_2^a$ such that both countries are indifferent to free trade in the case of perfect substitutes ($\sigma \to +\infty$). For finite $\sigma > 1$, both countries gain from trade for any point on the isocost curve (16), cf. the following section.

2.2 Free Trade

With free trade, the prices for harvest from a specific resource are the same globally. Thus also the resource price indizes are the same in both countries,

$$P_1 = P_2 \equiv P = \left(x_1^{\sigma-1} + x_2^{\sigma-1}\right)^{-\frac{1}{\sigma-1}} . \tag{12}$$

The Equivalent/Compensating variation CV_i for country i of a move from autarky to free trade with price index P (cf. equation (7)) can be formulated as

$$\mathrm{CV}_i = \gamma_i \ln\left(\frac{p_i^a}{P}\right) = \gamma_i \ln\left(\frac{\left(x_1^{\sigma-1} + x_2^{\sigma-1}\right)^{\frac{1}{\sigma-1}}}{x_i^a}\right) . \tag{13}$$

Indifference to autarky can be depicted by the following indifference curves in $x_1 - x_2$ space:

$$x_2^{\mathrm{indi}}(x_1) = x_1 \left[\left(\frac{x_i^a}{x_1}\right)^{\sigma-1} - 1\right]^{\frac{1}{\sigma-1}} , i = 1, 2 \tag{14}$$

As the price index is strictly increasing in both stock sizes, all points above the indifference curve are preferred to autarky.

In free-trade equilibrium, surplus production from stock x_i must equal aggregate demand from both countries,

$$g_i(x_i) = \frac{p_i^{-\sigma}}{P^{1-\sigma}} \left(\gamma_1 + \gamma_2\right) , \quad i = 1, 2 \tag{15}$$

Multiplying by the price of resource i, summing over i and rearranging yields the **isocost line** for an interior equilibrium as

$$x_2^{\text{ico}}(x_1) = \frac{r_1 + r_2 - \gamma_1 - \gamma_2}{r_2} - \frac{r_1}{r_2}\, x_1. \tag{16}$$

Using (4) and (6) in (15), and rearranging, we obtain the following conditions that implicitly determine the steady-state stock sizes (x_1^t, x_2^t):

$$x_1 = 1 - \frac{x_1^{\sigma-1}}{x_1^{\sigma-1} + x_2^{\sigma-1}}\, \frac{\gamma_1 + \gamma_2}{r_1}, \tag{17a}$$

$$x_2 = 1 - \frac{x_2^{\sigma-1}}{x_1^{\sigma-1} + x_2^{\sigma-1}}\, \frac{\gamma_1 + \gamma_2}{r_2}. \tag{17b}$$

These conditions can be interpreted as the isoclines in $x_1 - x_2$ space. Condition (17a) for example depicts all combinations of x_1, x_2 for given $\sigma, \gamma_1, \gamma_2, r_1, r_2$ for which demand for harvest from stock 1 equals stock growth such that $\dot{x_1} = 0$. Rearranging the x_1-isocline (17a) yields

$$x_2^{\text{me1}}(x_1) = x_1 \left(\frac{\gamma_1 + \gamma_2}{r_1\,(1 - x_1)} - 1 \right)^{\frac{1}{\sigma-1}}. \tag{18}$$

Inserting this condition in the isocost condition (16) gives the equilibrium stock size x_1^t as an implicit function of parameters only,

$$x_1^t \left(r_1 + r_2 \left(\frac{\gamma_1 + \gamma_2}{r_1\,(1 - x_1^t)} - 1 \right)^{\frac{1}{\sigma-1}} \right) = r_1 + r_2 - (\gamma_1 + \gamma_2)\,. \tag{19}$$

For general values of the elasticity of substitution σ, it is obviously not possible to solve for the steady-state stock sizes in closed form. It is however possible to prove the existence of a unique free-trade equilibrium:

Proposition 1. *1a) For $\sigma > 1$, there exists a unique free-trade equilibrium with positive stock sizes for both resources, $x_1^t, x_2^t > 0$.*

1b) Resource stocks under free trade and in autarky are ordered as follows

$$x_1^t \gtreqqless x_1^a \quad \textit{and} \quad x_2^t \lesseqqgtr x_2^a \quad \textit{for} \quad x_1^a \left(\frac{\gamma_2}{\gamma_1} \right)^{\frac{1}{\sigma-1}} \lesseqqgtr x_2^a. \tag{20}$$

Proof. Prerequisite: The stock size $x_1^{\mathrm{co}} = 1 - \frac{\gamma_1}{r_1} - \frac{r_2}{r_1}$ is a corner solution after the collapse of stock 2 such that all consumer expenses are directed at stock 1, cf. (28). For inner solutions, stock 1 receives less than the total consumer expenses, such that it holds that $x_1^t > x_1^{\mathrm{co}}$ for all $\sigma > 1$. It also holds that $x_1^a > x_1^{\mathrm{co}}$ as $x_1^{\mathrm{co}} = x_1^a - \frac{r_2}{r_1}$.

1a) The right-hand side (RHS) of (19) is independent of x_1 and positive. Define the left-hand side (LHS) of (19) as

$$\Omega(x) \equiv x \left(r_1 + r_2 \left(\frac{\gamma_1 + \gamma_2}{r_1 (1-x)} - 1 \right)^{\frac{1}{\sigma - 1}} \right). \tag{21}$$

We further consider two cases. In case 1, $\gamma_1 + \gamma_2 > r_1$, $\Omega(x)$ is defined and positive for all $x \in [0, 1)$. In case 2, $\gamma_1 + \gamma_2 \leq r_1$, $\Omega(x)$ is defined and positive for all $x \in (x_1^{\mathrm{co}}, 1)$.

Case 1. $\Omega(0) = 0 < r_1 + r_2 - (\gamma_1 + \gamma_2)$; $\lim\limits_{x \to 1} \Omega(x) \to +\infty$. For all $x \in (0, 1)$, $\Omega'(x) > 0$. Hence, there exists a unique $x > 0$ such that (19) holds with equality.

Case 2. $\Omega(x_1^{\mathrm{co}}) = r_1 - (\gamma_1 + \gamma_2) < r_1 + r_2 - (\gamma_1 + \gamma_2)$; $\lim\limits_{x \to 1} \Omega(x) \to +\infty$. For all $x \in (x_1^{\mathrm{co}}, 1)$, $\Omega'(x) > 0$. Hence, there exists a unique $x > x_1^{\mathrm{co}}$ such that (19) holds with equality.

1b) The intersection of the x_1-isocline (18) and the isocost line (16) determine the market equilibrium with equilibrium stock size x_1^t: $x_2^{\mathrm{me1}}(x_1^t) = x_2^{\mathrm{ico}}(x_1^t)$. It is straightforward to verify that $x_2^{\mathrm{ico}\prime}(x_1) < 0$ and that $x_2^{\mathrm{me1}\prime}(x_1) > 0$ for $x_1 > x_1^{\mathrm{co}}$. Thus, $x_1^t \gtreqless x_1^a$ if $x_2^{\mathrm{me1}}(x_1^a) \gtreqless x_2^{\mathrm{ico}}(x_1^a)$. Evaluating both expressions at x_1^a, we obtain

$$x_2^{\mathrm{me1}}(x_1^a) = x_1^a \left(\frac{\gamma_2}{\gamma_1} \right)^{\frac{1}{\sigma - 1}}$$

$$x_2^{\mathrm{ico}}(x_1^a) = x_2^a.$$

□

Condition (20) is always fulfilled if $\gamma_2 < \gamma_1$. If $\gamma_2 > \gamma_1$ there is some threshold value $\sigma' > 1$ such that for all $\sigma < \sigma'$ $x_1^t < x_1^a$ and for all $\sigma > \sigma'$

$x_1^t > x_1^a$.

If the countries differ in their expenses for resource products or in the biological productivity of their stocks, explicit expressions for the free-trade equilibrium can be calculated for the two limit cases of the CES utility function, the case of perfect substitutes ($\sigma \to +\infty$) and Cobb-Douglas preferences ($\sigma \to 1$).

As the literature on trade in renewable resources implicitly assumes that the traded harvests are perfect substitutes, we start with this case. If consumers do not differentiate between the two types of harvest, prices must be equal in equilibrium. As prices depend on stock sizes only (cf. equation 6), stock sizes must be the same. From (18) we thus obtain

$$x^{ps} = 1 - \frac{\gamma_1 + \gamma_2}{r_1 + r_2}. \tag{22}$$

The intuition is that the global expenditures for resources, $\gamma_1 + \gamma_2$ are spent over the two resources according to their productivities, as measured by the intrinsic growth rates, such that in equilibrium both stocks are of equal size. As it holds that $\lim_{\sigma\to\infty} P = \frac{1}{\max(x_1,x_2)}$, the indifference curves (14) simplify to rectangles in the limit case of perfect substitutes,

$$x_i^a = \max(x_1, x_2). \tag{23}$$

As

$$x^{ps} = \frac{r_1}{r_1 + r_2} x_1^a + \frac{r_2}{r_1 + r_2} x_2^a,$$

and $x_1^a > x_2^a$ it follows that $x_2^a > x^{ps}$ and $x_1^a < x^{ps}$, such that country 1 wins and country 2 loses from trade.

Figure 1 depicts this standard case: The intersection point of the isocost line (16) and the x_1-isocline (18) determines the trade equilibrium, here also given in closed form by (22). Country 1 has a higher autarky price than country 2, such that trade liberalization leads to a price decrease in country 1 and a price increase in country 2. It follows that the country with the smaller autarky stock gains from the trade while the one with the larger autarky stock loses.

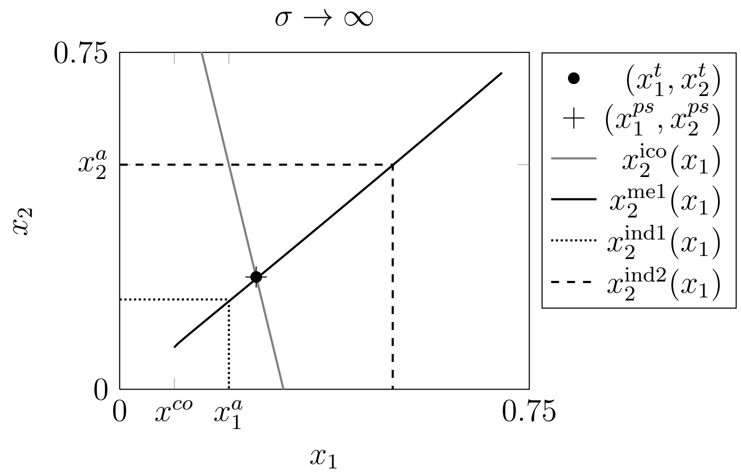

Figure 1: Trade in perfect substitutes: Country 1 with its lower autarky stock and higher autarky price gains while country 2 loses. Equilibrium at $x_1^t = x_2^t = x^{ps} = 0.25$ ($r_1 = 0.5$, $r_2 = 0.1$, $\gamma_1 = 0.4$, $\gamma_2 = 0.05$).

If both stocks have the same biological productivity, the trade equilibrium in case of perfect substitutes holds for all elasticities of substitution:

Proposition 2. *If* $r_1 = r_2$*, the unique free-trade equilibrium for all* $\sigma \geq 1$ *is*

$$x_i^t = x^{ps},\ i = 1, 2. \tag{24}$$

Proof. A unique trade equilibrium exists for $\sigma > 1$ (cf. Proposition 1). For $r_1 = r_2$, (22) solves (19) for all $\sigma > 1$. In the limit case $\sigma = 1$, (27) equals (22). □

For $r_1 = r_2$, the stock sizes and hence total biomass are independent of the preferences for diversity and equal to aggregate autarky levels, $x_1^t + x_2^t = x_1^a + x_2^a$. In this case, trade liberalization leads to balanced stock sizes for all $\sigma \geq 1$.

For $r_1 \neq r_2$, the effect of decreasing the elasticity of substitution from the limit case of perfect substitutes towards the second limit case of Cobb-Douglas preferences is depicted in Figure 2:

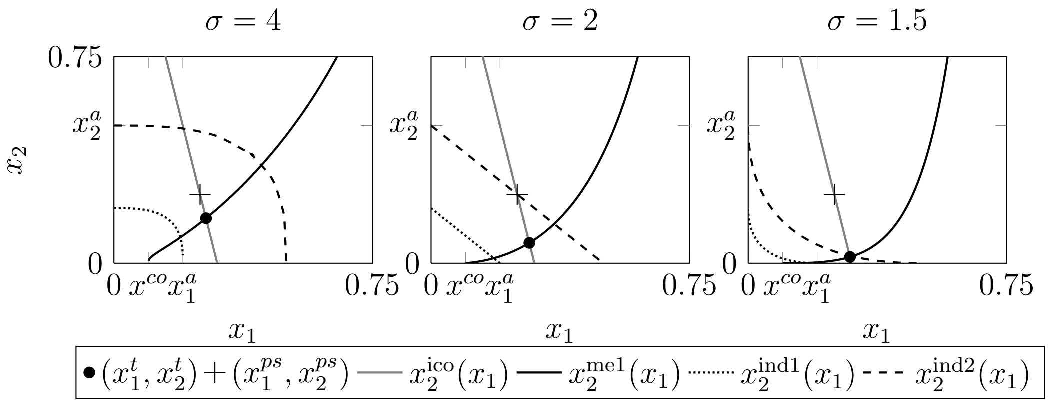

Figure 2: Trade equilibria at intersection of the isocost line (16) and the x_1-isocline (18). Decreasing σ moves the equilibrium on the isocost line (16) towards the biologically more productive stock ($r_1 = 0.5$,$r_2 = 0.1$,$\gamma_1 = 0.4$,$\gamma_2 = 0.05$). In the Cobb-Douglas limit case, stock 2 collapses.

The indifference curves become strictly concave for $\sigma > 2$, linear for $\sigma = 2$ and strictly convex for $\sigma < 2$ while keeping their symmetric intercepts at x_i^a on both axes. The indifference curves bending towards the origin with decreasing σ reflects the increasing importance of the love of variety to consumer welfare. The lower the elasticity of substitution, the larger the area of $x_1 - x_2$ combinations above the indifference curves that are preferred to autarky. At the same time, decreasing the elasticity of substitution weakens the reaction of consumer demand towards resource scarcity such that the equilibrium size of the biologically less productive stock decreases while the other one faces reduced demand and increases. This can be seen in Figure 2 by the movement of the intersection point of the x_1-isocline (18) on the isocost line (16). The equilibrium moves southeastwards, implying a decrease in stock 2 and an increase in stock 1. Decreasing σ hence has two effects: It moves the symmetric indifference curves towards the axes while it also moves the equilibrium on the isocost line (16) towards the axis of the biologically more productive stock, cf. Figure 2. For country 2 to gain from trade for $\sigma > 1$, the trade equilibrium has to approach the axis slower than the country's indifference curve. The following proposition shows that this is always the case.

Proposition 3. *There exists a $\sigma^* > 1$ such that both countries gain from trade for $\sigma \in (1, \sigma^*]$.*

Proof. It is a sufficient condition for country 1 to gain from trade that country 2 does, cf. (14). The indifference-to-autarky curve of country 2 (14) can be written as

$$x_2^{\text{ind2}}(x_1) = x_1 \left[\left(\frac{x_2^A}{x_1} \right)^{\sigma-1} - 1 \right]^{\frac{1}{\sigma-1}}, \tag{25}$$

and the x_1-isocline (18) as

$$x_2^{\text{me1}}(x_1) = x_1 \left[\frac{\gamma_1 + \gamma_2}{r_1 (1 - x_1)} - 1 \right]^{\frac{1}{\sigma-1}}. \tag{26}$$

A unique trade equilibrium with positive stock sizes exists for $\sigma > 1$ (cf. Proposition 1). The equilibrium stock sizes fulfill (26). Country 2 gains from trade if the term in brackets on the right-hand side of (25) is smaller than the term in bracket on the right-hand side of (26).

Now consider the two cases $\gamma_2 > \gamma_1$ and $\gamma_2 < \gamma_1$. For the case $\gamma_2 > \gamma_1$, the proof of the proposition is simple: Let $\sigma^* = \sigma'$, where $\sigma' > 1$ is the threshold value characterized in Proposition 1b). For $\sigma < \sigma'$ it follows that $x_2^t > x_2^a$. This implies that the trade equilibrium (x_1^t, x_2^t) lies to the northwest of $x_2^{\text{ind2}}(x_1)$ (convex for sufficiently small $\sigma < 2$), such that country 2 gains from trade, which proves the proposition for the case $\gamma_2 > \gamma_1$.

For the case $\gamma_2 < \gamma_1$ it follows from Proposition 1b) that $x_1^t > x_1^a$. Thus,

$$\left(\frac{x_2^a}{x_1^t} \right)^{\sigma-1} - 1 < \left(\frac{x_2^a}{x_1^a} \right)^{\sigma-1} - 1 \quad \text{and}$$
$$\frac{\gamma_1 + \gamma_2}{r_1 (1 - x_1^t)} - 1 > \frac{\gamma_1 + \gamma_2}{r_1 (1 - x_1^a)} - 1$$

Now fixing x_1 at x_1^a it holds that $\lim_{\sigma \to 1} \frac{\gamma_1+\gamma_2}{r_1 (1-x_1^a)} - 1 > 0$ while $\lim_{\sigma \to 1} \left(\frac{x_2^a}{x_1^a} \right)^{\sigma-1} - 1 = 0$. Thus, there must be some threshold value $\sigma^* > 1$ such that $\frac{\gamma_1+\gamma_2}{r_1 (1-x_1^a)} -$

$1 > \left(\frac{x_2^a}{x_1^a}\right)^{\sigma-1} - 1$ for all $\sigma < \sigma^*$. It follows that

$$\frac{\gamma_1+\gamma_2}{r_1\,(1-x_1^t)} - 1 > \frac{\gamma_1+\gamma_2}{r_1\,(1-x_1^a)} - 1 > \left(\frac{x_2^a}{x_1^a}\right)^{\sigma-1} - 1 > \left(\frac{x_2^a}{x_1^t}\right)^{\sigma-1} - 1$$

for all $\sigma < \sigma^*$. □

Without loss of generality, we defined country 2 to be the country with the lower autarky price (cf. 2). For the standard case of perfect substitutes, trade liberalization leads to a welfare decrease in country 2 as the country experiences a price increase relative to autarky. The love-of-variety effect outweighs the negative price-quantity effect for all $\sigma \in (1, \sigma^*]$. In the example of Figure 2, country 2 gains from trade for all $\sigma \in (1, 1.46]$.

In the limit case of Cobb-Douglas preferences, the link that increasing resource scarcity leads to a price increase and hence a demand reduction is disabled. Because of their intense love of variety, both consumers spend half their expenses on each type of harvest, irrespective of the individual prices and hence stock sizes. As there is no longer a substitution mechanism that works in the direction of balanced stock sizes, a stock collapse or a sequential collapse of both stocks may occur:

Proposition 4. *Let r_a (r_b) denote the stock with the higher (lower) intrinsic growth rate.*

If $\sigma = 1$ and $\gamma_1 + \gamma_2 < 2\,r_b$, no stock collapses and the trade equilibrium follows as

$$x_i^t = x_i^{cd} = 1 - \frac{\gamma_1+\gamma_2}{2\,r_i},\; i = 1, 2. \tag{27}$$

If $\sigma = 1$ and $\gamma_1 + \gamma_2 \geq 2\,r_b$ and $\gamma_1 + \gamma_2 < r_a$, the less productive stock collapses and the trade equilibrium follows as

$$x_a^t = x_a^{co} = 1 - \frac{\gamma_1+\gamma_2}{r_a},\; x_b^t = x_b^{cd} = 0. \tag{28}$$

If $\sigma = 1$ and $\gamma_1 + \gamma_2 \geq 2\,r_b$ and $\gamma_1 + \gamma_2 \geq r_a$, a sequential collapse of both stocks occurs,

$$x_i^t = x_i^{cos} = 0,\; i = 1, 2. \tag{29}$$

The limit case of free trade with Cobb-Douglas preferences can be understood as an autarky case with consumer expenses per stock adjusted to half the total expenses of both consumers, $x_i^{cd} = 1 - \frac{\gamma_1+\gamma_2}{r_i}$. If the less productive stock cannot sustain these expenses and collapses, the remaining stock has to sustain the total consumer expenses, hence $x_a^{cd} = 1 - \frac{\gamma_1+\gamma_2}{r_a}$ in this case.

In the example of Figure 2, we have that $\gamma_1 + \gamma_2 = 0.45 > 2\,r_2 = 0.2$ and $\gamma_1 + \gamma_2 = 0.45 < r_1 = 0.5$ such that stock 2 collapses for $\sigma = 1$. The trade equilibrium follows as $x_1^t = x_1^{co} = 0.1$, $x_2^t = x_2^{co} = 0$.

As corner solutions cannot be compared to inner solutions in the case of Cobb-Douglas prefences, a welfare comparison of autarky and free trade is limited to $\sigma > 1$.

3 Trade between a species-rich and a species-poor country

In the previous section, trade liberalization resulted in a price increase for country 2. Trading harvest from its formerly larger autarky stock always entailed a reduced total consumption of resource harvests in country 2. This negative quantity effect on consumer welfare was counterbalanced by a positive love-of-variety effect.

As the positive diversity effect was a result of modeling only one resource per country, we modify our model in this section by making country 1 a species-rich country with $n \geq 2$ species. Country 1 with its small autarky stock was the unambiguous beneficiary of trade in the previous section because trade led to an increase in domestic resource consumption. By a short model extension that introduces species-richness in country 1, we want to show that the diversity effect of trade may also be negative, bringing a country an increase in consumption and a decrease in welfare.

To keep the analysis tractable, we assume that country 1 has $j = 1, \ldots, n$ domestic stocks whose growth functions

$$g_{1j}(x_{1j}) = r_1\, x_{1j}\, (1 - x_{1j}) \tag{30}$$

have identical intrinsic growth rates $r_{1j} = r_1$. Country 2 continues to have only one stock x_2 that grows according to (4). Due to the assumption that the stocks in country 1 are equally productive, the utility function (1) of the consumers in country i can be represented as

$$u_i = y_i + \gamma_i \ln \left[\left(n\, h_{i1}^{\frac{\rho-1}{\rho}} + h_{i2}^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} \right]. \tag{31}$$

The term in square brackets in (31) can be rearranged as the quantity consumed in country i, H_i,

$$H_i = n\, h_{i1} + h_{i2} \tag{32}$$

times a diversity factor D_i,

$$D_i = \left(n \left(\frac{h_{i1}}{H_i} \right)^{\frac{\rho-1}{\rho}} + \left(\frac{h_{i2}}{H_i} \right)^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}}. \tag{33}$$

Under autarky, consumption in country 1 comprises its n domestic stocks. The diversity factor of country 1 under autarky follows as

$$D_1^a = n^{\frac{1}{\rho-1}}. \tag{34}$$

After trade liberalization, harvest from x_2 becomes available in country 1. The consumption bundle in country 1 increases to $n+1$ species and the diversity factor of country 1 under free trade follows as

$$D_1^{ft} = \left(n \left(h_{11}^{ft} / H_1^{ft} \right)^{\frac{\rho-1}{\rho}} + \left(1 - n\, h_{11}^{ft} / H_1^{ft} \right)^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}}. \tag{35}$$

The species-rich country 1 gains (loses) from free trade if $U_1^a = n\, h_{11}^a\, D_1^a$ is larger (smaller) than $U_1^{ft} = \left(n\, h_{11}^{ft} + h_{12}^{ft} \right) D_1^{ft}$. Even if trading $n+1$ species with country 2 increases the quantity consumed in country 1, the country might be worse off due to a negative diversity effect:

Proposition 5. *For all* $h_{11}^{ft}/H_1^{ft} < h^\star$ *with* $0 < h^\star < 1/(n+1)$ *it follows that*

$$D_1^{ft} < D_1^a. \tag{36}$$

Proof.

$$D_1^a = D_1^{ft} \tag{37}$$

$$\Leftrightarrow \qquad n^{\frac{1}{\sigma}} = n\left(\frac{h_{11}^{ft}}{H_1^{ft}}\right)^{\frac{\rho-1}{\rho}} + \left(1 - n\,\frac{h_{11}^{ft}}{H_1^{ft}}\right)^{\frac{\rho-1}{\rho}} \tag{38}$$

has a unique solution $h^\star = h_{11}^{ft}/H_1^{ft}$ with $0 < h^\star < 1/(n+1)$, as for $h_{11}^{ft}/H_1^{ft} = 0$, the left-hand-side (LHS) is larger than the right-hand-side (RHS), the RHS is monotone and strictly convex in h_{11}^{ft}/H_1^{ft}, and assumes a unique maximum $(1+n)^{1/\sigma}$ at $h_{11}^{ft}/H_1^{ft} = 1/(n+1)$, which is larger than the LHS. □

For $\sigma = 2$, the solution is

$$h^\star = \frac{1}{n}\left(\frac{n-1}{n+1}\right)^2. \tag{39}$$

If the share of domestic species in domestic consumption drops below $n\,h^\star = \left(\frac{n-1}{n+1}\right)^2$, diversity in country 1 decreases. This might happen if the n species of country 1 are not resilient to the additional demand from country 2 following trade liberalization. In the new steady-state with trade, the species-pour country 2 might dominate consumption in country 1.

This scenario is even easier to model in a North-South model such as Chichilnisky (1994): Country 1 might be a species-rich Southern country that begins trading with a Northern country 2, for example Norway with its well-managed cod or herring fisheries. In such a modeling framework, the open-access stocks of the Southern country would be overused and imports from the well-managed Northern stock would dominate consumption in the South. Even if total consumption in the South increases, South might be worse off due to decreased diversity.

4 Conclusion

Departing from the assumption that traded resources are perfect substitutes yields two important insights: First, the welfare effect of trade liberalization becomes more ambiguous as the price/quantity effect is expanded by a diversity effect that may outweigh increases or decreases in domestic consumption.

Second, increasing the consumers' love of variety weakens the link between resource scarcity and demand. Harvesting overexploited resources is expensive. If consumers are willing to pay the rising prices for harvests from increasingly depleted stocks, trade liberalization may enable higher levels of overexploitation than under autarky. In the limit case of Cobb-Douglas preferences, free trade may result in stock collapses. This consequence of the love of variety contrasts results from models which implicitly assume that the traded resources are perfect substitutes. In the limit case of perfect substitutes, trade liberalization decreases the demand for the most depleted resources such that it works in the direction of balanced stock sizes. Modeling trade in renewable resources as trade in perfect substitutes thus assumes the best-case scenario concerning the risk of trade-induced overexploitation and stock collapse. Integrating a love-of-variety effect in a trade model shows that trade liberalization may enable the love of variety to threaten variety.

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