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# Exogenous Productivity Shocks and Capital Investment in Common-pool Resources\*

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## Abstract

We model exogenous technology shocks in common-pool industries using a compound Poisson process for total factor productivity. Rapid diffusion of exogenous innovations is typical in the commons, but technology is rarely modeled this way. Technology shocks lower the equilibrium resource stock while causing capital buildup based on transitory profits with myopic expectations. The steady state changes from a stable node to a shifting focus with boom and bust cycles, even if only technology is uncertain. A fisheries application is developed, but the results apply to many settings with discontinuous changes in value and open access with costly exit.

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# 1 Introduction

Excess entry and investment are the hallmarks of congestible, common-pool resources. Symmetric externalities arise when resources are “rival” in consumption; when regulators or resource users are unable to effectively limit exploitation by other agents, the familiar “tragedy of the commons” arises, often manifest through overcapitalization. The result is that resource stocks are depleted and rents are dissipated. Yet why does capital investment often persist even as resource stocks shrink? This paper explores an additional explanation for excess investment in common-pool industries: discontinuous technological shocks.

Rapid diffusion of exogenously developed innovations is typical in common-pool resource industries, but technology is rarely modeled this way. Innovations can be developed in other industries and adapted to the common-pool resource (e.g., sonar in fisheries) or developed for similar resources elsewhere (e.g., better groundwater wells); in either case the technology is exogenous to the users of a given local resource. Improved groundwater wells allow access to deeper aquifers and the expansion of aquifer-dependent businesses. Better electronic fish-finders make all inputs more productive, raising the incentives for new vessels to enter. Until recently, research on technical change in fisheries has focused on identifying and measuring productivity growth and technical efficiency. In a normative, bioeconomic framework technology is often modeled as being time invariant or changing smoothly over time (Murray (2006); Squires and Vestergaard (2009)). While this approximation is convenient from a modeling perspective, in practice technology appears to move discontinuously. Jin et al. (2002), for example, find large year-to-year variation in total factor productivity change in the New England groundfish fishery. Some authors attribute this type of variation in productivity to a “ratchet effect” of capital investment driven by stock variability and government subsidies (Ludwig et al. (1993); Hennessey and Healey (2000)) while others point to exogenous development of technologies that are adapted to the fishery (Jin et al. (2002)). Because of the race to exploit, the adoption of new technologies tends to spread almost instantaneously throughout the industry. Our results show that the “ratchet effect” attributed to policy and stock fluctuations can be replicated in an open access model with exogenous technology shocks and costly entry and exit, even without stock uncertainty or policy actions.

We model technological shocks using a Compound Poisson (CP) process in which the occurrence of a shock has a constant expected arrival rate and the size of the shock is determined by a random draw from the exponential distribution. The article characterizes the response of capital and resource stocks when investment is quasi-malleable. These technology shocks perturb the open access equilibrium, causing an increase in extraction ability for a smaller steady state resource stock. Temporarily positive profits result while the system is out of equilibrium; this paradoxically induces a buildup of the more productive capital when less capital is needed to achieve the new equilibrium extraction rate. With a logistic growth function for the resource stock, the nature of the steady

state and the approach path change from a stable node to a stable vortex because highly productive harvesting outpaces the fleet's and the stock's ability to adjust. The result is that the fishery experiences boom and bust cycles as it attempts to adjust to the new steady state. We present simulations for a fishery example based on a modification of the myopic expectations case in Berck and Perloff (1984), hereafter referred to as BP, where we limit exit to a fixed rate of depreciation (this resembles Berck and Perloff (1984) as well as the quasi-malleable investment case in Clark et al. (1979)). We focus on a single aspect of capitalization, namely fleet size.

The remainder of the paper will proceed as follows: section 2 will discuss the empirical motivation and related literature. Section 3 will present the model. We will explain the CP process and how this process can be incorporated into the total factor productivity term of a production function (or the catchability coefficient of the Schaefer production function in the fisheries context). Section 4 presents the results of simulations from this model that replicate boom and bust patterns observed in fisheries. Section 5 concludes.

## 2 Empirical Motivation

Models of constant or continuously growing technology are not consistent with what is observed in practice, especially in industries with open access to the exploitation of a resource. Without positive profit margins or large dominant firms there is little incentive for investment in endogenous technical change; thus technology is developed exogenously and adopted or adapted to the open access resource. When a potential new application of an exogenously developed technology is realized by the resource exploiters, it is adopted by the entire industry almost immediately. Hannesson (2008) documents the rapid fleetwide adoption of successive new technologies in the Norwegian winter herring fleet from 1937 to 1971 (figure 1); the pattern persisted even as the resource stock headed toward collapse and even if adopting the technology required reinvestment in the fleet. The rapid adoption is driven by the very nature of open access resources as impure public goods; they are diminishable (rival) and non-excludable. Competition over the impure public good produces the strong incentives leading to adoption of technologies as their effectiveness becomes realized. Rapid adoption is then necessary to remain an efficient competitor.

A precondition for rapid adoption is ready access to capital markets; the ability to adopt technologies when they are known, available, and the incentive is present. This condition is easily satisfied in developed countries where borrowing is relatively easy and fixed costs of adopting new technologies are typically small relative to returns. However, in less developed countries where there are significant borrowing constraints adoption may diffuse more slowly throughout the industry. Adapting our model to include various diffusion processes is straightforward. Simple extensions could include an empirically calibrated parameter that governs the adoption rate after the introduction of the technology. Be-

cause focus here is primarily on developed countries we will maintain the rapid adoption modeling approach.

Feedback from technological progress has received relatively little attention in management models, especially regarding the perverse incentives for reinvestment by resource users. Exogenous technology shocks remain largely unexamined in this context, despite some empirical literature on discrete change and a growing theoretical literature on continuous technical change in renewable resources. Empirically, discontinuous change can be measured by using productivity residuals and index number methods (Squires (1992), Jin et al. (2002)), by estimating the general index of Baltagi and Griffin (1988) when sufficient data are available (Hannesson et al. (n.d.)), or by explicitly accounting for firm-specific adoption of particular technologies in the estimation of production (Kirkley et al. (2004)). Hannesson (2007) shows that productivity growth can mask stock declines. Murray (2007) demonstrates the consequences of managers overlooking technological change when estimating the stock and setting harvest limits. Squires and Vestergaard (2009) derive a modified golden rule for renewable resource harvest when productivity grows smoothly over time, demonstrating that technology can undo the so-called “stock effect”, or the rising unit cost of harvest which normally acts as a brake on effort as the resource stock declines. Smith (1972) examines endogenous technical change in common-pool resources.

There is a larger literature on entry and investment in renewable resources, but little overlap with the literature on technological change. Berck and Perloff (1984) model entry in a deterministic open access fishery and show that the equilibrium effort and stock levels are the same under myopic and rational expectations; both lead to overfishing and rent dissipation, but the approach paths are different. Homans and Wilen (1997) show that if total allowable catch and season length are the only regulatory controls, overcapitalization is exacerbated. These approaches rely on free entry and exit of capital, however. Models of irreversible investment in fisheries date back to Clark et al. (1979), who show that with non-malleable (or quasi-malleable) capital, the economically optimal harvest and investment policy may involve permanent (or at least prolonged) overcapitalization, depending on the size of the initial resource stock.

We develop a fisheries application, but the results apply to many settings with discontinuous changes in value and open access with costly exit. Many congestible, open access resources exhibit similar features that could be modeled using the Compound Poisson approach developed here. In addition to the groundwater example described above, many capacity-constrained network resources like broadband systems, freeways, and power grids have users that (i) often do not face the true social cost of entry, (ii) make quasi-irreversible investments that rely on the network to produce benefits, and (iii) can be expected to behave myopically because of limited information on the activity of other users. These resources also face discontinuous changes in the value of their use, such as viral news stories that crash web sites, traffic accidents that strand commuters, and the availability of waves of new electricity-intensive electronics. Siegel (1985) and Hendricks and Kovenock (1989) describe how the oil and gas industry can

exhibit a “race to drill” when land tenure rules and locational information are imperfect. Dasgupta and Stiglitz (1980b), Dasgupta and Stiglitz (1980a), and Tandon (1983) explain how even the innovation process itself can behave like a common-pool resource inciting an inefficient “race to invent”.

### 3 Modeling Technical Change with Compound Poisson Processes

#### The Compound Poisson Process

We will start by briefly outlining some of the properties of the CP process as it will be used here. The CP process has a variety of applications. It is often used to capture random events where the time interval between events is independent from one occurrence to the next. Let  $q(t)$  be the technology parameter in a standard production function which we model as being time-dependent. We model  $q(t)$  here as a simple CP process.

$$dq(s) = \phi(s)d\lambda(s) \quad P(d\lambda(s) = 1) = \gamma ds$$

The CP process has a constant intensity parameter  $\gamma$  and the exponential distribution  $\phi(s) \sim \exp(1/\xi)$  is used as the compounding distribution. The exponential distribution is used because we assume only positive shocks to technology occur - that is, technology is only improving over time. As a result  $q(t-\Delta) \leq q(t)$  for  $\Delta \geq 0$ . We assume the  $\phi(s)$  is independent of  $\lambda(s)$  for all  $s \in [0, t]$ . Having defined  $dq(s)$  in this manner we can recover  $q(t)$  as the integral from 0 to  $t$ .

$$q(t) = \int_0^t dq(s) = \int_0^t \phi(s)d\lambda(s) = \sum_{i \in N_t} \phi(s_i)$$

$$N_t \equiv \{i : d\lambda(s_i) = 1, s \in [0, t]\}$$

Here,  $\lambda(t)$  serves as a counting measure, keeping track of each time the Poisson process receives a shock. The jump size is then given by the exponential distribution. Thus,  $q(t)$  is simply the accumulation of the exponential shocks over time. The bottom right panel of figure 6 shows an example of the evolution of the process  $q(t)$ .

Poisson processes are within the family of Lévy processes which are càdlàg, meaning right continuous with left limits. Because of the lack of right continuity we introduce the notation  $q(t_-) = \lim_{\Delta \rightarrow 0} q(t - \Delta)$  to indicate the left limit. This allows us to write the derivative of the composition of two functions  $y = g(q(t))$ , with the nested function CP, as Sennewald and Walde (2006)

$$\frac{dy(t)}{dq(t)} = g(q(t_-)) + \phi(t)d\lambda(t) - g(q(t_-))$$

The expected change in the technology parameter at any instant is defined simply as the interaction of the expectation of the exponential distribution and

the expected arrival rate of the Poisson process over an increment of time. The expected value for the technology parameter at any time is defined as the expected number of arrivals times the expectation of the exponential distribution at each arrival.

$$E[dq(s)] = E[\phi(s)d\lambda(s)] = E[\phi(s)]E[d\lambda(s)] = \xi\gamma ds$$

$$E[q(t)] = E\left[\sum_{i \in N_t} \phi(s_i)\right] = E[\#N_t]\xi = t\gamma\xi$$

Where  $E[\#N_t]$  is the expected cardinality of the set  $N_t$ . Having modeled  $q(t)$  in this way carries with it the implication that technological progress is unbounded as  $t$  increases. Note however that this is also true for cases in which technological progress is assumed to be a linear or exponentially growing trend, as is often the case. Thus, having unbounded technological progress is not without precedent from a modeling standpoint. An interesting extension of our modeling approach would be to make technological progress dependent upon returns to the fishery. This could be used to bound the technological progress either through the jump size, intensity parameter, or both. Unbounded technological growth also implies that any open access resource, renewable or otherwise, will eventually be completely depleted. The intuition behind this is that in an open access setting the cost of exploitation is the only binding constraint on the industry. Unbounded technological progress drives costs to virtually nothing, simultaneously driving the resource to commercial exhaustion.

## Technology Shocks in the Bioeconomic Model

We now wish to incorporate the CP into the bioeconomic framework through the technology parameter of the standard Schaefer production function. This new technology-dependent production function can be written as

$$h(t) = q(t)s(t)x(t)$$

Where  $s(t)$  captures the size of the fleet and  $x(t)$  gives the size of the stock. Consistent with Berck and Perloff (1984) and Clark et al. (1979),  $s(t)$  and  $x(t)$  will be treated as continuous despite their discrete nature.

In order to bring this into the bioeconomic framework we must couple the biological growth function with the economic production function and specify the rent. Following Berck and Perloff (1984), the present value of quasi rents per vessel and the its equation of motion are given by

$$y(t) = \int_t^\infty e^{-r(z-t)}(pq(z)x(z) - c)dz$$

$$\frac{dy}{dt} = ry - (pq(z)x(z) - c) \tag{1}$$

Assuming that entrants base their entry decision on the present value of expected rents using current profits as an adaptive, or myopic estimate of future

profits, Berck and Perloff (1984) arrive at an equation of motion for the stock that asserts that the change in the size of the fleet is proportional to the present value of rents

$$\frac{ds}{dt} = \delta y = \frac{\delta}{r}(pq(t)x(t) - c) \quad (2)$$

This is an equilibrium expression for the vessel construction market. Berck and Perloff (1984) assume that vessel construction costs are quadratic in the rate of entry,  $\frac{ds}{dt}$ , and entry occurs until the marginal cost of vessel construction equals the present value of expected rents, which is the expression in equation 2 where  $\delta$  is a parameter of the entry cost function. The only obvious difference between our framework and that of Berck and Perloff (1984) is the insertion of the technology parameter. The biological equation of motion is given by the growth function less the amount that is harvested each period.

$$\frac{dx}{dt} = \Gamma(x(t)) - q(t)s(t)x(t) \quad (3)$$

The model has been set up in the standard continuous time, surplus production framework. The system is in equilibrium when  $\frac{ds}{dt} = 0$  and  $\frac{dx}{dt} = 0$ , i.e., when the change in the stock is zero so that the surplus growth is exactly equal to the harvest, and the fleet size is no longer in flux. Solving the system of equations defined by equations 2 and 3 in equilibrium

$$\begin{aligned} \frac{ds}{dt} &= \frac{\delta}{r}(pq(t)x(t) - c) = 0 \\ x^*(t) &= \frac{c}{pq(t)} = f_x(q(t)) \end{aligned} \quad (4)$$

$$\begin{aligned} \frac{dx}{dt} &= \Gamma(x(t)) - q(t)s(t)x(t) = 0 \\ s^*(t) &= \frac{\Gamma(x^*(t))}{q(t)x^*(t)} \\ &= \Gamma\left(\frac{c}{pq(t)}\right)p/c = f_s(q(t)) \end{aligned} \quad (5)$$

The focus of this paper is on the response of the system to changes in the technology. The system can change in two ways: the equilibrium levels will change, and the nature of the approach path to the equilibrium can change. First, the change in the equilibrium stock level is characterized by the differential

$$\begin{aligned} \frac{dx^*(t)}{dq(t)} &= f_x(q(t_-)) + \phi(t)d\lambda(t) - f_x(q(t_-)) \\ &= \frac{c}{p(q(t_-) + \phi(t)d\lambda(t))} - \frac{c}{p(q(t_-))} \end{aligned} \quad (6)$$

Intuitively, the equilibrium stock size will be smaller as fishermen are capable of harvesting more fish for any given fleet size. This can be seen here clearly as



$\frac{dx^*(t)}{dq(t)} \leq 0$  since  $\phi(t)d\lambda(t) \geq 0$ . That is to say, the new equilibrium stock size is always smaller following a technology shock. This is consistent with the basic result of Squires and Vestergaard (2009), who show that equilibrium stock size shrinks smoothly with a continuously growing technology parameter. Recall that  $d\lambda(t)$  is a random variable and  $P(d\lambda(s) = 1) = \gamma ds$  or  $P(d\lambda(s) = 0) = (1 - \gamma)ds$ , thus,  $\frac{dx^*(t)}{dq(t)} = 0$  most of the time for  $\gamma$  small, as we would expect.

The change in the equilibrium fleet size will not be unambiguous like the change in the stock size. This is because the  $f_s(q(t))$  is dependent upon the growth function, which is nonlinear. The equilibrium fleet size will depend on how the growth changes at the new equilibrium.

$$\begin{aligned} \frac{ds^*(t)}{dq(t)} &= f_s(q(t_-)) + \phi(t)d\lambda(t) - f_s(q(t_-)) \\ &= \left[ \Gamma\left(\frac{c}{p(q(t_-)) + \phi(t)d\lambda(t)}\right) - \Gamma\left(\frac{c}{p(q(t_-))}\right) \right] p/c \end{aligned} \quad (7)$$

Equilibrium fleet size will be larger following the technology shock if the new equilibrium fish stock increases surplus growth. The equilibrium fleet size will be smaller when growth is reduced. This says nothing, though, about the initial response of the fleet to the technology shock. To say something about initial responses to shocks, we must further investigate the off-equilibrium dynamics.

## Characterizing the Equilibrium

Growth functions for biological processes are nonlinear; even the simplest logistic growth function is a nonlinear differential equation. As long as the surface is sufficiently smooth we can characterize the local behavior of the system by linear approximation. In particular, the system can be linearized around the critical point, or equilibria. The nature of the equilibrium at a given point of the linearized system will be the same as that of the nonlinearized system under standard continuity and differentiability assumptions. This is the approach followed here. The linearization of equations 2 and 3 about the equilibrium yields the following system of equations relating  $s$  to  $x$ .

$$\begin{pmatrix} \Delta \dot{x} \\ \Delta \dot{s} \end{pmatrix} \approx \begin{pmatrix} \Gamma'(x^*) - q(t)s^* & -q(t)s^* \\ q(t)\delta p/r & 0 \end{pmatrix} \begin{pmatrix} x - x^* \\ s - s^* \end{pmatrix} = A \begin{pmatrix} x - x^* \\ s - s^* \end{pmatrix} \quad (8)$$

To determine the nature of the equilibrium we can analyze the determinant of the eigenvalue matrix  $A - \mu I$ . After plugging in the equilibrium condition the determinant will be

$$\Rightarrow \mu^2 - \left( \Gamma' \left( \frac{c}{q(t)p} \right) - q(t) \frac{p}{c} \Gamma \left( \frac{c}{q(t)p} \right) \right) \mu + q(t) \frac{c\delta}{r} = 0 \quad (9)$$

$$\mu^2 + b\mu + c = 0$$

The eigenvalues of the system will then be given by the roots

$$\mu = \frac{-b \pm \sqrt{b^2 - 4c}}{2}$$

and the discriminant will be

$$\left( \Gamma' \left( \frac{c}{q(t)p} \right) - q(t) \frac{p}{c} \Gamma \left( \frac{c}{q(t)p} \right) \right)^2 - 4q(t) \frac{c\delta}{r}$$

Since  $4q(t)c\delta/r$  is strictly positive the eigenvalues will either both be negative and real, or imaginary with a negative real term. When the eigenvalues are both negative and the surface is a sink, approach paths to the equilibrium are direct. However, when the discriminant is less than zero the eigenvalues will be imaginary and the approach path will be a vortex with the equilibrium as its focus. As a concrete example consider the case where the growth is given by the logistic growth function in equation 10 where  $g$  is the intrinsic growth and  $k$  is the carrying capacity.

$$\Gamma(x) = gx(1 - x/k) \tag{10}$$

The discriminant of the system with logistic growth will then be less than zero when

$$\begin{aligned} \left( g \left( 1 - \frac{2c}{q(t)pk} \right) - q(t) \frac{p}{c} g \left( \frac{c}{q(t)p} \right) \left( 1 - \frac{c}{q(t)pk} \right) \right)^2 - 4q(t) \frac{c\delta}{r} < 0 \\ \left( \frac{gc}{pk} \right)^2 - q(t)^3 4c \frac{c\delta}{r} < 0 \\ \sqrt[3]{\frac{g^2 cr}{4\delta p^2 k^2}} < q(t) \end{aligned} \tag{11}$$

Since  $q(t)$  is unbounded it will eventually exceed the threshold established by equation 11. In our experience under most reasonable parameterizations of the growth function the threshold is exceeded quite early on the exploitation path. Figure 2 shows the phase plane gradients of the resource stock and the fleet when the threshold has been exceeded, with arrows indicating the spiraling direction of convergence from off-equilibrium points. Consequently, with increasing technology we will eventually see a fishery in which the fleet size is oscillating as it attempts to approach the steady state.

Notice that this threshold contains an expression for the intrinsic growth rate of the fish stock relative to the entry cost parameter  $\delta$ , as well as other economic parameters and the carrying capacity. This threshold describes a point where the ability of entry costs to act as a break on rising harvest pressure and protect stock recovery is exceeded by the ability of each existing vessel to deplete the stock. In other words, technology makes entry continue to appear profitable even as the harvest capacity exceeds the stock's ability to replenish itself.

Figure 3 illustrates this point more clearly by redrawing the stock-fleet phase plane and illustrating example approach paths on either side of the transition threshold. The black arc represents the locus of equilibrium points in the stock-fleet plane, at different values of  $q(t)$ , with the transition threshold marked in red. A smoothly changing  $q(t)$  would trace out this arc over time. Perturbations on either side of the threshold result in very different dynamics.

## Technology Shocks with Rational Expectations

We now temporarily relax the assumption of myopic expectations and examine the case where agents form and respond to rational expectations about the future. In a rational expectations framework, agents will consider expected future changes in technology, stock, and fleet size when making entry and exit decisions. In particular, the present value of quasi rents in the system described above is augmented by consideration of the expected time path of technology, given by

$$\begin{aligned} y &= \int_t^\infty e^{-r(z-t)} (pE_t[q(z)]x(z) - c) dz \\ &= \int_t^\infty e^{-r(z-t)} (p[q(t) + (z-t)\xi\gamma]x(z) - c) dz \end{aligned} \quad (12)$$

The equation of motion for expected quasi rents is given by

$$\begin{aligned} \frac{dy}{dt} &= ry - (pq(t)x(t) - c) + p(\phi(t)d\lambda(t) - \xi\gamma) \int_t^\infty e^{-r(z-t)} x(z) dz \\ &= ry - (pq(t)x(t) - c) + p(\phi(t)d\lambda(t) - \xi\gamma)B(t) \end{aligned} \quad (13)$$

The first two terms are identical to equation 1 and is simply the change in the present value of rents. The final term on the right hand side of equation 13 accounts for long run revenue adjustments when current technology shocks (today's draw from the CP process) deviate from their expected value. The impact of today's deviation on the resource stock at every subsequent moment is then factored into the evolution of expected rents. In this case,  $s^*(t) = \Gamma(x^*(t))/q(t)x^*(t)$  as before and additionally  $y^*(t) = 0$ , but the expression for  $x^*(t) = 0$  is given by

$$x^*(t) = \frac{c + p(\phi(t)d\lambda(t) - \xi\gamma)B(t)}{pq(t)} = \tilde{f}_x(q(t)) \quad (14)$$

Repeating the analysis of section 3, the change in the equilibrium stock size is now

$$\begin{aligned} \frac{dx^*(t)}{dq(t)} &= \tilde{f}_x(q(t_-)) + \phi(t)d\lambda(t) - \tilde{f}_x(q(t_-)) \\ &= \frac{c + p(\phi(t)d\lambda(t) - \xi\gamma)B(t)}{p(q(t_-) + \phi(t)d\lambda(t))} - \\ &\quad \frac{c + p(\phi(t)d\lambda(t) - \xi\gamma)B(t)}{pq(t_-)} \end{aligned} \quad (15)$$

Two observations are worth noting here. First, the equilibrium stock size is smaller than under myopic expectations because firms expect future productivity gains, which induces more entry earlier and thus more depletion earlier. Second, the effect of a shock on the equilibrium stock size is dampened by the continual adjustments to the evolution of expected rents in response to deviations from the expected path. The equilibrium fleet size is then given by

$$\begin{aligned} A(t) &= p(\phi(t)d\lambda(t) - \xi\gamma)B(t) \\ s^*(t) &= \Gamma\left(\frac{c + A(t)}{pq(t)}\right) \frac{p}{c + A(t)} \end{aligned} \quad (16)$$

The change in fleet size now becomes

$$\begin{aligned} \frac{ds^*(t)}{dq(t)} &= f_s(q(t_-) + \phi(t)d\lambda(t)) - f_s(q(t_-)) \\ &= \Gamma\left(\frac{c + A(t)}{p(q(t_-) + \phi(t)d\lambda(t))}\right) \frac{p}{c + A(t)} - \Gamma\left(\frac{c + A(t)}{p \cdot q(t_-)}\right) \frac{p}{c + A(t)} \end{aligned} \quad (17)$$

Again, the effect of a technology shock is less dramatic than in the myopic case because of the expected long run revenue adjustments. In this sense, the rate of entry and stock drawdown following a major technology shock could be considered indicators of the extent of myopia in the industry.

## 4 Simulation

The theoretical results from the myopic expectations case of section 3 make two points that we wish to emphasize and show through simulation. The first is to propose and characterize the CP process as a model of technological change that mirrors empirical findings from open access resources, where shocks accrue to the system randomly and irregularly and the adoption of technology into the fishery is nearly instantaneous. The second point of our theoretical analysis is that as technology increases it surpasses a threshold, beyond which the approach paths to the equilibrium switch from stable convergence to spiraling convergence, or boom and bust cycles. Discontinuous shocks produce off equilibrium dynamics that make the approach path relevant and observable. The cyclicity of the approach path means that we would expect to see boom and bust cycles, particularly in the years following a technology shock.

The simulations focus on the case of myopic expectation because it is our belief that this is a fairly close approximation to behavior in many open access scenarios. We simulate the system defined by the two differential equations 2 and 3. For the growth function  $\Gamma(\cdot)$  we use the logistic growth function defined by equation 10. The parameters of the simulation can be found in table 1. The process is simulated over 100 years on daily time intervals  $dt = 1/365$  and then sampled annually at the end of the simulated year. The simulation is initialized

using a technology parameter of  $q(0) = 1$  and with the stock and fleet at their equilibrium values  $x(0) = \frac{c}{pq(0)}$ ,  $s(0) = \frac{\Gamma(x(0))}{q(0)x(0)}$ .

## Boom and Bust Cycles

Figures 4 and 5 plot the time path of variables for the two approach paths illustrated in the phase plane in figure 3, demonstrating shocks that lead to two different sides of the transition threshold. In figure 4, the fishery begins in equilibrium and after a small technology shock, adjusts smoothly to a larger equilibrium fleet size (implying larger surplus growth) and lower fish stock. Profits are quickly dissipated by entrants. In figure 5, on the other hand, a large shock moves the fishery beyond the transition point. Profits, fleet size, and fish stocks fluctuate for about 30 years before settling down.

## Compound Poisson Technology Simulation

While the system begins with stable convergence to the equilibrium, the technology shocks quickly change the nature of the equilibrium to one of boom and bust cycles. This produces the erratic fluctuations in the stock, fleet size and profits that appear in figure 6. This pattern closely resembles the time path of stocks and yields reported by Hennessey and Healey (2000) as a “ratchet effect” of stock variability and government policy. Technology shocks induce transitory periods of growth, but the fish stocks remain in long run decline despite relatively steady per-vessel profits that could hide the severity of stock depletion.

## 5 Conclusion

This article proposes a useful modeling tool for open access resource dynamics that more closely reflects observed patterns of innovation and adoption, and explores the consequences for renewable resource use. Discontinuous technological processes can have significant economic and resource impacts. Although smooth measures of growth based on long run expectations may be accurate over decades, short run dynamics will differ markedly from the long run forecast when discrete shocks are present. Economic resources will be suboptimally allocated through dimensions such as overcapitalization and resource depletion.

In the fishing context, overfishing for a short time may push resource stocks below their sustainable limits. Previous explanations of excess capacity and stock declines in de facto open access fisheries, such as the ratchet effect, ignore this important driver of observed outcomes. Accurate technological accounting could be built directly into catch-per-unit effort measures which are often used by regulators as an indicator of stock abundance.

Management systems should be designed to anticipate and deal with sudden changes in exploitation power, particularly in cases when its not feasible to regulate or ban specific technologies. Requiring ex ante public disclosure of

investment plans and announcing real-time resource limitations may dissuade myopic behavior, leading to fewer wasted inputs and dampening the wide capacity swings that could lead to resource collapse. When output taxation is feasible and productivity levels are stationary, it is well known that regulators can achieve optimum rent even though individual agents face open-access incentives; with technology shocks, an adaptive system of graduated taxes may be required to reduce expected quasi-rents for myopic actors following a shock.

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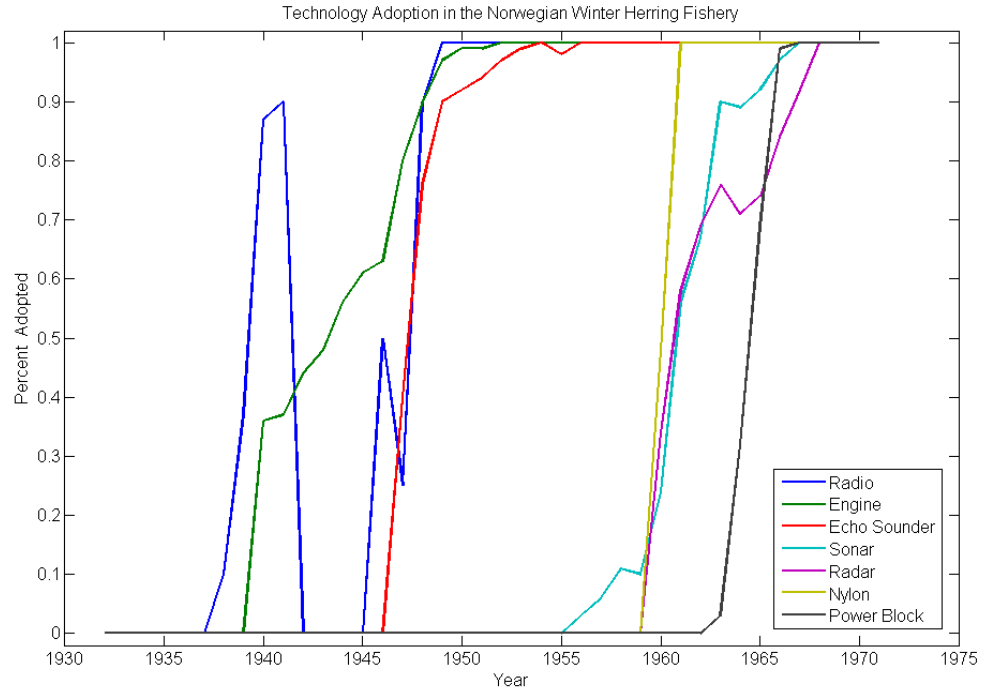


Figure 1: Technology Adoption in the Winter Herring Fishery

Growth Parameters	
Intrinsic growth	$g = 0.75$
Carrying capacity	$k = 1$
Economic Parameters	
Interest rate	$r = 0.05$
Price	$p = 3.5$
Operating costs	$c = 2.33$
Entry Proportion	$\delta = 0.001$
Technology Parameters	
Poisson intensity	$\gamma = 0.1$
Jump size	$\beta = 0.5$

Table 1: Simulation Parameter Values



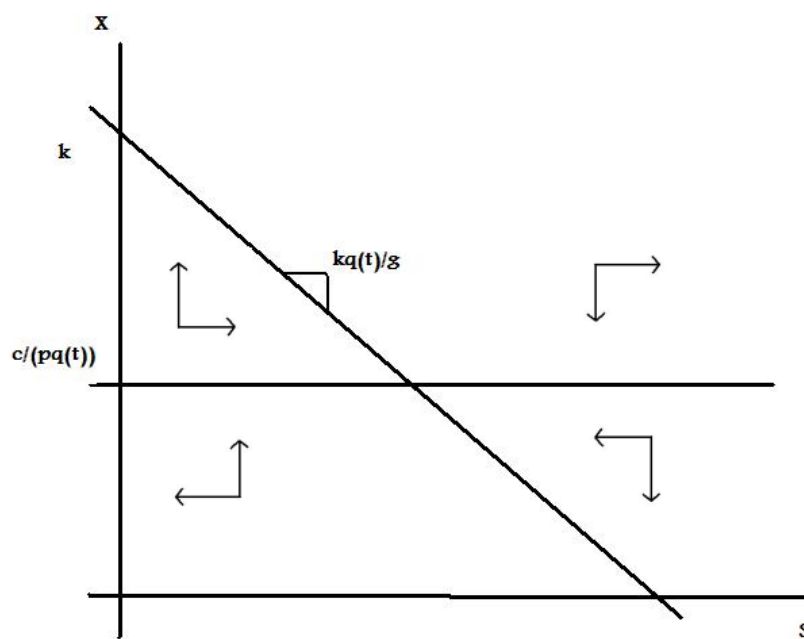


Figure 2: Dynamics in the stock-fleet plane

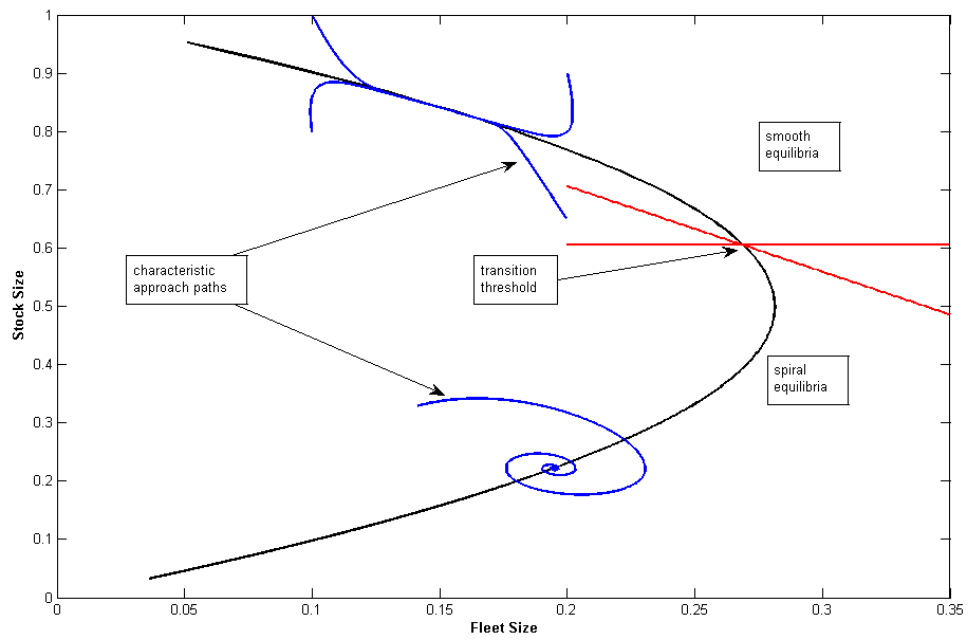


Figure 3: Differences in approach path for changing technology

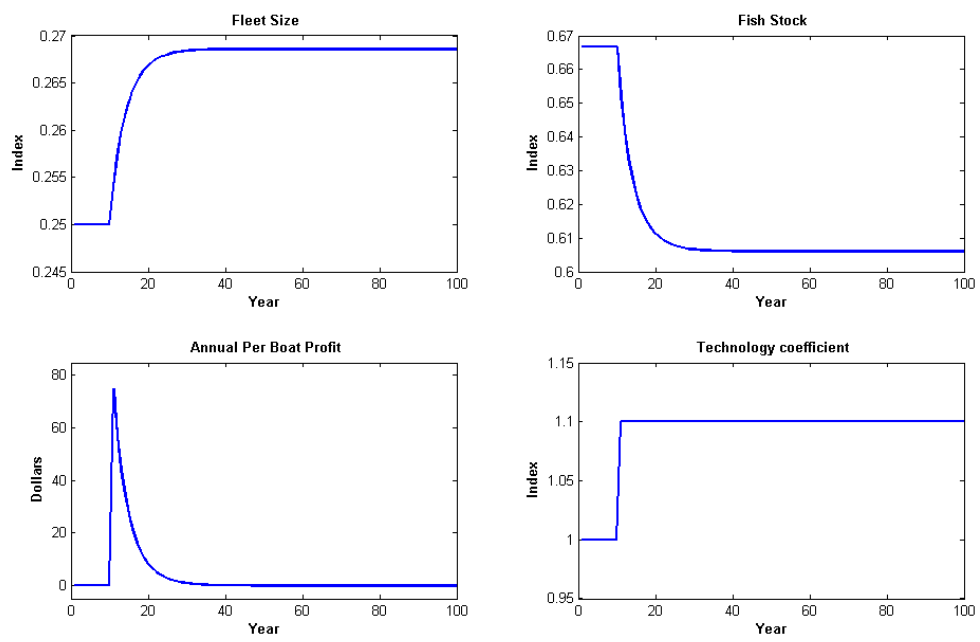


Figure 4: Small shock with smooth transition to equilibrium

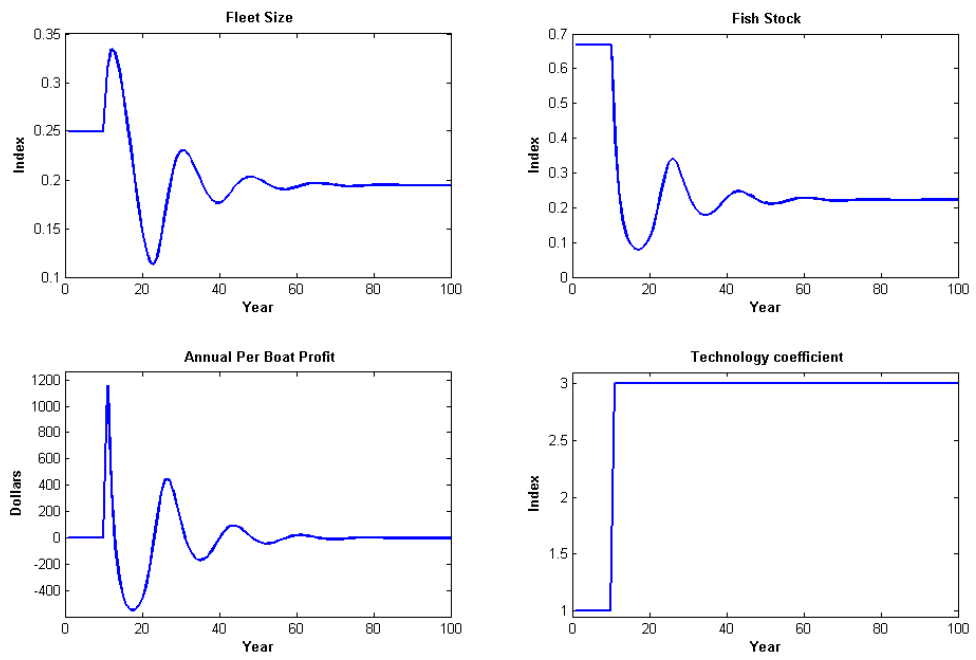


Figure 5: Big shock inducing oscillating equilibrium

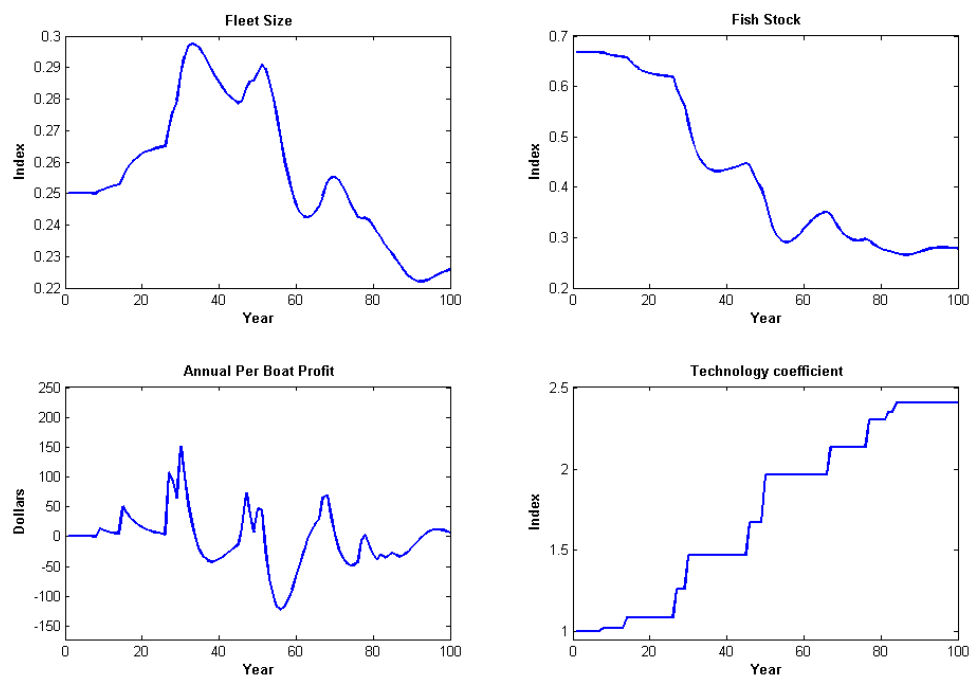


Figure 6: Compound Poisson Process Simulation