Governing the Resource: Scarcity-Induced Institutional Change*

May 18, 2010

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Abstract

We provide a dynamic model of natural resource management where the optimal institutional structure that governs resource use changes with resource depletion. Copeland and Taylor (2009) analyze how characteristics of a natural resource determine whether its steady-state management regime is open access, communal property, or private property. We extend this and other studies of endogenous institutions to analyze how and when resource governance may change in transition to the steady state, taking into account the fixed costs of institutional change and the variable costs of enforcement and governance. Assuming that governance cost is increasing in the difference between open-access and the actual harvest, we show that open access can be optimal if the resource is abundant relative to its demand and/or if governance costs are high. Once open access is rendered inefficient due to increased resource scarcity, further depletion warrants institutional change. In the face of set-up costs, optimal governance implies non-monotonic resource dynamics. These findings explain the co-evolution of resource scarcity and property rights—from open access to common property and beyond. We also extend the Demsetz-Taylor theory that price induced scarcity may or may not be sufficient to induce institutional change by adding dynamics to the steady state conditions of Taylor (2008).

JEL Codes: D23, O13, Q20.

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1. Introduction

A variety of institutional forms exists for the management of natural resources around the world, ranging from open access (no property), common property, private property, and state property. A large body of literature in institutional and resource economics has emerged to explain why different management regimes prevail for different natural resources (wildlife, land, non-renewable resources, and renewable resources) at different times and places.[1] Despite the fact that this literature is overwhelmingly oriented to renewable resources (especially forests, fisheries, water and grazing land), it has typically abstracted, until quite recently, from the relationship between institutional change and resource dynamics.

Many case studies indicate that changing resource scarcity is associated with institutional change. While open access characterizes the organization of some resources for long periods, many resources exhibit shifts in their property-right regimes as resource scarcity changes over time. It is this dynamic aspect of institutional change that this paper aims to address. The reason that "no type of governance system has been shown to be successful in all implementations" (Ostrom 2007) is presumably that no institution is appropriate for all types of renewable resources at all times and at all places. We show how different governing structures of the same resource may be appropriate at different stages of a resource's evolution, taking into account the dynamics of natural resource and resource scarcity, as well as the costs of institutional change.

Demsetz (1967) famously sketched and illustrated an economic theory of property rights. However, formalization and verification of Demsetz's central proposition—that a new institution emerges when its benefit exceeds the cost—has only recently begun to emerge (section 2). Some studies analyze the optimal timing of institutional change by incorporating a one-time fixed-cost of adopting resource governance. Because these models abstract from resource dynamics, or do not feature resource extraction as a control variable, changes in resource scarcity do not play a role in institutional change. Copeland and Taylor (2009) provide a general model of resource management with explicit variable costs of monitoring harvests in their comparison of "Hardin" (open access), "Ostrom" (common property), and "Clark" (private property) management regimes, and analyze resource characteristics that determine which governance form will prevail in the steady state. This provides a solid foundation for institutional choice across resources, but does not capture how governance of a particular resource may change as resource scarcity changes over time as resource is extracted.

Our objective is to focus on the evolution of resource governance in transition to and the steady state. Building on the literature of endogenous property rights, we develop a dynamic resource-use model of how governance of a resource evolves over time depending on resource scarcity as well as changes in the surrounding economic environment. We solve the model for the optimal allocation in the presence of both fixed costs of institutional change and variable costs of maintaining governance.

We find conditions under which institutional change occurs as a resource stock is depleted (or increases). Not surprisingly, open access is optimal at all stock levels if governance costs are high enough. Otherwise, optimal governance involves switching from open access to governance

[1] . A branch of such literature is referred to as the *economics of common property resources* or the *economics of common property regimes* (e.g. Bromley, 1992).

as the resource is depleted. The dynamics of resource scarcity—as represented by the shadow value of resource—depend on the nature of governance costs. With zero fixed costs of institutional change, governance is adopted, and open access abandoned, once the resource has been depleted to its steady-state level. The steady-state stock is lower than the first-best level – with zero governance costs – as long as variable governance costs are positive. Both the resource stock and its shadow price change monotonically over time.

In contrast, if institutional change requires positive set-up costs, then overshooting occurs. Open access is allowed until the resource stock falls below its steady-state level, after which harvesting is restricted until the stock recovers to the steady state. That is, fixed costs of institutional change result in a non-monotonic profile of the optimal resource stock.

Our analysis also describes how the timing of institutional change depends on the costs and benefits of resource management. In particular, the optimal timing is delayed if the harvest price is larger or if the cost of governance is larger. While a higher price increases the gains from institutional change, higher governance costs indicate lower net benefits of institutional change.

The exercises that follow help to illuminate how resource scarcity is related to property rights and how this relationship depends on governance costs. Governance may start early in the course of optimal resource depletion or may never occur. In the latter case, the problem is that Hardin's (1968, p. 1247) "mutual coercion, mutually agreed upon" is too costly.[2] Our analysis supplements Taylor's (2008) dynamic, open-access model of bison depletion of a small open economy facing an exogenous world price of the resource (bison hides) by providing a comparative institutional framework in a similar context. We find conditions under which the efficient property rights regime would remain in open access. The same framework is suitable for comparing efficient governance paths across different resources. By characterizing institutional change as the optimal outcome in the presence of governance costs, this study also contributes to the literature on organizational evolution. Most existing studies on this topic assume non-rational resource users in evolutionary-game frameworks (e.g. Sethi and Somanathan 1996). Our framework allows a complementary result; since open access is not necessarily a tragedy, it does not necessarily result from behavioral anomalies.

Libecap (2008) observes that the assignments of property rights tend to be delayed in many cases: they are adopted only after resource degradation has taken place. Our non-monotonicity result indicates that, given the cost of institutional change, the observed delay is not necessarily inefficient.

The result is also consistent with studies that posit and discuss a *Natural Resource Kuznets Curve* for forests (Panayatou 1993, Foster and Rosenzweig 2003), fisheries,[3] and other natural resources (Krautkraemer, 1994; and Roumasset et al., 2007).

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[2] Although Hardin is often associated with central government control, his 1968 article has an entire subsection entitled "mutual coercion, mutually agreed upon," which could apply equally well to common property governance by a community.

[3] The trends in abundance and biomass of Atlantic herring from the Northeast Fisheries Science Center surveys indicate a U shape, with a decline in the 1960s and an increase in the late 1980s (New England Fishery Management Council 2002).

In what follows, section 2 reviews the theory of institutional change and a number of case studies that indicate the role of resource scarcity in institutional change. Section 3 describes a general, dynamic model of natural resource use with explicit costs of resource governance. Section 4 explains the main results of the paper regarding the evolution of resource governance over time. Section 5 concludes the paper with suggestions for further research.

2. Case studies and theory of institutional change

While open access characterizes the organization of some common pool resources for long periods, many resources experience shifts in their property-right regimes as resource scarcity changes over time. One class of examples demonstrates the transition from open access to common property. The lobster fishery in Maine provides an illustrative example. Back in the colonial period, lobsters were abundant and managed as an open access resource. As an *Economist* article documents, a group of Massachusetts servants became so "fed up" with their diet of lobster that they took their owners to court and won a judgment that it not be served to them more than three times a week.[4] As the demand for lobster increased, local lobstermen started to organize themselves (the "lobster gangs" in Maine, Acheson 1988) in order to exclude outsiders from lobstering and to restrict their own harvesting, thereby avoiding rent dissipation due to open access. Ample evidence suggests institutional change from open access to restricted access (Ostrom 1990, Scott 2008) including the rural land use in Switzerland and Germany (Netting 1981); Groundwater use in Southern California (Ostrom 1965); fishing cooperatives in Japan (Platteau and Seki 2000); and watersheds ("Ahupua`a") in Hawaii (La Croix and Roumasset 1990).

One of the most famous institutional transitions from common to private property concerns the enclosures in England and Wales, especially during the "long 16th century" and from the late 18th to the mid-19th centuries. The early enclosures were partly an economic response to higher wages and rising wool prices. Later, intensification of crop production was more important (Moore, 1966; North and Thomas, 1971; McCloskey, 1976; Allen, 1983). Forest land (*Iriaichi*) in rural villages in Japan also was converted from community to private-property management after the Second World War (McKean 1986, Kijima et al. 2000).

What explains emergence of property right regimes? Demsetz (1967) has suggested that they emerge when the benefits of reduced rent-dissipation exceed their costs. Thus tribal hunting rights for beaver among the Montagnes who inhabited large regions around Quebec were established when trade with Europe increased the effective demand for beaver pelts beyond the point where the gains of internalization became larger than the costs. In contrast, Native-Americans in the Southwest did not establish private hunting rights over bison, due in large part to the high costs of internalization resulting from the migratory patterns of the animals. This seminal paper left many questions for other economists to explore. What should be included in benefits and costs of institutional change? When will an institution change from one form to another? Is it current benefits and costs that are critical to the timing of institutional change or the present value thereof? Is it possible to classify resources according to which institution will be optimal for each resource? Are there conditions under which property or the lack thereof will always be more efficient than other institutions? If so, what kind of property?

[4] "Pots of Flesh," *The Economist* July 1, 2004.

The benefits of institutional change are implicitly equated with the losses of open access in a first-best setting. What should be included in the costs of change has been largely answered by assumption. Most of the literature on the economics of property rights after Demsetz has equated the costs of institutional change with monitoring and enforcement costs.[5] North and Thomas (1971) and Davis and North (1971) are exceptions in this regard, comparing the net benefits of institutional change with the political costs of changing the rules.[6] In what follows, we abstract from the political costs of change and restrict our attention to enforcement and information costs.[7]

The question of timing has been only partially answered. For a one-time fixed-cost investment, Anderson and Hill (1975, 1990) showed that private property would efficiently emerge when the present value of reduced rent dissipation net of enforcement costs is maximized. This helped to concretize the costs of institutional change and bring some dynamics into the picture. One entry point for resource economics into the theory of institutional change was the dramatic depletion of bison in the American West. Lueck (2002) models bison as a renewable resource and shows that the optimal transition from open access to the first-best property rights regime is sooner where the rents from resource use are higher and if the exogenously fixed cost of resource governance is lower.[8] Taylor (2008) provides a more standard model of renewable resources and combines it with the assumption that the price of bison hides was fixed by the European leather market. He finds that open-access depletion closely tracks actual depletion rates up to the near extinction of the species.

Other discussions focus on which institution – common property, private property, or no property – may be preferred to others. Demsetz (1967) cited anthropological evidence showing that both the Montagnes and the "Indians of the Labrador Peninsula had a long-established tradition of property in land," established in the colonial period. Ostrom (1990 and 1998) helped to cast the "common property resource" problem as one of comparative institutions (as had been encouraged by Coase, e.g. 1988 and 1998) by noting that neither private property nor Hardin's (1968, 1978) Leviathan (state control) should be viewed as "the only way" and by advancing community management as an alternative institution.

Alston and Mueller (2003) have suggested that open access and private property are fully equivalent if land is sufficiently remote from the market and if enforcement costs are zero. For land closer to the market, property will be worthwhile if the increased value associated with the

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[5] Anderson and Hill (1975 and 1990) consider the fixed cost of property enforcement (fencing). Deininger (2003) and Copeland and Taylor (2008) focus on the variable costs of enforcement and monitoring. See also Eggertsson (1990) for a comprehensive review and several examples.
[6] Accordingly, institutional change is said to come about when the benefits thereof exceed the (political) costs to the primary action group.
[7] In the early days of the *New Institutional Economics*, Demsetz (1967) and North and Thomas (1973) viewed institutional change as the spontaneous product of benefit-cost calculus. Later, North (e.g. 1981) spelled out the role of the state in fomenting appropriate or inappropriate institutional change.
[8] Governance costs are modeled as a one-time fixed cost of switching from open access to first-best resource management. Instead of solving for the time path of the first-best stock independently, as in Lueck (2002), our model allows for the resource stock be depleted endogenously according to optimal open access management until governance becomes optimal at the existing stock.

instillation of high-powered incentives brings benefits greater than the enforcement costs of enforcement. They further note that the intermediate form of common property may be preferred in situations where its benefits net of organizational costs (including enforcement) are higher than private property. Libecap (1989) enumerates factors that contribute to the success (or failure) of common property relative to other institutions such as homogeneity of potential group members.[9]

Until the seminal work by Copeland and Taylor (2009), these comparative studies did not incorporate the dynamics of optimal resource use. Copeland and Taylor's model incorporated the costs of enforcing property rights in the form of the costs of monitoring harvests by resource users. Their steady-state analysis illuminates how the optimal institution is determined by the characteristics of the resource and the users of the resource (discount rate of resource users, intrinsic biological growth rate of renewable resources, population size, monitoring costs, harvest technology, and the demand for the harvest).[10] Our analysis aims at optimal governance of a particular resource over time as well as some applications of institutional choice across resources.

3. A model of institutional change

Consider a renewable resource management problem with an exogenous demand for harvest and governance costs. The term governance refers to any forms of harvest restrictions to a level below what would prevail under open access. Without governance, the resource would be open access and experience eventual rent dissipation. The resource manager's objective is to maximize the present value of the resource rents by choosing the dynamic harvest profile, taking into account the cost of governance. This section presents the assumptions of the model.

Resource dynamics

Let S_t be the stock of a renewable resource at time t. Without harvest, the growth of the resource stock at time t is given by $F(S_t)$ where $F(S) > 0$ for all $S \in (0, K)$, $F(0) = F(K) = 0$, and $F'' < 0$. The parameter $K > 0$ represents the carrying capacity of the resource. Without harvest, K would be the long-term steady-state stock whenever the initial stock is positive.

Net benefits of resource use

Let x_t>0 represent the harvest at time t. Given x_t, the net (flow) benefit of resource use for the society at time t is given by the consumer surplus associated with the resource good minus the cost of harvesting:

$$NB_t = \int_0^{x_t} P(\omega) d\omega - c(S_t) x_t,$$

where P is an inverse demand function and c the unit harvesting cost function. The inverse demand P is continuously differentiable with $P' \leq 0$. We assume that P is stationary over time. (We will discuss the effect of changes in demand in section 4.3.) The unit harvesting cost

[9] See Dixit (2004) for a concise summary of Libecap's (1989) discussion of preconditions for successful and unsuccessful group cooperation regarding mineral rights in California, oil fields in Texas, fisheries, and federal land policies in late nineteenth century western U.S.

[10] Several other studies (e.g. Hotte, Long and Tian 2000, Margolis and Shogren 2009) investigate the effect of an increase in the resource price on institutional change using static or steady-state analysis.

function c is decreasing and convex in stock, and satisfies $c'(S) < 0$, $c''(S) > 0$ for all S, and $\lim_{S\to 0} c(S) = \infty$.

Costs of Constitutional Governance

Without enforcement or governance, the resource is open access: harvest will continue to the point where the rent diminishes to zero. The associated harvest x_{oa} satisfies

$$P(x_{oa}(S)) = c(S).$$

Open access harvest x_{oa} at time t depends on the stock level at time t as long as unit harvest cost c is stock-dependent and $P' < 0$.

The model explicitly takes into account the costs of governance, i.e. of limiting harvests to a level below x_{oa}. Governance includes the negotiation, information processing and enforcement regarding harvesting rules (what, who, when, and how); decision-making; monitoring, bonding, and sanctions; and conflict resolution. For example, homogeneity of group membership lowers the costs of designing and enforcing harvesting rules in accordance with member differences in harvesting capacity (Libecap, 1989; Dixit, 2004).

While some of the governance costs are recurrent in nature, implementing governance (or institutional change) involves a one-time investment. In many cases governance involves a lumpy investment, and the timing of investment determines the evolution of institutions. In fact, many previous models of institutional change focused on the timing of investment (e.g. Anderson and Hill 1990, Lueck and Miceli 2007). Hence, we consider both the fixed and the variable costs of governance. Let $C \geq 0$ be the investment cost of institutional change. Let G be the variable (or recurrent) governance cost. Once investment is made at time T, the variable cost G at each time $t \geq T$ depends on the difference between the open-access harvest level and the actual harvest at time t. We also assume that G is a linear function:

$$G(x_t; x_{oa}) = g(x_{oa}(S_t) - x_{oa}),$$

where $g > 0$ is a constant. The further the resource manager restricts the harvest, the larger the governance cost. The present value of the total governance cost, evaluated at time 0, is given by

$$e^{-\rho T} C + \int_T^{\infty} e^{-\rho t} g(x_{oa}(S_t) - x_t) dt.$$

4. Optimal resource governance

4.1 Resource scarcity and institutional change

The social planner's optimization problem in the presence of governance costs is:[11]

$$\max_x \int_0^{\infty} e^{-\rho t} \left[\int_0^{x_t} P(\omega) d\omega - c(S_t) x_t - g(x_{oa}(S_t) - x_t) \right] dt$$

$$s.t. \quad \dot{S}_t = F(S_t) - x_t, \quad 0 \leq x_t \leq x_{oa}(S_t) \quad \textit{for all } t > 0$$

given $S_0 \in (0, K]$. In this problem, the fixed governance cost C is assumed to be zero. The case where C>0, as well as the role of C in institutional change, is discussed in section 4.2. What is

[11] The optimal solution to the above problem corresponds to the “second best” in the sense of Dixit (2004), i.e. optimal in the presence of transaction costs.

different from a standard renewable-resource management model is the presence of governance costs, g, and the constraint that harvest does not exceed the open-access level, $x_t \le x_{oa}(S_t)$. The maximum principle implies the following conditions for optimality:

$$P(x_t)-(c(S_t)-g)-\lambda_t \begin{cases} >0 & \Rightarrow x_t = x_{oa}(S_t); \\ =0 & \text{if } 0 < x_t < x_{oa}(S_t); \\ <0 & \Rightarrow x_t = 0. \end{cases} \tag{1}$$

$$\dot{\lambda}_t - \rho\lambda_t = c'(S_t)x_t + gx_{oa}'(S_t) - \lambda_t F'(S_t), \tag{2}$$

with the transversality condition $\lim_{t\to 0} e^{-\rho t}\lambda_t S_t = 0$, and where λ_t is the current-value shadow price of resource stock at time t. From the left-hand side of condition (1), we see that raising g has the effect of lowering the marginal harvesting cost by the same amount. When the first order condition holds with equality, the Euler equation of the system is given by

$$\begin{cases} \dot{x}_t = \dfrac{[P(x_t)-c(S_t)+g][-\rho+F'(S_t)]-c'(S_t)F(S_t)-gx_{oa}'(S_t)}{-P'(x_t)}, \\ \dot{S}_t = F(S_t)-x_t. \end{cases} \tag{3}$$

In general, dynamic resource economic models with downward sloping demand and nonlinear harvesting cost may have multiple steady-state equilibria (Clark and Munro 1975). What follows is one of the main results of this paper, which holds even when there are multiple steady states.

Proposition 1 *Suppose* $S_0 = K$. *There is a threshold marginal governance cost level* $\bar{g} > 0$ *such that (i) open access at all* t *(i.e.* $x_t = x_{oa}(S_t)$ *for all* t*) is optimal if* $g \ge \bar{g}$*; (ii) it is optimal to adopt governance and restrict harvest at a level lower than the open-access level for sufficiently large* t *if* $g < \bar{g}$.

See the appendix for the proof and remarks regarding the nature of the optimal harvest path and uniqueness of the steady state. Here we explain an intuition behind this result. Part (i) holds because the present value of the governance cost, $\int_0^\infty e^{-\rho t} g(x_{oa}(S_t)-x_t)dt$, exceeds the present value of total surplus from resource use, $\int_0^\infty e^{-\rho t}\left[\int_0^{x_t} P(\omega)d\omega - c(S_t)x_t\right]dt$, for any harvest path if the marginal governance cost is sufficiently large. Part (ii) implies that the optimal resource use may involve open access when the resource stock is abundant, followed by harvest below the open-access level as the stock converges to a steady-state level. This result follows because the constraint $x_t \le x_{oa}(S_t)$ can be binding only when stock level is large. The phase diagram in Figure 1 illustrates a case where part (ii) applies. The figure assumes an inverse demand $P(x) = 1/x$, a simple unit harvesting cost $c(S) = c/S$, and a resource growth function given by a logistic function $F(S) = rS(1-S/K)$, where $r > 0$ is the intrinsic rate of resource growth and $K > 0$ the carrying capacity of the resource. The parameter values are $\rho = 0.03$, $c = 5$, $r = 0.5$, $K = 10$, and $g = 3$. The curve ODAC represents the open-access harvest level $x_{oa}(S)$ at each stock level. The curves OE and BAE represent the optimal trajectories (the stable arm of the Euler equation system 3) when the constraint $x_t \le x_{oa}(S_t)$ is not binding. The steady state S^* is about 6.51, with the steady-state harvest level x^*=1.14. In this example, $g < \bar{g}$ (as defined in

Proposition 1) and the constraint $x_t \le x_{oa}(S_t)$ is binding for $S \ge S_g$ =8.22. Hence, the arrows CAE indicate the optimal harvest path given S_0=K. The optimal harvest level equals the open-access level (i.e. no governance) until the stock level hits S_g, beyond which the optimal harvest is lower than $x_{oa}(S_t)$ as the stable arm indicates.

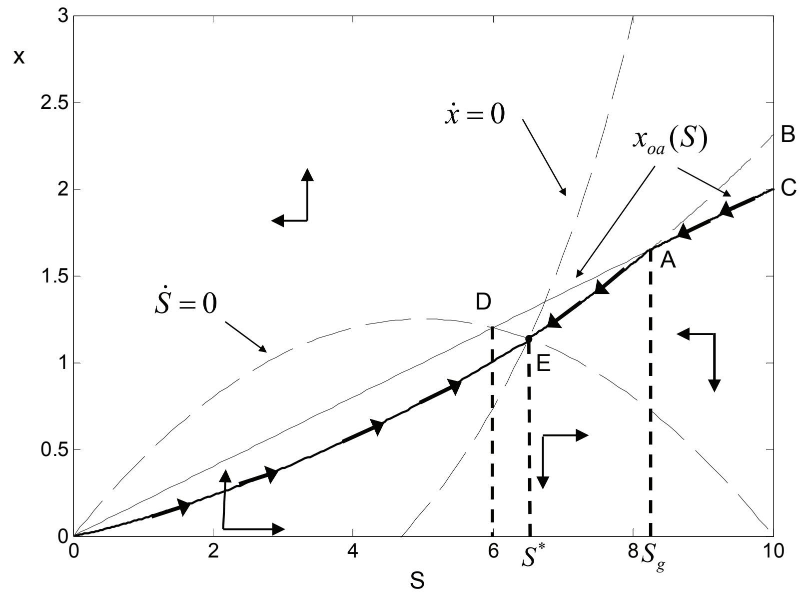

Figure 1: A case where open access is optimal when stock is large.

Thus Proposition 1 implies that resource scarcity induces governance in the optimal solution. It indicates that the governance institution of a resource is not necessarily a fixture throughout the resource's life cycle. As we observe with many cases studies listed in section 2, institutional changes occur, and the changes involve transitions from open access with no governance to common property and to private property.

While the above analysis demonstrates endogenous institutional change, we are not able to derive further analytical results regarding the dynamics of institutions, e.g. how governance responds to particular parameters. While the level of governance ($g(x_{oa}(S_t)-x_t^*)$) increases monotonically over time in the above example, the generality of this result is not certain. A model with a fixed harvest price in the following section allows us to investigate such questions.

4.2 Institutional change in a model with exogenous prices

Optimal resource management given governance costs

A constant harvest price is an assumption applicable to a small-open economy or a local small-scale natural resource taking the market price of harvest as given. As we will see below, an analysis with this assumption generates rich results regarding if and when institutional change is optimal given the cost of governance. We also consider two types of governance cost: the fixed cost C>0 and marginal governance cost g>0.

Let p>0 be the constant harvest price. Assume that $p-c(K)\geq 0$, that is, harvesting can generate positive rents at a resource stock level sufficiently large. The social planner's objective function is the present value of the flow of rents from resource use minus governance costs:

$$\int_0^\infty e^{-\rho t}\left[\{p-c(S_t)\}x_t - g(x_{oa}-x_t)\right]dt .$$

Suppose that the maximum harvest rate $\bar{x}>0$ is given at each instant (perhaps due to the finite number of resource users even under open access). We assume that $\bar{x}$ exceeds the maximum sustainable yield (MSY, $\max_{0\leq S\leq K} F(S)$). Let $\underline{S}$ be the steady-state stock level associated with open access: $p-c(\underline{S})=0$. Such $\underline{S}$ exists under the assumption on c. The open-access harvest x_{oa} depends on the current stock level and satisfies the following.

$$x_{oa}(S)=\begin{cases}0 & if\ S<\underline{S};\\ F(S) & if\ S=\underline{S};\\ \bar{x} & if\ S>\underline{S}.\end{cases}$$

Because $\bar{x}$ exceeds the maximum sustainable yield, continued open access implies that the stock converges to $\underline{S}$, where complete rent dissipation occurs. Given governance costs, the social planner's problem is to maximize the present value of resource rents by choosing the timing of investment and a time path of harvests if governance is adopted:

$$\max_{x,T}\int_0^T e^{-\rho t}[p-c(S_t)]x_{oa}(S_t)dt - e^{-\rho T}C + \int_T^\infty e^{-\rho t}\left[\{p-c(S_t)\}x_t - g(x_{oa}(S_t)-x_t)\right]dt$$

$$s.t.\quad \dot{S}_t=\begin{cases}F(S_t)-x_{oa} & for\ 0\leq t\leq T;\\ F(S_t)-x_t & for\ t>T,\end{cases}$$

$$0\leq x_t\leq x_{oa}(S_t)\quad for\ all\ t,$$

given $S_0\in(0,K]$. In the remainder of the analysis, we assume that $S_0\approx K$ in order to describe the optimal resource allocation starting at a time when the resource is untouched.

The first term of the objective function represents the rents while open access is allowed. The second term is the present value of the investment cost when institutional change occurs at time T. The last term represents the present value of rents upon governance.

If C=G=0 (no governance costs), this problem would be reduced to a widely used, standard renewable resource management model (Clark 1990). Because the objective function and the state dynamics is linear in the control variable, the solution would be the most rapid approach path to the steady state where g=0 (Spence and Starrett 1975). In what follows we demonstrate that (1) the optimal solution given g>0 continues to be the most rapid approach path as long as the investment cost C is zero; (2) however, the optimal solution is not a most rapid approach path and generates a non-monotonic resource stock transition in the presence of the investment cost C.

Case 1: No fixed cost

First suppose C=0 (no fixed cost for institutional change). Observe that the integrand can be rewritten as $\{p+g-c(S_t)\}x_t - gx_{oa}$. Hence, the marginal governance cost g has two effects: (1)

it effectively increases the marginal benefit (or the marginal revenue) of harvesting (from p to $p+g$); and (2) it decreases the instantaneous rent (by gx_{oa}).

The singular solution S^* satisfies the following equation:

$$\Phi(S^*) \equiv -c'(S^*)F(S^*) - [\rho - F'(S^*)][p+g-c(S^*)] = 0.$$

There is a stock level S' at which $p+g=c(S')$ due to the assumption on c, and hence $\Phi(S')>0$. Because Φ is continuous and $\Phi(K)<0$, a solution to $\Phi(S^*)=0$ exists between S' and K. With the additional assumption $\Phi'(S^*)<0$, there is a unique solution.[12] If $S^* < \underline{S}$, then S^* is not approachable even under open access and hence the optimal solution is open access with no governance at all *t*.

If $S^* \geq \underline{S}$, then the optimal solution is one of the following two that generates the larger present value.

1. (With governance) Choose x_{oa} as long as $S_t > S^*$ and $x^* \equiv F(S^*)$ when $S_t = S^*$. That is, choose $\bar{x}$ until the stock decreases to S^*, and then choose x^* forever.
2. (Without governance) Choose x_{oa} at all t. That is, choose $\bar{x}$ until the stock decreases to $\underline{S}$, and then choose x_{oa} forever.

The present value with governance (the first case) is

$$\Pi_g = \int_0^{\tau(S_0,S^*,\bar{x})} e^{-\rho t}\{p-c(S_t)\}\bar{x}dt + e^{-\rho\tau(S_0,S^*,\bar{x})}\frac{[p-c(S^*)]x^* - g(x_{oa}-x^*)}{\rho}.$$

where $\tau(S_0,S^*,\bar{x})$ is the time it takes the resource of size S_0 to reach the open-access level S^* given constant harvest rate $\bar{x}$:

$$\tau(S_0,S^*,\bar{x}) \equiv \int_{S_0}^{S^*}\frac{1}{F(w)-\bar{x}}dw.$$ [13]

The present value with no governance (the second case) is

$$\Pi_{ng} = \int_0^{\tau(S_0,\underline{S},\bar{x})} e^{-\rho t}\{p-c(S_t)\}\bar{x}dt \quad where\ \dot{S}_t = F(S_t)-\bar{x},\ S_o = S^*,$$

Therefore, the present value under the optimal solution is given by $\max\{\Pi_g, \Pi_{ng}\}$. By canceling out the common elements in Π_{ng} and the first term of Π_g, we obtain the following proposition.

Proposition 2

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[12] Function Φ has a negative first-order derivative if functions *c* and *F* take commonly assumed functional forms ($c(S)=c/S$ and *F* is logistic ($F(S)=rS(1-S/K)$) or is a Gompertz growth function $F(S)=rS\ln(K/S)$).

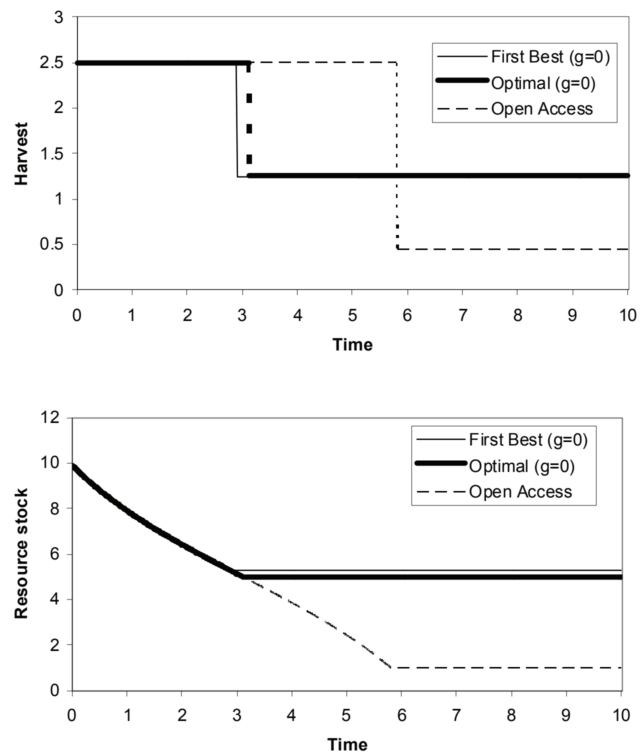
[13] This equality holds because $dS_t/dt = F(S_t)-\bar{x}$ implies $dt = dS_t/(F(S_t)-\bar{x})$, and hence $\int_0^\tau dt = \int_{S_0}^{S^*}\frac{1}{F(w)-\bar{x}}dw$.

In the constant price model, suppose C=0. Given any initial stock $S_0 \geq S^*$*, the optimal solution involves positive governance costs if and only if*

$$\frac{[p-c(S^*)]x^* - g(x_{oa}-x^*)}{\rho} \geq \int_0^{\tau(S^*,\underline{S},\bar{x})} e^{-\rho t}\{p-c(S_t)\}\bar{x}dt \quad where\ \dot{S}_t = F(S_t)-\bar{x}.$$

If the inequality holds, then (i) the optimal investment timing for institutional change from open access to governance is given by $\tau(S_0, S^*, \bar{x})$*; (ii) the resource stock decreases monotonically to the steady state; (iii) the shadow price of resource increases monotonically to the steady-state level; and (iv) the steady state S* is smaller than the first best level that would prevail if g=0.*

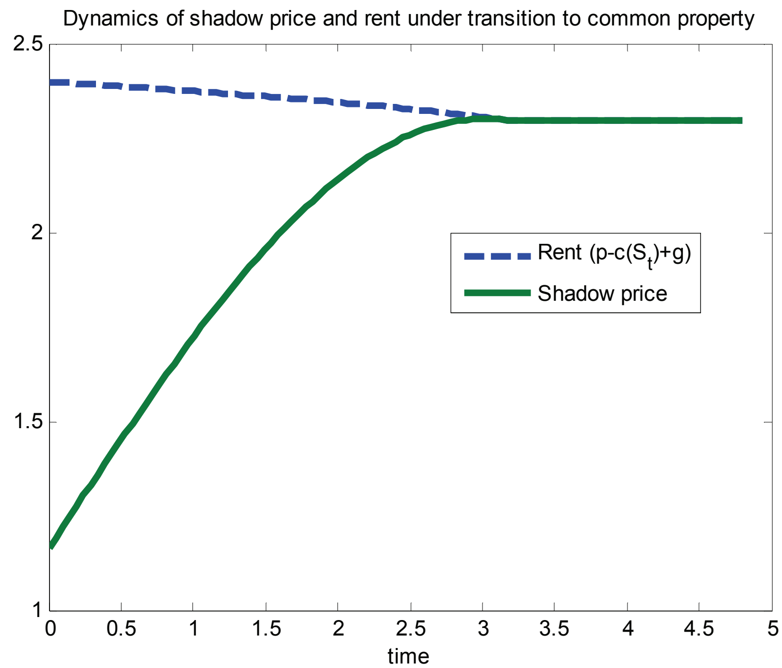
Figure 2 describes a case where the above condition holds. Under optimal governance, harvest is restricted to the steady-state level x^* before the stock reaches the open access level $\underline{S}$. The stock is maintained at the singular solution S^*, and generates positive rents.



Note: The figure is based a constant-price model in section 4.2. The parameter values are ρ= 0.03, $c(S)$ = 1/S, p=2, r=0.5, K=10, $\bar{x}$ = 2.5, g= 1, and $S_0 = 9.9$.

Figure 2: Optimal governance for a constant-price model.

Figure 3 describes the dynamics of the rent and the shadow price of the resource under transition to governance. The rent is defined by p-$c(S_t)$+g, the marginal net benefit of harvesting in each instant. The shadow price is the costate variable associated with the resource stock under the optimal solution, and is equal to the derivative of the value function. Given constant harvest price and $c' < 0$, the rent decreases over time as stock is depleted. This fact may appear inconsistent with the conjecture that increased resource scarcity induces institutional change. However, this puzzle is resolved if we look at the dynamics of the shadow price of the resource—the fundamental measurement of resource scarcity. In fact, the shadow price increases as resource becomes scarce (Proposition 2 part iii). They converge to the steady-state value when the stock reaches the steady state level (at time t=3.16 in this case). While the rent decreases monotonically on the transition path, the shadow price increases monotonically, reflecting increased resource scarcity.



Note: The figure is based on a constant-price model with the parameter values used for Figure 2.

Figure 3: Rent and shadow price under transition to governance (C=0).

Case 2: Positive fixed cost

In the presence of fixed investment cost, the most rapid approach path is not optimal.

Proposition 3 *In the constant price model, suppose* $S_0 > S^*$ *(the steady state when governance is adopted) and adopting a governance structure involves a fixed-cost investment* C.

(i) *Adopting governance is optimal if*

$$C \le \frac{[p-c(S^*)]F(S^*) - g(\bar{x}-F(S^*))}{\rho} - \int_0^{\tau(S^*,\underline{S},\bar{x})} e^{-\rho t}[p-c(S_t)]\bar{x}dt. \qquad (1)$$

where $S_0 = S^*$ *and* $\dot{S}_t = F(S_t) - \bar{x}$ *on the right-hand side.*

(ii) *When adopting governance is optimal, the optimal timing of investment implies a non-monotonic stock path: the resource stock falls below* S^*, *and then increases to and stays at* S^* *thereafter.*

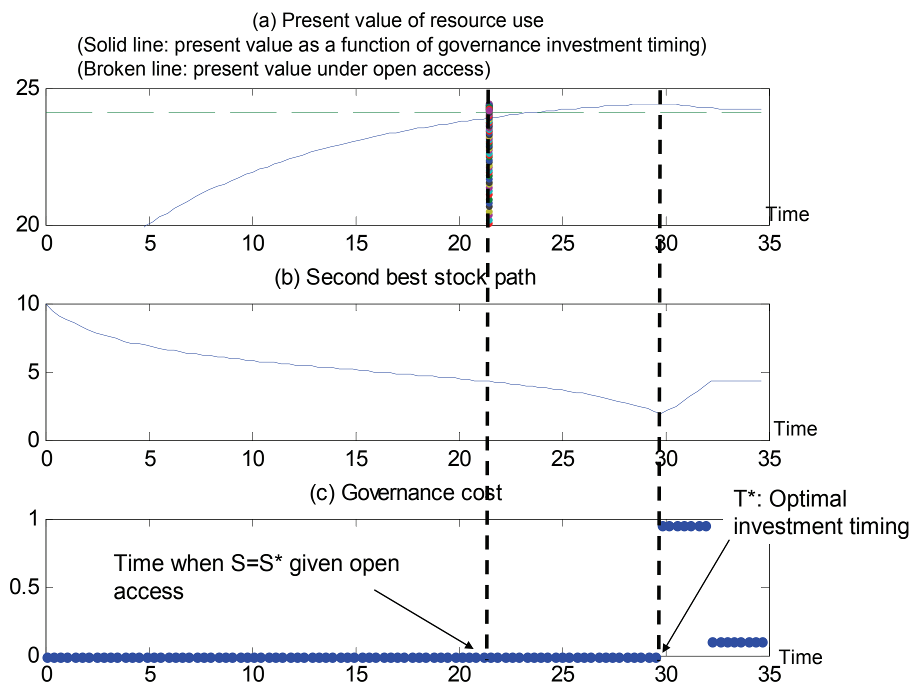
Part (i) follows by comparing the present values under open access versus under governance. Part (ii) follows because the marginal net benefit of delaying governance is positive when the stock level is the steady state under governance. We provide a brief sketch of this result (see the appendix for a complete proof). At an arbitrary time *T*, the marginal benefit of delaying governance is a sum of two components: (1) the marginal increase in rents from resource use by allowing open access and (2) the marginal savings from delaying the fixed-cost investment for governance:

$$e^{-\rho T}[p-c(S_T)]\bar{x}+\rho e^{-\rho T}\left(C+\frac{g\bar{x}}{\rho}\right).$$

The marginal cost of delaying governance is the opportunity cost of delaying governance by an instant:

$$\frac{d}{dt}\left\{-e^{-\rho(T+\tau(S_T,S^*,0))}\frac{[p-c(S^*)+g]x^*}{\rho}\right\}=\rho\left(1+\frac{\partial\tau}{\partial S_T}\frac{dS_T}{dT}\right)e^{-\rho(T+\tau(S_T,S^*,0))}\frac{[p-c(S^*)+g]x^*}{\rho}.$$

Here the opportunity cost arises because (1) the stock decreases at rate $|F(S_T)-\bar{x}|$ under open access; and (2) under governance, it takes longer for a smaller stock to return to the steady state. Evaluating the marginal costs and benefits at the steady-state stock level S^*, we observe that the marginal benefit of delaying exceeds the marginal cost by an amount $e^{-\rho T}\rho C>0$. Hence, if C>0 and if governance is optimal, then the optimal resource transition exhibits non-monotonicity: the resource is driven down to a level below the steady state, investment for governance is made and harvest is restricted to zero until the stock recovers to the steady-state level, and then the harvest is controlled at the steady-state level $F(S^*)=x^*$ thereafter. Thus, even without exogenous price shocks, it is optimal to allow the stock to fall below the steady-state level—there is a benefit from delaying governance due to the investment cost for institutional change.



Note: The figure is based a constant-price model in section 4.2. The parameter values are ρ= 0.1, $c(S)$ = 1/S, p=2, r=0.5, K=10, $\bar{x}$ = 1.37, C= 7.9, g=0, and $S_0=10$.

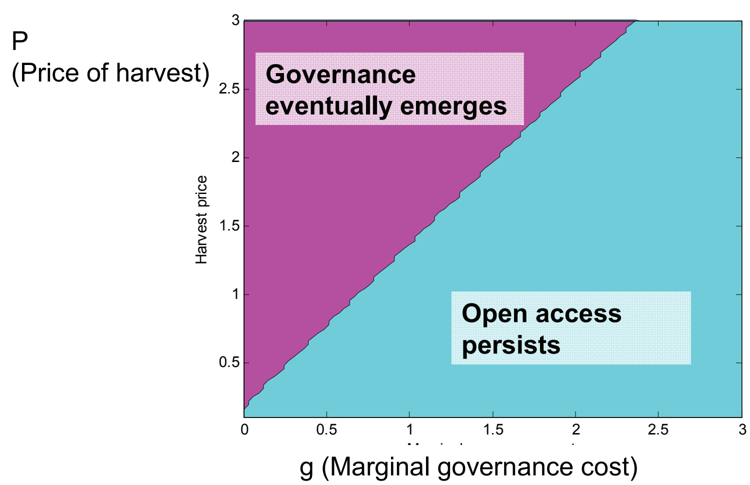
Figure 4: Resource Kuznets Curve: Overshooting given an investment cost for institutional change.

Figure 4 illustrates a case where governance is optimal. Panel (a) represents the present values of governance as a function of investment timing (the solid line) and under open access (the broken line). Notice that the present value of governance increases even after stock reaches the steady state level (at t=21.3). The optimal investment timing is T^*=29.5, when it becomes optimal to restrict harvest (to zero) so that stock grows back to the steady state level. This example illustrates an interesting case where adopting governance when the stock reaches the steady-state level S^* for the first time generates a lower present value than open access while adopting governance at the optimal timing T^* is superior to open access. Panel (b) describes the dynamics of the resource stock while panel (c) plots the (variable) governance cost over time. Both dynamics are non-monotonic because of overshooting.

This overshooting result is consistent with Libecap's (2008) observation that, in many cases, property rights are adopted to natural resource management only after resource is sufficiently degraded. As the panel in the middle illustrates, it is also consistent with empirical observations of a natural resource Kuznets Curve whereby a resource stock such as standing timber is depleted and later built back up, albeit not to its first-best steady state (e.g. Panayatou 1993, Foster and Rosenzweig 2003).

Governance costs and institutional change
What follows is a number of observations regarding if (Proposition 4) and when (Proposition 5) switching from open access to governance is optimal.

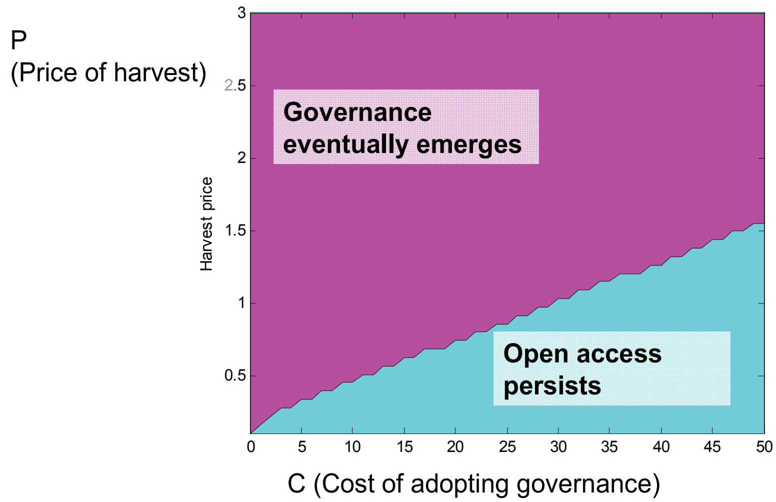
Proposition 4 *If transition to governance (from open access) is optimal given* $\underline{g}>0$*, then it is optimal for any* $g<\underline{g}$*. If transition to governance is optimal given* $\underline{C}>0$*, then it is optimal for any* $C<\underline{C}$*. If transition to governance is optimal given* $\underline{p}>0$*, then it isoptimal for any* $p>\underline{p}$.



The figure assumes ρ = 0.03, $c(S)$ = 1/S, $F(S)$ = rS(1-S/K) with r = 0.5, K = 1, $\bar{x}$ = 2.5 (= 2*MSY), and S_0=K. p ranges from 0.11 to 3, and g from 0 to 3.

Figure 4: Institutional change and marginal governance cost.

See the appendix for the proof. Proposition 4 states that the gains from adopting governance is decreasing in the governance costs and increasing in the harvest price, as illustrated in Figures 4 and 5. Figure 4 describes the relationship between institutional change, harvest price, and marginal governance cost. Given $S_0=K$, transition to governance is optimal if the parameter values fall under the upper triangular region in the figure. The higher the harvest price and the lower the governance cost *g*, the larger the net benefit of governance over open access.



The figure assumes ρ = 0.03, $c(S) = 1/S$, $F(S) = rS(1\text{-}S/K)$ with $r = 0.5$, $K = 1$, $\overline{x} = 2.5$ (= 2*MSY), and $S_0=K$. *p* ranges from 0.11 to 3, and *C* from 0 to 50.

Figure 5: Institutional change and the cost of adopting goverannce

Figure 5 describes the relationship between institutional change, harvest price, and the fixed cost of adopting governance. Again, eventual transition to governance is preferred to perpetual open access if the harvest price is high or if investment cost is small.

We obtain a monotonic relationship between harvest price and institutional transition. The optimal timing of switching to governance is delayed if harvest price is larger.

Proposition 5

Suppose S_0 exceeds the steady state upon governance. Let T be the optimal timing of governance.*

(i) $\frac{\partial T^*}{\partial g} > 0$ *provided T*>0. For sufficiently large g, governance is not optimal ($T^* = \infty$).*

(ii) $\frac{\partial T^*}{\partial C} > 0$ *provided T*>0. For sufficiently large C, governance is not optimal ($T^* = \infty$).*

(iii) $\frac{\partial T^*}{\partial p} > 0$ *provided T*>0.*

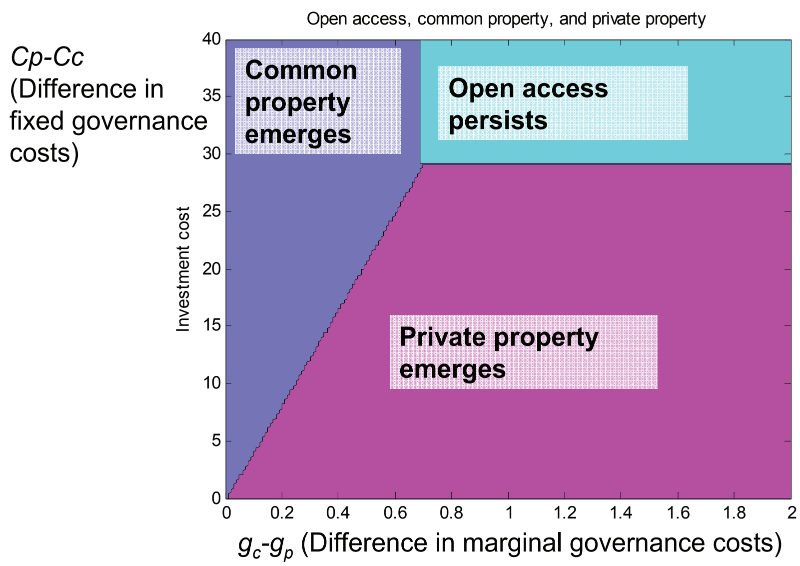
See the appendix for the proof. This proposition holds because the optimal steady-state stock decreases and the time it takes for resource to reach the steady-state level increases as *p* increases. Similarly, the optimal switching time is later if *g* is larger because the steady state under governance is decreasing in the marginal governance cost. With *g* large enough, perpetual open access is optimal and governance never adopted.

So far, we study institutional change from open access to a generic governance structure with fixed and variable costs of governance. Here we distinguish two major forms of governance: common property and private property. Let C_c (C_p) be the fixed governance cost of introducing common (private) property and g_c (g_p) be the corresponding marginal governance cost. We assume that the fixed cost is lower and the variable cost is larger under common property:

$$C_c < C_p, \quad g_c > g_p.$$

While implementing private property is more costly than initiating collective action under common property, governance under private property is less costly.

Figure 6 illustrates the optimal institutional change when both common and private property regimes are available.



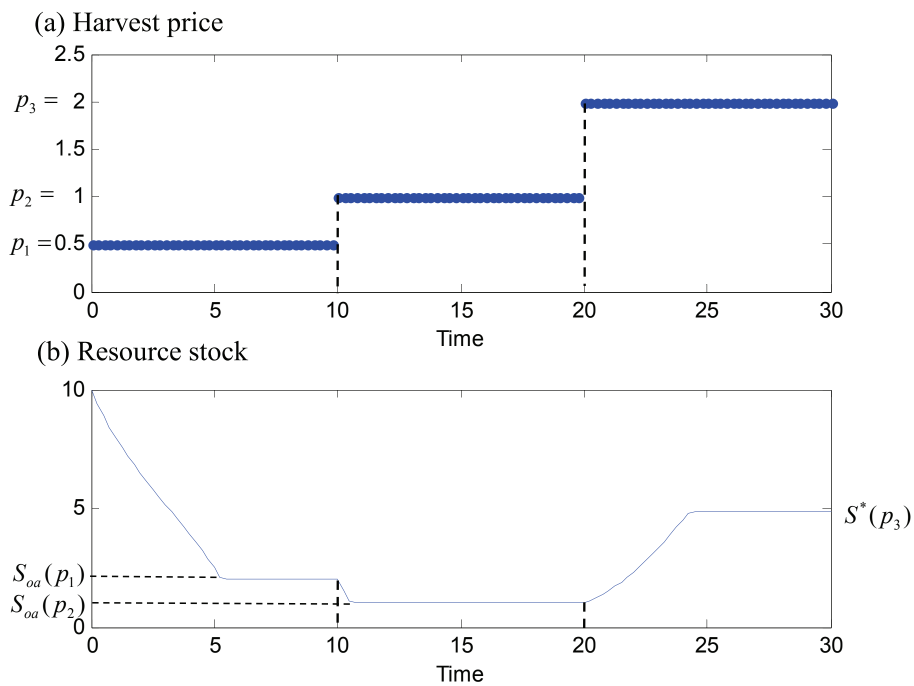
The figure assumes rho = 0.05, p=1, c(S) = 1/S, r= 0.5, K=10, $\bar{x}$ = 2*MSY =4, $S_0 = K$, and C_c=g_p=0. Axes measure $C_p - C_c$ (investment cost) between 0 and 40, and $g_c - g_p$ between 0 and 2.

Figure 6: Open access, common property versus private property.

Common property is preferred if its marginal governance cost is smaller than the marginal governance cost under private property. Private property is preferred if its fixed governance cost is small relative to the fixed cost of adopting common property.

4.3 Institutional change due to price shocks

It turns out that unexpected increase in harvest price can cause the optimal transition of resource stock to be non-monotonic even if the fixed cost of institutional change is zero. This is because the steady-state stock under open access decreases as harvest price increases, and not all price increases justify institutional change. Figure 8 describes unexpected price increases from $p_1 = 0.5$ to $p_2 = 1$ at t=10 and from p_2 to $p_3 = 2$ at t=20 (panel a), with the resulting optimal resource stock trajectory (panel b). Given the parameter values, the optimal governance is to allow open access at all *t* when the harvest price equals p_1 or p_2. Therefore, the stock decreases under these price levels, first to $S_{oa}(p_1)$, and then $S_{oa}(p_2)$ (the steady-state stock levels under open access given $p = p_1$ and $p = p_2$). However, when price increases further to p_3, governance is justified: harvest is restricted to zero until the stock reaches $S^*(p_3)$, the steady state given $p = p_3$. As a result, the resource stock trajectory exhibits a non-monotonic path.



Note: The figure is based a constant-price model with no fixed cost. The parameter values are ρ= 0.03, *r*=0.5, *K*=10, $\bar{x}$ = 2.5, and *g*=1.

Figure 7: Optimal governance given unexpected increases in harvest price.

Hence, a monotonic price increase does not necessarily induce monotonic changes in the resource stock. This observation is consistent with several studies that discuss intertemporal changes in resource stock and institutions as resource prices change. The change from p_1 to p_2, where price increases but stock decreases, corresponds to the case of buffalo as documented in Taylor (2009) while the change from p_1 (or p_2) to p_3 corresponds to the case of beaver as discussed in Demsetz (1967).

5. Discussion

We provide a dynamic model of natural resource governance to analyze and illustrate how institutional change occurs with depletion (or accumulation) of a natural resource. The analysis relates resource governance in the steady state to resource/economic characteristics and also to changes in resource scarcity as the resource stock transitions to its steady state level. The resource manager incurs a cost of institutional governance in order to restrict resource use to a level below what would prevail under open access. The model provides a precise sense in which governance becomes optimal once resource scarcity has reached a critical level and open access is optimal when resource abundance renders the benefits from adopting governance less than its costs. Unless the governance cost is above some threshold, it becomes optimal to switch from open access to positive governance and positive resource rents once the resource has been depleted to a specific stock level (Proposition 1). If governance costs are sufficiently large, the optimal resource management regime is open access at all resource stock levels. Inasmuch as extinction may be optimal even in first-best models (Spence, 1973), the presence of governance costs increases the likelihood of optimal extinction.

The dynamics of resource scarcity—as represented by the shadow value of resource—depend on the nature of governance costs. With a constant harvest price and zero fixed costs of institutional change, governance is adopted, and open access ceased, once the resource has been depleted to its steady-state level. Both the resource stock and its shadow price change monotonically over time (Proposition 2).

In contrast, if institutional change requires positive set-up costs, then overshooting occurs (Proposition 3). Open access is allowed until the resource stock falls below the steady-state level, and then harvest is restricted until the stock recovers to the steady state. Similarly, the dynamics of governance costs is also non-monotonic: they start with a low level when resource is abundant, followed by an increase and a decrease to the steady-state level. That is, fixed costs of institutional change result in a non-monotonic profile of the optimal resource stock. Such a transition path to the steady state is consistent with a *Resource Kuznets Curve* that has been observed with some resources. Unexpected monotonic increases in harvest price also imply a non-monotonic resource-stock trajectory.

Our analysis also describes how the timing of institutional change depends on the costs and benefits of resource management. In particular, the optimal timing is delayed if the harvest price is larger or if the cost of governance is larger (Propsosition 5). While a higher price increases the gains from institutional change, higher governance costs indicate lower net benefits of institutional change (Proposition 4).

That the steady-state institutions differ for different resources has been discussed and explained (e.g. Copeland and Taylor 2009). Our model and simulation results illuminate the timing of institutional change for a given resource according to governance costs and resource scarcity. As Copeland (2005) argues, work on the effects of international trade (or price changes in general) on renewable resources with endogenous institutional change is still in its early stages. This paper's result adds to the existing literature by describing institutional change not only due to changes in prices or technologies but due to endogenous change in resource scarcity.

A number of extensions would be useful. One is to consider how changes in demand, harvesting costs, and governance costs over time influence institutional change. Another is to analyze how sequential transitions from open access to common property and then to private property occur with or without changes in demands and technologies for harvesting and governance. With constant price and no fixed costs, institutional change occurs only once. It may be possible to generate a transition from common to private property for the case of increasing price and changing governance costs.

We focused on explaining the optimal institutional changes given the cost of institutional governance. An analysis of how competitive and strategic interactions among resource users, and those between incumbent users and entrants, influence the equilibrium institutional changes is left for future research (see e.g., de Meza and Gould, 1992, Scott 2008).

Appendix
Proof of Proposition 1
Step 1. The solution without constraint $x_t \le x_{oa}(S_t)$.
The necessary conditions for an interior solution includes

$$P(x_t) - (c(S_t) - g) = \lambda_t, \quad \text{(A1)}$$

$$\dot{\lambda}_t - \rho\lambda_t = c'(S_t)x_t + gx_{oa}'(S_t) - \lambda_t F'(S_t). \quad \text{(A2)}$$

This is the necessary condition for the interior first best solution when the unit harvesting cost is $c(S_t) - g$ and when the constraint $x_t \le x_{oa}(S)_t$ is not imposed:

$$\max_x \int_0^\infty e^{-\rho t}\left[\int_0^{x_t} P(\omega)d\omega - (c(S_t) - g)x_t - gx_{oa}(S_t)\right]dt$$

$$\text{s.t.} \quad \dot{S}_t = F(S_t) - x_t, \quad 0 \le x_t.$$

Step 2. Unconstrained optimal harvest is increasing in stock.
Differentiate both sides of condition (A1) with respect to t, and we have

$$P'(x_t)\dot{x}_t - c'(S_t)\dot{S}_t = \dot{\lambda}_t.$$

Together with condition (A2), we obtain the Euler equation for harvest:

$$\dot{x}_t = \frac{[P(x_t) - c(S_t) + g][-\rho + F'(S_t)] - c'(S_t)F(S_t) - gx_{oa}'(S_t)}{-P'(x_t)}.$$

Similarly, the equation of motion determines the Euler equation for resource stock. Figure 1 represents the phase diagram given these two equations.
(In the figure, S_ρ represents the stock level such that $\rho = F'(S_\rho)$, i.e. the steady-state stock level if the unit harvest cost were constant. As $S_t \to S_\rho$ from above, $P(x_t)$ must increase to infinity for $\dot{x}_t = 0$ to hold. For $S_t \le S_\rho$, $\dot{x} > 0$ at all $x_t \ge 0$. Hence, the $\dot{x} = 0$ isocline touches the S axis at S_ρ, and is positively sloped for $S > S_\rho$.) Observe that $\dot{x}_t < 0$ at S_t to the right of the $\dot{x} = 0$ isocline, and $\dot{S}_t > 0$ at x_t below the $\dot{S}_t = 0$ isocline. Hence, $\dot{x}_t < 0$ when $S_t > S^*$ along the optimal trajectory to the steady state (the convergent separatix), as indicated in the phase diagram. Therefore, the optimal harvest is increasing in stock.
Step 3. $x_t^* = x_{oa}(S_t)$ is possible when S_t is large.
Note that the optimal harvest must not exceed the open-access level:

$$x_t \le x_{oa}(S_t)),$$

where $P(x_{oa}(S_t)) \equiv c(S_t)$ or $x_{oa}(S_t) \equiv P^{-1}(c(S_t))$. When S_t is large, the curve $x_{oa}(S_t)$ in the diagram lies below the $\dot{x}_0$ isocline because

$\dot{x}_t \,|_{(x_{oa}(S_t),S_t)} = \dfrac{g[-\rho + F'(S_t)] - c'(S_t)F(S_t) - gx_{oa}'(S_t)}{-P'(x_t)} > 0$. For some parameter values, the unconstrained optimal harvest x_t^{**} is close to the $\dot{x}_t = 0$ isocline and hence the constraint for optimal governance, $x_t \le x_{oa}$ can be binding. ■

Remark:

1. When g is large enough, it follows that $\dot{x}_t < 0$ for all x_t for S_t large enough. In such a

case, the phase diagram would look like the following (Figure A1). With such large g, the saddle path of the interior solution is qualitatively similar to the case with a smaller g. With a large g, the corner solution $x_t = x_{oa}(S_t)$ for all t will be the optimal solution.

2. The above diagrams are based on numerical example with a unique interior steady state. In general, there may be multiple steady states because $\dot{x}_t = 0$ isocline may intersect the $\dot{S}_t = 0$ for twice or more. This result is well known in the resource economics literature (e.g. Gordon and Munro 1975). Even with multiple steady states, the statement of the propositon is valid when $S_0 = K$ or if S_0 is large enough to exceed the saddle point associated with the largest stock level.

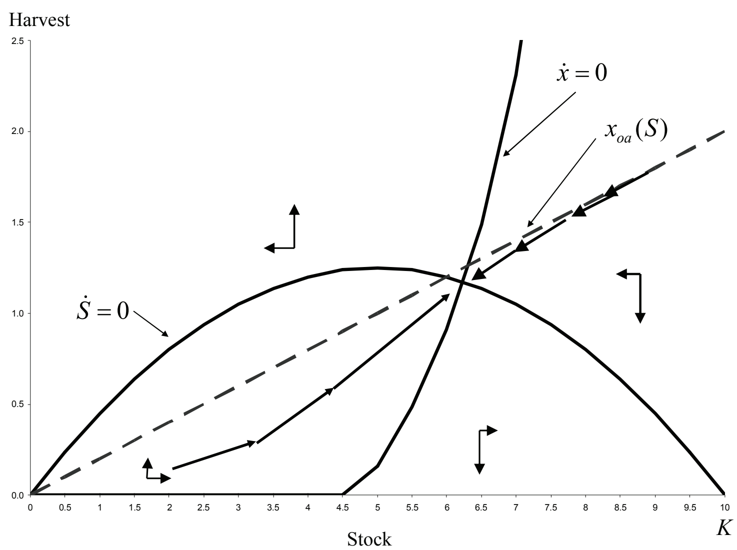


Figure A1: Phase diagram when *g* is large

Proof of Proposition 2 (iii)

Let V_g be the value function when governance is adopted at the optimal timing:

$$V_g(S) = \begin{cases} \int_0^{\tau(S,S^*,\bar{x})} e^{-\rho t}[p - c(S_t)]\bar{x}dt + e^{-\rho\tau(S,S^*,\bar{x})}\Pi^* & if\ S \geq S^* \\ & where\ S_t = F(S_t) - \bar{x} \quad for\ t \in (0, \tau(S,S^*,\bar{x})); \\ -\dfrac{(1-e^{-\rho\tau(S,S^*,0)})g\bar{x}}{\rho} + e^{-\rho\tau(S,S^*,0)}\Pi^* & if\ S < S^*, \end{cases}$$

where $\Pi^* \equiv \dfrac{[p - c(S^*)]x^* - g(\bar{x} - x^*)}{\rho}$, the steady-state present value of governance.

Let $\lambda(S) \equiv V_{g'}(S)$ be the shadow price of resource stock under governance. We show that λ is decreasing for $S > S^*$.

For $S > S^*$, the first order derivative of V_g is given by

$$V_{g'}(S) = e^{-\rho\tau(S,S^*,\bar{x})}[p - c(S^*)]\bar{x}\frac{\partial\tau(S,S^*,\bar{x})}{\partial S} + \int_0^{\tau(S,S^*,\bar{x})} e^{-\rho t}\left[-c'(S_t)\frac{\partial S_t}{\partial S}\right]\bar{x}dt$$

$$-\rho\frac{\partial\tau(S,S^*,\bar{x})}{\partial S}e^{-\rho\tau(S,S^*,\bar{x})}\Pi^*$$

$$= e^{-\rho\tau(S,S^*,\bar{x})}\frac{\partial\tau}{\partial S}\left[\{p - c(S^*)\}\bar{x} - \{p - c(S^*)\}x^* + g(\bar{x} - x^*)\right] + \int_0^{\tau(S,S^*,\bar{x})} e^{-\rho t}\left[-c'(S_t)\frac{\partial S_t}{\partial S}\right]\bar{x}dt,$$

where the first two terms follow from the Leibniz's rule. The second-order derivative is

$$V_{g''}(S) = \left\{-\rho\left(\frac{\partial\tau}{\partial S}\right)^2 + \frac{\partial^2\tau}{\partial S^2}\right\}e^{-\rho\tau(S,S^*,\bar{x})}\left[\{p - c(S^*)\}\bar{x} - \{p - c(S^*)\}x^* + g(\bar{x} - x^*)\right]$$

$$+ e^{-\rho\tau(S,S^*,\bar{x})}\left[-c'(S^*)\frac{\partial S^*}{\partial S}\right]\bar{x}\frac{\partial\tau}{\partial S} + \int_0^{\tau(S,S^*,\bar{x})} e^{-\rho t}\left[-c''(S_t)\frac{\partial S_t}{\partial S} - c'(S_t)\frac{\partial^2 S_t}{\partial S^2}\right]\bar{x}dt,$$

where $\frac{\partial\tau(S,S^*,\bar{x})}{\partial S} = \frac{\partial}{\partial S}\int_S^{S^*}\frac{1}{F(\omega) - \bar{x}}d\omega = -\frac{1}{F(S) - \bar{x}} > 0$ and $\frac{\partial^2\tau}{\partial S^2} = \frac{F'(S)}{\{F(S) - \bar{x}\}^2}$. Hence

$$-\rho\left(\frac{\partial\tau}{\partial S}\right)^2 + \frac{\partial^2\tau}{\partial S^2} = \frac{-\rho}{\{F(S) - \bar{x}\}^2} + \frac{F'(S)}{\{F(S) - \bar{x}\}^2} = \frac{-\rho + F'(S)}{\{F(S) - \bar{x}\}^2} < 0$$

for all $S > S^*$ because $\rho > F'(S^*)$ and $F'' < 0$. So the first term of $V_{g''}$ is negative. The second term is zero because $\partial S^*/\partial S = 0$. The third term is negative because $c'' > 0$, $\frac{\partial S_t}{\partial S} > 0$, $c' < 0$, and $\frac{\partial^2 S_t}{\partial S^2} < 0$. It follows that $\lambda'(S) = V_{g''}(S) < 0$ for all $S > S^*$. Because the stock is monotonically decreasing under governance given $S_0 > S^*$, it follows that the shadow value of resource increases monotonically until the stock reaches the steady state S^*. More precisely, the realized path of shadow price λ^* satisfies $d\lambda_t^*/dt = \lambda'(S)dS/dt = \lambda'(S)[F(S) - \bar{x}] < 0$ for all $t \in (0, \tau(S,S^*,\bar{x}))$. ■

Proof of Proposition 3

Suppose governance involves fixed cost $C > 0$ and marginal governance cost $g \geq 0$. Let T^* be the optimal timing of investment (to switch to governance). $x^* \equiv F(S^*)$, the steady-state harvest upon governance. Let $\tau(S_1, S_2, x) \equiv \int_{S_1}^{S_2}\frac{1}{F(S) - x}dS$ be the time it takes for the resource to reach the level S_2 starting from S_1 with harvest rate x in each instant. Let $\tau^* \equiv \tau(S_0, S^*, \bar{x})$. Once invest for governance is made, the optimal harvest rule x_g^* is given by

$$x_g^*(S)=\begin{cases}\bar{x} & if\ S>S^*;\\ x^* & if\ S=S^*;\\ 0 & if\ S=S^*.\end{cases}$$

Because the optimal harvest equals the open-access level $\bar{x}$ for any t where $S_t>S^*$, it follows that $T^*\geq\tau^*$ (i.e. it is never optimal to invest when open access is optimal). The present value of governance with timing T between τ^* and $\tau_{oa}\equiv\tau(S_0,S_{oa},\bar{x})$ (i.e. the time when stock reaches the open-access steady state level when open access is allowed at all time) is given by

$$V(T)=\int_0^T e^{-\rho t}[p-c(S_t)]\bar{x}dt-e^{-\rho T}C-e^{-\rho T}\frac{1-e^{-\rho\tau(S_T,S^*,0)}}{\rho}g\bar{x}+e^{-\rho(T+\tau(S_T,S^*,0))}\frac{[p-c(S^*)]x^*-g(\bar{x}-x^*)}{\rho}$$
$$=\int_0^T e^{-\rho t}[p-c(S_t)]\bar{x}dt-e^{-\rho T}\left(C+\frac{g\bar{x}}{\rho}\right)+e^{-\rho(T+\tau(S_T,S^*,0))}\frac{[p-c(S^*)+g]x^*}{\rho}.$$

The first term represents the present value of harvesting until governance is adopted during which $\dot{S}_t=F(S_t)-\bar{x}$. The second term is the present value of the sum of the fixed and the variable governance costs. The variable cost component represents the present value of governance costs to restrict harvest to zero from the time governance is adopted (T) until the time stock returns to the steady state level ($T+\tau(S_T,S^*,0)$) and then to x^* after the steady state is reached). The third term is the present value of rents under governance. The discount factor $e^{-\rho(T+\tau(S_T,S^*,0))}$ involves two time periods, T and $\tau(S_T,S^*,0)$. (After investment occurs at time $T>\tau^*$, the resource stock is below the optimal steady state S^*. Once governance is adopted, the optimal harvesting rule is given by x^* specified above, and hence zero harvest is chosen until the stock recovers to the level S^*. The time it takes for S_T to increase to S^*, given zero harvests, is given by $\tau(S_T,S^*,0)$.)■

Proof of part (i). Suppose T^* maximizes V. Because $V(T^*)\geq V(\tau(S_0,S^*,\bar{x}))$ by the definition of T^* and the present value of rents under open access is given by $V_{oa}\equiv\int_0^{\tau(S_0,\underline{S},\bar{x})}e^{-\rho t}[p-c(S_t)]\bar{x}dt$, a sufficient condition for governance to be preferred to open access is $V(\tau(S_0,S^*,\bar{x}))\geq V_{oa}$. Cancelling out the common parts from both sides and arranging terms, we obtain inequality (1) as the sufficient condition.

Proof of part (ii). The first order derivative of V is

$$V'(T)=e^{-\rho T}[p-c(S_T)]\bar{x}+\rho e^{-\rho T}\left(C+\frac{g\bar{x}}{\rho}\right)-\rho\left(1+\frac{\partial\tau}{\partial S_T}\frac{dS_T}{dT}\right)e^{-\rho(T+\tau(S_T,S^*,0))}\frac{[p-c(S^*)+g]x^*}{\rho},$$

where

$$1+\frac{\partial\tau}{\partial S_T}\frac{dS_T}{dT}=1+\frac{\partial}{\partial S_T}\int_{S_T}^{S^*}\frac{1}{F(S)}dS\cdot[F(S_T)-\bar{x}]=1-\frac{F(S_T)-\bar{x}}{F(S_T)}=\frac{\bar{x}}{F(S_T)}>0,$$

for all T (because $S_T\in(0,K)$). It follows from $F(S^*)=x^*$ and $\tau(S^*,S^*,0)=0$ that the derivative evaluated at time τ^* satisfies

$$V'(\tau^*) = e^{-\rho T}[p - c(S^*)]\bar{x} + e^{-\rho T}\rho\left(C + \frac{g\bar{x}}{\rho}\right) - e^{-\rho T}\left[\{p - c(S^*) + g\}x^* \frac{\bar{x}}{F(S^*)}\right] = e^{-\rho T}\rho C > 0.$$

This inequality implies that the present value of governance when investment occurs at a time later than τ^* is larger than the present value when τ^* is the switching time. ■

Proof of Proposition 4

Let $W(S; S_0, g)$ be the present value of resource use, given marginal governance cost g and initial stock S_0, when the most rapid approach path to S is taken:

$$W(S; S_0, g) = \int_0^{\tau(S_0, S, \bar{x})} e^{-\rho t}\{p - c(S_t)\}\bar{x}dt + e^{-\rho\tau(S_0, S, \bar{x})} \frac{p - c(S)F(S) - g(\bar{x} - F(S))}{\rho}.$$

Clearly, we have $\max W(S,; S_0, g) = W(S_g^*; S_0, g)$. If $0 \le g' < g$, we have

$$W(S_{g'}^*; S_0, g') > W(S_g^*; S_0, g') > W(S_g'; S_0, g),$$

where the first inequality follows because the most rapid approach path $S_{g'}^*$ is optimal given g' and the second inequality holds because function W is strictly decreasing in the marginal governance cost g. The proof that the gains from transition to governance is decreasing in the fixed cost for adopting it, C, works in a similar way. ■

Proof of Proposition 5

Let S_c^* be the steady state under optimal governance. Governance (restricting harvest below x_{oa} starts at time $\tau(S_0, S_c^*, \bar{x})$, when the stock reaches the steady state given constant open-access harvest rate $\bar{x}$. We have

$$\frac{d\tau(S_0, S_c^*, \bar{x})}{dg} = \frac{d\tau(S_0, S_c^*, \bar{x})}{dS_c^*}\frac{dS_c^*}{dg},$$

where $\frac{d\tau(S_0, S_c^*, \bar{x})}{dS_c^*} = \frac{1}{F(S_c^*) - \bar{x}} < 0$. As for the sign of $\frac{dS_c^*}{dg}$, recall that the singular solution is given by

$$\Phi(S_c^*) \equiv -c'(S_c^*)F(S_c^*) - [\rho - F'(S_c^*)][p + g - c(S_c^*)] = 0.$$

Totally differentiate the expression with respect to S_c^* and g, and we have

$$\Phi'(S_c^*)dS^* - [\rho - F'(S_c^*)]dg = 0, \quad \textit{i.e.}\ \frac{dS^*}{dg} = \frac{\rho - F'(S_c^*)}{\Phi'(S_c^*)},$$

where $\rho - F'(S_c^*) > 0$ and $\Phi'(S_c^*) < 0$ by the assumption. Hence, $\frac{d\tau(S_0, S_c^*, \bar{x})}{dg} > 0$. The proof that the optimal timing for institutional transition is increasing in C and p works in a similar way. ■

Existence and uniqueness of the optimal governance solution with constant harvest price

We analyze the existence, uniqueness and the optimality of the singular solution to the optimal governance problem with constant harvest price. In the problem, the Hamiltonian is linear in the control variable. Spence and Starrett (1975) discuss the nature of the solutions to such problems. Following their argument, we can express the problem in terms of the state variable S_t alone as follows:

$$\max_{(S_t)_{t>0}} \int_0^\infty e^{-\rho t} W(S_t)dt \text{ subject to } S_t \in [0,K] \text{ for all } t \text{ given } S_0 \in [0,K],$$

where $W(S_t) = [p+g-c(S_t)]F(S_t) - \rho\int_{S_0}^{S_t}[p+g-c(\omega)]d\omega$. Function W is twice continuously differentiable on $(0,K]$. If W is single-peaked, then it is optimal to use a most-rapid approach path to the stock level that satisfies the singular solution, S^*, such that $W'(S^*)=0$.

$$W'(S_t) = -c'(S_t)F(S_t) - [p+g-c(S_t)][\rho - F'(S_t)].(A1)$$

There is a stock level S' at which $p+g=c(S')$ due to the assumption on c, and hence $W'(S')>0$. Because W' is continuous and $W'(K)<0$, a solution to $\Phi(S^*)=0$ exists between S' and K. With an additional assumption $W''(S^*)<0$, there is a unique solution. The second order derivative of W is given by

$$W''(S_t) = -c''(S_t)F(S_t) + [p+g-c(S_t)]F''(S_t) + c'(S_t)[\rho - 2F'(S_t)],(A2)$$

where the fist two terms on the right hand side of (A2) are negative. It may not be the case that $W''<0$, and thus we need further assumptions to have a unique steady state. With the Schaefer model—a model commonly used in resource economics—we have

$W''(S) = -\frac{\rho c}{S^2} - \frac{2(p+g)r}{K} < 0$ for all $S \in (0,K]$ if $F(S) = rS(1-S/K)$ (the logistic growth) and

$W''(S) = -(p+g+\frac{c}{S})\frac{r}{S} - \frac{\rho c}{S^2} < 0$ for all $S \in (0,K]$ if $F(S) = rS\ln(K/S)$ (the Gompertz growth function). Therefore, the uniqueness and the optimality of the singular solution hold for commonly used models.

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