Fixed Costs, Efficient Resource Management and Conservation

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Abstract

This paper develops a framework to analyze the impacts on resource development of efficient management practices that account for possible resource conserving technological, institutional and taste changes. Compared with traditional resource management that ignores these future possibilities, efficient management may not delay or reduce resource development. Under efficient management, higher probability of resource conserving changes may not delay or reduce resource development. These ambiguities are due to the existence of fixed and increasing marginal costs in resource development and restoration. Our results complement real option theory in studying the role of uncertainty in resource management. (JEL Q20, D81)

Key Words: resource management, fixed costs, stochastic dynamic optimization

1 Introduction

There is a growing literature on optimal management of resources over time taking into account limitation of resource availability and environmental quality. In particular, in assessing future development plans, it is important to incorporate possible changes in taste, technology and institutions. But these types of changes have been ignored in many practical decision making processes. For example, there is no mention of investigation and consideration of future new technologies, tastes and institutions in some major resource management manuals, such as *the Principles and Guidelines*,[1] a major document for water project evaluation in the U.S., and the *1980 Operations Manual* of the World Bank.

Economists have long studied the effects of "incorrectly" dealing with these changes in resource management. In particular, real option theory, such as Arrow and Fisher (1974), Henry (1974), Fisher, Krutilla and Cicchetti (1972), and Dixit and Pindyck (1994), investigates the impacts of open-loop instead of the optimal closed-loop management. Open-loop approach replaces random variables with their expected values without allowing future adjustments. The literature found that, compared with the optimal management, open-loop approach leads to more or early resource development.

This paper asks a more basis question: what is the impact of *ignoring* these changes altogether, relative to the optimal closed-loop decision? In particular, does it cause early or more resource development? Unlike future prices for which their expected values are usually used in project assessment, future changes in technology, taste and institutions are often just ignored. Our question is thus more relevant for studying these changes, while real option theory is relevant for studying price changes.

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[1] "Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies," by U.S. Water Resources Council, 1983.

Generally, technological, taste and institutional changes are likely to be resource conserving: if they do occur, there will be a smaller demand for developed resources. For example, flood zone management may reduce the need for a flood control dam, and new irrigation technologies and water markets can reduce the necessity of an irrigation dam. High yield seed varieties may reduce the land needed to satisfy food demand. Increased environmental awareness may increase the damage of cutting a piece of forest.[2] Therefore, it seems that ignoring these changes may lead to excessive development. This paper shows that this may not be true.

We show that, compared with ignoring these changes, optimal management *may not* conserve resources. In particular, it may not delay resource development, and it may not reduce the expected total development. Further, under optimal management, higher probability of future resource conserving changes *may* lead to earlier and more expected development. These surprising results are not caused by any market distortions, but by the existence of fixed costs and increasing marginal costs in resource development. Expecting the possibility of less future demand, more resource may be developed now so that no development happens in the future and the fixed cost is saved. In contrast, if future changes are ignored, development may be prescribed in both periods (in smaller scales) to save variable costs. Thus optimal management may lead to early development. Moreover, if the incentive to save the fixed cost is strong enough, current development may be so much that it cannot be fully compensated by the expected reduction in future development. In this case, optimal management actually leads to more expected total development.

The existence of fixed and increasing marginal costs is widely observed in natural resource development and restoration. For example, building an irrigation dam incurs certain design and evaluation costs that are not related to the project size. The fixed cost is also reflected in the

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[2] As a concrete example, most of the water projects constructed in the past century in Western United States are now deemed over-developed precisely because of the technological, institutional, and taste changes occurred more recently (see Reisner (1986)).

minimum economical dam size. Increasing marginal cost is reasonable if there is a capacity limit beyond which overtime pay is required for workers, or if the costs of conveyance facilities and maintenance are considered. Similarly, cutting forest and reforestation require significant cost of access (such as constructing roads to the forest) that is much independent of the project size, and marginal operation costs typically are increasing with the size of forest cut or the scale of reforestation.

Our study then indicates that resource conservation implications of optimal management depend on the cost structure of the problem at hand. Efficient management may force early and more development, especially when fixed costs are high.[3] Emphasizing fixed costs is consistent with the adjustment cost literature (Abel and Eberly (1994)) and the economic explanation of irreversibility (Zhao and Zilberman (1995)).

To facilitate the discussion, we call the management practice that ignores future changes the "traditional approach," alluding to the fact that these changes have been ignored traditionally. We call the efficient management "new approach," hoping that resource management practices will follow the optimal algorithm.

The paper is organized as follows. Section 2 formulates the model and describes the basic assumptions. Section 3 studies optimal resource transformation under the efficient management system. We will study a numerical example of cutting forest for agricultural land facing possible future new technologies. Section 4 compares the two management practices. Section 5 concludes the paper and discusses possible extensions.

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[3] Fixed costs are usually ignored in project evaluation on the grounds that they are inconsequential in deciding the size of a project (once the minimum size is surpassed).

2 Problem Definition and Model Formulation

Consider a management task that develops a natural resource which provides environmental amenity in its natural state and monetary benefits if developed. For simplicity, we only allow uncertainty about future technologies that affect the benefit of developed resources. Let S be the total available resource, and K_0 the current stock of developed resource, so that $S - K_0$ of the resource is still in the natural state. Let V be the function describing the value of environmental amenity provided by the resource in the natural state, so that initially the value is $V(S-K_0)$. $V(\cdot)$ is twice continuously differentiable, with $V' > 0$ and $V'' \leq 0$. Let $\pi(K, A)$ be the monetary benefit of developed resource K when the technology level is A. $\pi(\cdot, \cdot)$ is twice continuously differentiable in both arguments with $\pi_K > 0$, $\pi_{KK} < 0$ and $\pi_{KA} < 0$. Higher A thus corresponds to new resource conserving technology: less developed resource K is needed.[4]

We posit that the resource can be transformed between its natural state and the developed state at certain costs. For example, forest can be "developed" (or cut) to agricultural land, and the latter can be "restored" (or reforested) to forestry. Development and restoration involve both fixed and variable costs, which we expand Abel and Eberly (1994) to formulate. Let I denote the amount of transformation, with $I > 0$ representing development and $I < 0$ restoration. In the forestry example, $I > 0$ measures the acreage of forest that is cut, and $I < 0$ measures the acreage of land that is reforested. Let c be the transformation cost correspondence. For $I \neq 0$, $c(I)$ is single valued (i.e. a function), and is assumed to be twice continuously differentiable and convex. This represents the variable costs of transformation. We make the intuitive assumption that $c'(I) > 0$ for $I > 0$ and $c'(I) < 0$ for $I < 0$. c maps $I = 0$ to two values, $\{c_0^-, c_0^+\}$, where c_0^- represents the fixed cost of restoration, and c_0^+ represents that of development. Further, $\lim_{I \downarrow 0} c(I) = c_0^+$,

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[4] Note that A can also represent the level of institutional structure that reduces demand for resource development. We can capture the taste effect by adding a random variable to function V. This will not affect the basic result of our model.

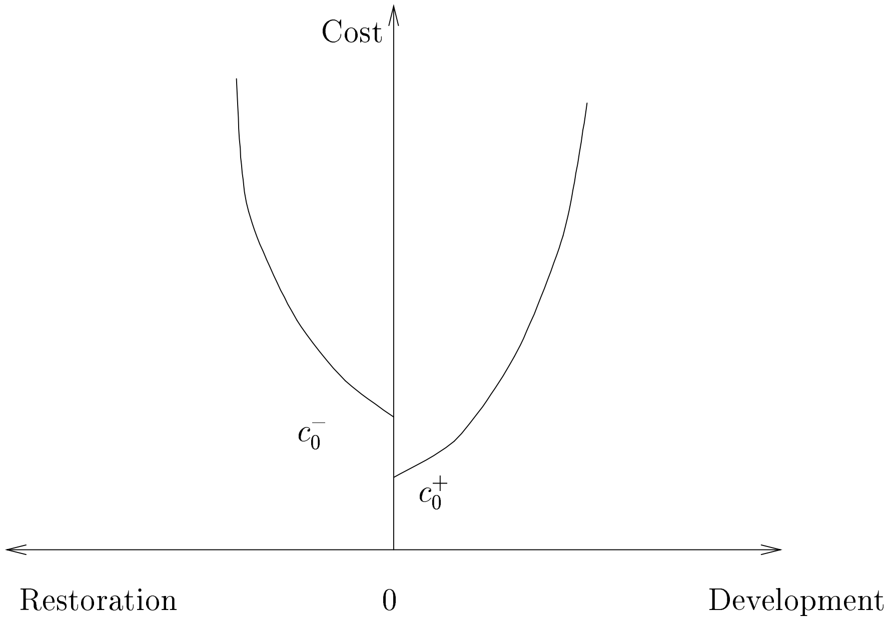

Figure 1: Cost Function of Resource Transformation

and $\lim_{I\uparrow 0} c(I) = c_0^-$. Let s be a signal function such that $s(I) = 1$ for $I \neq 0$, and $s(I) = 0$ for $I = 0$. Then $s(I)c(I)$ is single valued, and is the transformation cost function. The shape of the cost function is illustrated in Figure 1.

We assume that the net social benefit is additively separable in the monetary benefit of developed resource, the cost of resource transformation, and the environmental value of the natural resource. Thus given initial capacity K_0 and level of technology A, the social benefit associated with a transformation of I is

$$Q(K_0, I, A) = \pi(K_0 + I, A) - s(I)c(I) + V(S - K_0 - I) \tag{1}$$

The properties of the functions π, c, and V imply that Q is twice continuously differentiable in its first and third arguments, and its second argument except at 0.

We consider a two period decision problem with two technologies: the traditional A^T and the modern A^M, with $A^T < A^M$. In period one, only the traditional technology is available, and in period two, modern technology is available with probability p. Without loss of generality, we assume the situation is such that in the first period, it is always necessary to develop the natural resource.[5]

Let $\beta \in (0,1)$ be the social discount factor, then the socially optimal decision is:

$$\begin{aligned} W(p) &= \max_{I_1 \in \mathcal{I}_1} w(I_1, p) \\ &= \max_{I_1 \in \mathcal{I}_1} \{Q(K_0, I_1, A^T) + \beta p \max_{I_2 \in \mathcal{I}_2(I_1)} Q(K_0 + I_1, I_2, A^M) + \beta(1-p) \max_{I_2 \in \mathcal{I}_2(I_1)} Q(K_0 + I_1, I_2, A^T)\} \end{aligned} \tag{2}$$

where w is the total two period welfare, as a function of the first period development and the probability of new technology. W is the social welfare when I_1 is optimally chosen. $\mathcal{I}_1 = [0, S - K_0]$. $\mathcal{I}_2(I_1) = [-K_0 - I_1, S - K_0 - I_1]$.

The traditional resource management approach that ignores new technologies would choose first period decision I_1 assuming $p = 0$. The second period decision is made given the realized technology level and I_1. Note that the decision maker has to respond to the new technology shock if A^T occurs.

3 Resource Transformation Under Efficient Management

It turns out that both the time pattern and the expected magnitude of resource development depend on the level of the new technology. In particular, they depend on whether the new technology falls into certain regions. These regions are classified through a deterministic analysis in Section 3.1.

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[5] Similar methods of analysis can be applied to other situations in the first period such as restoration being necessary, both development and restoration being possible, and no transformation being optimal.

The analysis also demonstrates the intuition for the result that accounting for new technology may not delay or reduce resource development due to fixed costs. Section 3.2 investigates the resource transformation patterns under uncertainty for technologies in each region.

3.1 The Deterministic Scenario: Regions of New Technology

In this section, we assume $p = 1$ and study what happens as the level of the new technology changes. For this purpose, we let $A \geq A^T$ be the new technology level and denote the optimal transformation decisions in the two periods as $\{I_1^*(A), I_2^*(I_1^*(A), A)\}$.

Suppose that there is no fixed cost of transformation: $c_0^+ = c_0^- = 0$. Then the objective function of the deterministic problem is strictly concave, and the first order conditions are sufficient. Straightforward comparative statics tells

$$\text{sign}(\frac{dI_1^*(A)}{dA}) = \text{sign}(\frac{dI_2^*(I_1^*(A), A)}{dA}) = \text{sign}(\pi_{KA}) < 0. \tag{3}$$

That is, less resource is developed in both periods as the new technology becomes more advanced (i.e. more resource conserving). We can also show that $I_1^* > I_2^*$, since resource developed in period one provides services in both periods (thus having a higher marginal benefit).

Now suppose that there are fixed costs of transformation and for the problem to be interesting, suppose $I_2^* > 0$ when $A = A^T$. Then as A rises above A^T, both I_1^* and I_2^* decrease until A reaches a certain level, denoted as A^J, at which I_2^* jumps to zero and I_1^* jumps up. I_2^* jumps down because as A reaches A^J, the benefit of second period development fails to compensate for the fixed cost. I_1^* then jumps up to provide some of the needed capacity in the second period. In fact, $I_1^*(A^J)$ may even be higher than $I_1^*(A^T)$. We can show that total development $I_1^* + I_2^*$ jumps down at A^J. For $A > A^J$, I_2^* remains at zero and I_1^* decreases in A. It is conceivable that as A further increases,

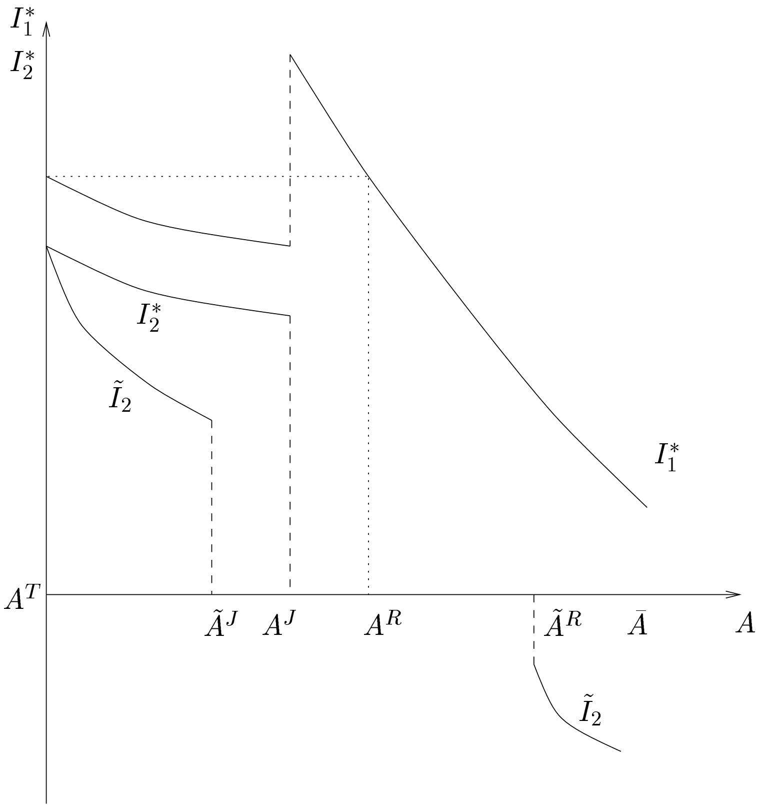

Figure 2: Resource Development and Regions of New Technologies

resource restoration becomes necessary (so that $I_2^* < 0$). For simplicity we rule out this scenario by setting an upper bound $\bar{A}$ on the levels of technologies that we consider.[6]

The optimal decisions $(I_1^*(A), I_2^*(A))$ are illustrated in Figure 2, which also defines three regions of the new technology. The first region is $\mathcal{A}_1 \equiv [A^T, A^J)$, in which both I_1^* and I_2^* are positive and decreasing. The second region is $\mathcal{A}_2 \equiv [A^J, A^R)$, where A^R is the point with $I_1^*(A^R) = I_1^*(A^T)$. In this region the first period development is higher than that without the new technology $I_1^*(A^T)$. New technologies in this region reduce but do not delay resource development in a deterministic world. The third region is $\mathcal{A}_3 \equiv [A^R, \bar{A}]$, in which there is no development in period two.

As we will show later, $\mathcal{A}_2$ is an important region in comparing the development patterns under

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[6] Empirically a socially optimal decision *with certainty* rarely involves "build now and restore later." Thus this assumption may not be unrealistic. Further, it does not affect the major results of the paper.

the two resource management systems. In essence, it is a region where more I_1 is developed to save the second period fixed cost (since $I_2^* = 0$). This region is non-empty when c_0^+ is sufficiently high (Proposition 2 in Appendix A.1). Essentially higher c_0^+ reduces A^J (i.e. making it more likely that no further development happens in period 2) while not affecting A^R, enlarging the region $\mathcal{A}_2$. Higher variable cost of development also reduces A^J if the discount factor β is not too low, but its effect on A^R is ambiguous.

Now consider the traditional management approach: the decision maker ignores future new technology when deciding the current development, and optimally responds to the new technology when it actually happens. Let $\{\tilde{I}_1, \tilde{I}_2(A)\}$ be the vector of solutions, then we know $\tilde{I}_1 = I_1^*(A^T)$ and $\tilde{I}_2 = I_2^*(I_1^*(A^T), A)$. As A rises from A^T, $\tilde{I}_2$ decreases faster than I_2^* (because $\tilde{I}_1 > I_1^*(A)$ for $A > A^T$), and thus jumps to zero earlier than I_2^*. Let $\tilde{A}^J$ be the jump point of $\tilde{I}_2$, we know $A^T < \tilde{A}^J < A^J$. We correspondingly define $\mathcal{A}_{11} = [A^T, \tilde{A}^J)$ and $\mathcal{A}_{12} = [\tilde{A}^J, A^J)$.

$\tilde{I}_2$ remains at zero as A rises from $\tilde{A}^J$. But after a certain level of A, it *may* be optimal to restore the initial development: $\tilde{I}_2$ jumps to a negative number. We denote this jump point as $\tilde{A}^R$, and $\tilde{A}^R$ may be in $\mathcal{A}_2$ or $\mathcal{A}_3$. Figure 2 describes a scenario with $\tilde{A}^R \in \mathcal{A}_3$. If this is indeed true, we define $\mathcal{A}_{31} = [A^R, \tilde{A}^R)$ and $\mathcal{A}_{32} = [\tilde{A}^R, \bar{A}]$.

Figure 2 indicates that if $A \in \mathcal{A}_2$, ignoring the new technology in fact leads to a smaller project: instead of choosing size $I_1^*(A)$, the project is now sized at a smaller scale $I_1^*(A^T)$ (note that $I_2 = 0$ under both management practices). Thus we know

Remark 1 *In a deterministic world, the efficient resource management practice that recognizes future new technology may lead to earlier or more resource development, when the technology falls in the region* $\mathcal{A}_2$.

We will generalize the result in Remark 1 to the stochastic world in Section 4. To do so, we first look at the efficient resource transformation patterns for different technology regions. In particular, we fix the new technology A^M at a certain level and investigate how the development patterns respond to the probability p of the new technology being available.

3.2 The Socially Optimal Development Patterns

Let $\{\hat{I}_1(p), \hat{I}_2^M, \hat{I}_2^T\}$ be the vector of solutions to (2) corresponding to probability p, where $\hat{I}_2^M = \hat{I}_2(\hat{I}_1, A^M)$ and $\hat{I}_2^T = \hat{I}_2(\hat{I}_1, A^T)$. Then the first order condition of I_1 and the implicit function theorem indicate

$$\frac{d\hat{I}_1}{dp} = -\frac{\beta}{D}[\frac{dQ_2^M}{dI_1} - \frac{dQ_2^T}{dI_1}] \tag{4}$$

when the derivative is well defined, where $D < 0$ is the second order coefficient of I_1, $Q_2^M = Q(K_0 + \hat{I}_1, \hat{I}_2(\hat{I}_1, A^M), A^M)$ is the second period social benefit when the new technology is available, and $Q_2^T = Q(K_0 + \hat{I}_1, \hat{I}_2(\hat{I}_1, A^T), A^T)$ is that when the new technology is not available, given optimal first period development.

Without the fixed costs of transformation, we obtain the standard result: higher p reduces first period development $\hat{I}_1$ and the expected total development $\hat{TI}(p) \equiv \hat{I}_1(p) + p\hat{I}_2^M + (1-p)\hat{I}_2^T$. Further, $\hat{I}_2^T$ and $\hat{I}_2^M$ cannot both be negative: it is not optimal to develop the resource today, knowing that part of it will always be reversed tomorrow. This is summarized in Proposition 1, which is proven in Appendix A.2.

Proposition 1 *Without the fixed cost of transformation, higher probability of new technology both delays and reduces resource development. In the optimal development pattern, there is always further development in period two if the new technology does not occur (i.e.* $\hat{I}_2^T > 0$*), and there may be development or restoration if the new technology does occur (i.e.* $\hat{I}_2^M$ *may be positive or* *negative).*

Introducing fixed costs of transformation greatly complicates the analysis and leads to a wide range of possible transformation patterns. Appendix A.3 shows that we obtain definitive results only when the technology A^M falls into regions $\mathcal{A}_{11}$ and $\mathcal{A}_{31}$: both $\hat{I}_1$ and $\hat{TI}$ are decreasing in p. Multiple possibilities arise for other levels of technologies. In the following numerical example, we show that when $A^M \in \mathcal{A}_{12} \cup \mathcal{A}_2$, both $\hat{I}_1$ and $\hat{TI}$ may be increasing in p.

3.2.1 A Numerical Example

Consider the decision of how much forest should be cut for agricultural land. Suppose the value of environmental amenity is linear in K: $V(K) = a_v K$. The monetary benefit of agricultural land is the net benefit of agricultural production, which depends on both the agricultural output and its demand and cost functions. Suppose given output y, the net benefit calculated from the demand and cost functions is quadratic: $B(y) = a_b y - \frac{1}{2} b_b y^2$. Suppose further that the reduced form production function is $f(A, K) = s_y A^{1/\alpha} K$, where s_y is a scale coefficient, A is the level of technology, and α is the output elasticity of land.[7] Then the benefit function $\pi(K, A) = B(f(K, A))$. We assume quadratic transformation cost functions: $c(I) = c_0 + v_c I^2$ for $I > 0$, and $c(I) = d_0 + v_d I^2$ for $I < 0$. The parameter values are listed in Table 1.

The solution of the deterministic model (with $p = 1$), presented in Figure 3, helps to classify regions of technologies. It shows that $\mathcal{A}_1 = [0.65, 0.845)$, $\mathcal{A}_2 = [0.845, 0.875)$ and $\mathcal{A}_3 = [0.875, 1.2]$. We can also show that $\mathcal{A}_{11} = [0.65, 0.836)$, $\mathcal{A}_{12} = [0.836, 0.845)$, $\mathcal{A}_{31} = [0.875, 1.136)$ and $\mathcal{A}_{32} = [1.136, 1.2]$.

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[7] The reduced form is based on a constant returns to scale Cobb-Douglas production function with two factors, land and labor. Consider an individual farmer's profit maximization decision (by choosing labor input) facing given output price P, labor price w, technology level A, land K, and production function $g(K, L, A) = AK^{\alpha} L^{1-\alpha}$. Optimal labor input level L^* can be calculated from the first order condition, and substituting it back into g function, we get $g(K, L^*, A) = s_y A^{1/\alpha} K$ with s_y depending on P, w, and α.

Table 1: Assumed Parameter Values in the Simulation

Parameter	Value	Meaning
S	30	total resource stock
K_0	5	initial developed resource
A^T	0.65	level of the traditional technology
$\bar{A}$	1.2	upper bound of the new technology
β	1/1.07	the discount rate
s_y	1.0	production function scale coefficient
α	0.5	production function parameter
a_b	25	utility function parameter
b_b	2	utility function parameter
a_v	0.4	environmental amenity function parameter
c_0	6	fixed cost of development
v_c	0.75	variable development cost parameter
d_0	7	fixed cost of restoration
v_d	0.5	variable restoration cost parameter

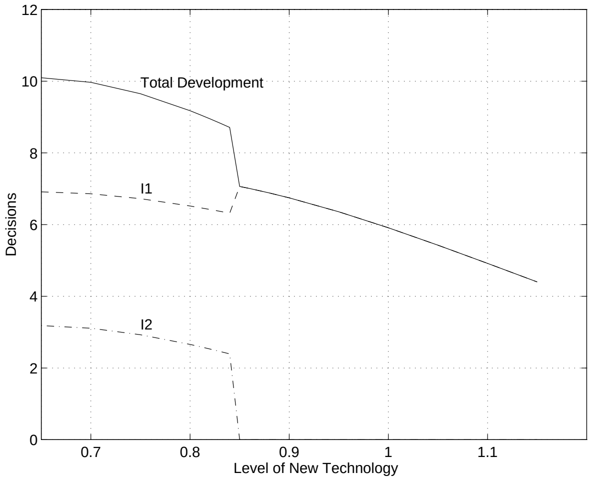
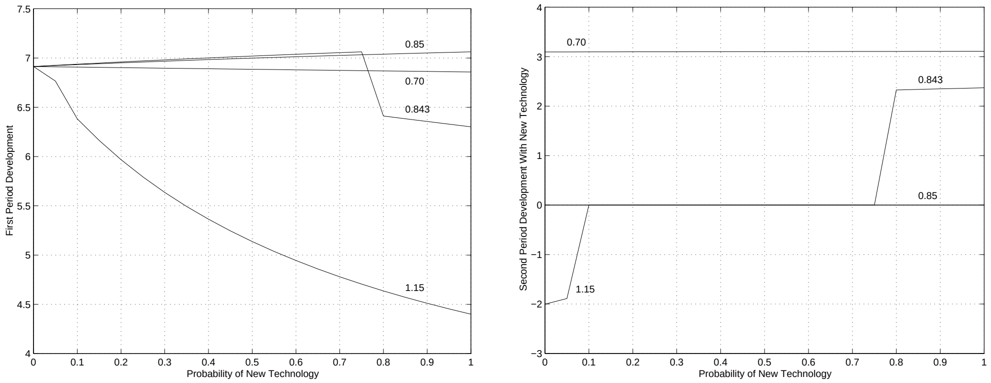
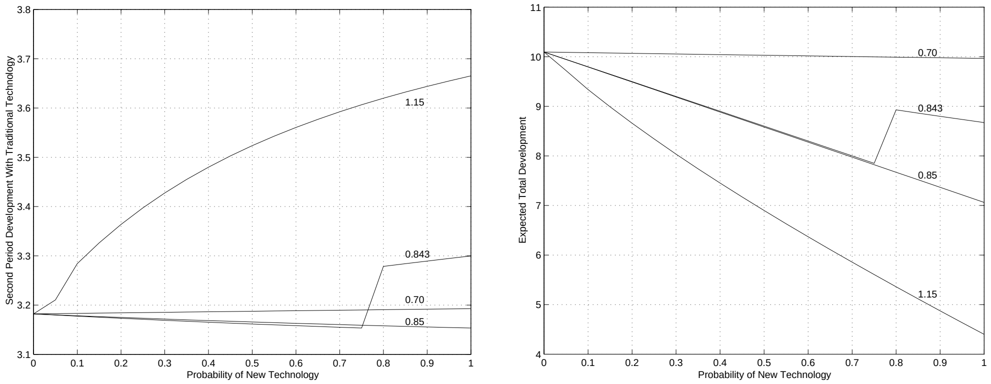


Figure 3: Developments in the Deterministic Model



(a) First Period Development $\hat{I}_1$

(b) Second Period Development With New Technology $\hat{I}_2^M$



(c) Second Period Development With Traditional Technology $\hat{I}_2^T$

(d) Expected Total Development $\hat{TI}$

Figure 4: Optimal Resource Transformation Schedules

Figure 4 presents the optimal transformation schedules as functions of probabilities for four technology levels: $0.70 \in \mathcal{A}_{11}$, $0.843 \in \mathcal{A}_{12}$, $0.85 \in \mathcal{A}_2$, and $1.15 \in \mathcal{A}_{32}$. Both $\hat{I}_1$ and $\hat{TI}$ are continuously decreasing in p for $A^M = 0.70$ (and for $A^M \in \mathcal{A}_{31}$), confirming our analytical results. They are continuous but increasing in p for $A^M = 0.85$ (and for all $A^M \in \mathcal{A}_2$), and are discontinuous in p for $A^M = 0.843$ and $A^M = 1.15$.

We have several observations from the simulation. First, $\hat{I}_1$ may be increasing in p for some A^M (0.85 and 0.843) and some p. Second, due to the jumps, the expected total development $\hat{TI}$

may not always be decreasing in p (e.g. for $A^M = 0.843$ at $p = 0.8$). In this case, $\hat{I}_1(p)$ and $\hat{TI}(p)$ for $p \in (0,1)$ are not bounded by $\hat{I}_1(0)$ and $\hat{I}_1(1)$ and $\hat{TI}(0)$ and $\hat{TI}(1)$ respectively. In summary,

Remark 2 *(1) Higher probability of new conservation technology may not necessarily delay resource development (e.g. for* $A^M = 0.843$ *and* 0.85*). (2) Higher probability of new conservation technology may not necessarily reduce the expected total resource development (e.g. for* $A^M = 0.843$*). (3)* $\hat{I}_1(0)$ *(*$\hat{TI}(0)$*) and* $\hat{I}_1(1)$ *(*$\hat{TI}(1)$*) provide natural bounds for* $\hat{I}_1(p)$ *(*$\hat{TI}(p)$*) if the transformation schemes at* $p = 0$ *and* $p = 1$ *are the same. This is not true when the schemes at* $p = 0$ *and* $p = 1$ *are different.*

4 Implications of Efficient Resource Management

In this section, we compare the development patterns achieved under the two resource management approaches: the efficient one and the traditional one. Traditional approach assumes $p = 0$ when choosing I_1, and optimally responds to the realized technology in the second period. Let $\{\tilde{I}_1, \tilde{I}_2^M(A^M), \tilde{I}_2^T\}$ be the vector of solutions. We know $\tilde{I}_1 = I_1^*(A^T)$ and $\tilde{I}_2^T = I_2^*(I_1^*(A^T), A^T)$. $\tilde{I}_2^M$ may be positive, negative, or zero, depending on the level of new technology. One possible trajectory is sketched out in Figure 2. In our numerical example, $\tilde{I}_2^M$ is positive (3.0952) for $A^M = 0.70$, negative (-2.0003) for $A^M = 1.15$, and zero for $A^M = 0.843$ and 0.85.

Inspecting Figure 4 reveals that, compared with the traditional approach efficient management does not necessarily delay resource development. In fact, it leads to earlier development for all p when $A^M = 0.85$, and for $p < 0.75$ when $A^M = 0.843$. More generally, efficient management delays development (lower I_1) if $\hat{I}_1'(p) < 0$ for all p and leads to earlier development (higher I_1) if $\hat{I}_1'(p) > 0$ for all p. Thus efficient management delays development when A^M is in $\mathcal{A}_{11}$ and $\mathcal{A}_{31}$, and may cause earlier development for other A^M levels.

Let $\tilde{TI}(p)$ be the expected total development under the traditional approach, then we know $\tilde{TI}(0) = \hat{TI}(0)$. It is straightforward to verify that when $\hat{TI}(p)$ is differentiable,

$$\frac{d\hat{TI}(p)}{dp} - \frac{d\tilde{TI}(p)}{dp} = \left(1 + p\frac{d\hat{I}_2^M}{d\hat{I}_1} + (1-p)\frac{d\hat{I}_2^T}{d\hat{I}_1}\right)\frac{d\hat{I}_1}{dp} + \left[(\hat{I}_2^M - \hat{I}_2^T) - (\tilde{I}_2^M - \tilde{I}_2^T)\right] \tag{5}$$

Then if $|\frac{d^2 I_2(I_1,A)}{dI_1 dA}|$ is small (i.e. the term in the square bracket of (5) is close to zero), $\frac{d\hat{TI}(p)}{dp} < \frac{d\tilde{TI}(p)}{dp}$ if $\hat{I}_1'(p) < 0$. Then efficient management reduces expected development when A^M is in $\mathcal{A}_{11}$ and $\mathcal{A}_{31}$. But the result is ambiguous for other technology levels and we resort to our numerical example.

Figure 5 compares the expected total development under the two management approaches for the four technology levels. The solid curves stand for total development under the efficient approach and the dashed curves are for traditional management. $\tilde{TI}(p)$ associated with $A^M = 0.85$ is very close to that associated with $A^M = 0.843$, and they are represented by one dashed curve in the figure. We see that efficient management reduces expected total development when A^M is at 0.70 and 1.15, but raises total development when A^M is at 0.843 and 0.85.

In a certain sense, we can interpret p as a "degree of mistake" of the traditional approach: If $p = 0$, there is no mistake of ignoring the new technology, and if $p = 1$, there is a big mistake of ignoring the technology. We can interpret the distance between $\hat{TI}$ and $\tilde{TI}$ as the "degree of mismanagement" (of the resource) of the traditional approach. There is no mismanagement of the resource (in aggregate) if $\hat{TI} = \tilde{TI}$. Then the $\hat{TI}$ and $\tilde{TI}$ curves associated with $A^M = 0.843$ and $A^M = 1.15$ tell that there may not be a monotonic relationship between the degree of mistake and the degree of mismanagement.

In summary, we know

Remark 3 *Compared with traditional resource management, the efficient approach may not delay or reduce resource development, depending on the level of the new technology.*

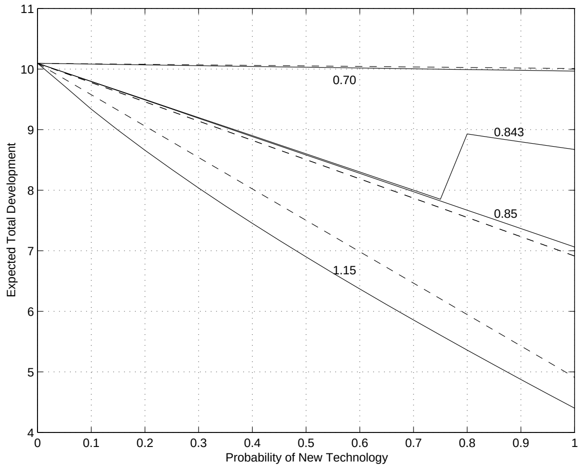


Figure 5: Expected Total Development Under the Two Evaluation Methods: $\hat{TI}$ and $\tilde{TI}$

In essence, fixed costs drive the results in Remark 3. First, the incentive to save fixed costs exists in the deterministic model: the major characteristics of region $\mathcal{A}_2$ is that more resource is developed in period one to save the fixed cost c_0^+ in period two (note that $I_2^* = 0$). Second, this incentive directly translates into $\hat{I}_1'(p) > 0$ for $A^M \in \mathcal{A}_2$ in the stochastic model: as p decreases, the incentive becomes less stronger, leading to a lower I_1. Finally, for $A^M \in \mathcal{A}_2$, as more resource is developed in period one to save future fixed costs, overall development increases since the decrease in $\hat{I}_2^T$ (weighted by $(1-p)$) cannot fully compensate for the increase in $\hat{I}_1$ (note that $\hat{I}_2^M$ and $\tilde{I}_2^M$ are both zero).

5 Discussion and Conclusion

This paper develops a framework to analyze the impacts on resource development of efficient management practices that account for possible resource conserving technological, institutional and taste changes in the future. The chief messages are: (1) Compared with traditional resource management that ignores these future possibilities, efficient management may not delay or reduce resource development, depending on levels of these changes. (2) Under efficient management, higher probability of these resource conserving changes may not delay or reduce resource development.

Surprisingly, these ambiguities arise without any policy or market distortions. They are due entirely to the cost structure of resource transformation, in particular the existence of fixed and increasing marginal costs. The incentives to save future fixed costs may prompt more resource development in early periods, and the expected future reduction in development may not be enough to compensate for the increased earlier development. This conclusion highlights the importance of fixed costs in stochastic dynamic investment analysis in general. This explicit role of fixed cost has been systematically ignored in the literature.

Our results complement real option theory in studying the role of uncertainties in resource management. ROT shows that if the management practice considers certain uncertainties, but in an inappropriate way that does not allow corresponding resource adjustment, then more and/or early resource development will happen. This result is relevant for many price uncertainties. We show that if the management practice simply ignores some uncertainties, then less and/or late development may happen if the fixed costs are high. Our result is relevant for most taste, technology and institution uncertainties.

Our findings have some important policy implications. While the new management practice may not conserve resource, it is always efficient. Policy makers and the public in general should be open-minded about the possible resource transformation patterns brought forth by the new management practice. Our results also call for a more detailed scrutiny of the cost structure of a project, especially the differentiation between fixed and variable costs. Such differentiation is not required in some evaluation handbooks, such as the Principles and Guidelines.

Appendix: Model Details

This appendix describes the details of the model explaining the results in the paper.

A.1 Nonempty of $\mathcal{A}_2$

We show that the region $\mathcal{A}_2$ is nonempty when the fixed cost of development is sufficiently high.

Proposition 2 *Given other parameters of the model, $\mathcal{A}_2$ is nonempty if c_0^+ is sufficiently high.*

Proof We only need to prove that A^R is higher than the jump point A^J. Comparing the first order conditions of I_1^* at A^T and A^R, and noting that the optimal I_1 levels are the same, we know A^R is higher than A^T by an amount determined by $I_2^*(A^T)$. Let $\bar{c}_0^+$ be the fixed cost level so that I_2^* jumps down to zero at $A = A^T$. If $c_0^+ = \bar{c}_0^+ - \delta_1$ where δ_1 is an arbitrarily small number, then I_2^* jumps down at $A^J(\delta_1) = A^T + \delta_2$, and δ_2 can be made arbitrarily small by reducing δ_1. Given $I_2^*(A^T)$ which determines the distance between A^R and A^T, we can set δ_1 to make sure that $A^J(\delta_1)$ falls between A^T and A^R. Given that A^J is continuous in c_0^+, we know $\mathcal{A}_2$ is nonempty if c_0^+ is sufficiently high. QED

A.2 Proof of Proposition 1

Now we prove Proposition 1, which describes the optimal development patterns without fixed costs of transformation. Note that without fixed costs, the first order conditions of (2) indicate that $\frac{dQ_2^M}{dI_1} = c'(\hat{I}_2^M)$ and $\frac{dQ_2^T}{dI_1} = c'(\hat{I}_2^T)$. Since $\pi_{KA} < 0$ and $A^M > A^T$, we know $\hat{I}_2^T > \hat{I}_2^M$ for any $\hat{I}_1$. The convexity of $c(\cdot)$ together with (4) then implies $\frac{d\hat{I}_1}{dp} < 0$. That is, higher probability of the new technology reduces first period development. Since both A^T and A^M are fixed, we know immediately that $\frac{d\hat{I}_2^M}{dp} > 0$ and $\frac{d\hat{I}_2^T}{dp} > 0$.

Note that $\frac{dT\hat{I}(p)}{dp} = \left(1 + p\frac{d\hat{I}_2^M}{d\hat{I}_1} + (1-p)\frac{d\hat{I}_2^T}{d\hat{I}_1}\right)\frac{d\hat{I}_1}{dp} + \hat{I}_2^M - \hat{I}_2^T$. The term in bracket is positive because $\frac{d\hat{I}_2^M}{d\hat{I}_1} < 1$ and $\frac{d\hat{I}_2^T}{d\hat{I}_1} < 1$. Thus $\frac{dT\hat{I}(p)}{dp} < 0$ since $\hat{I}_2^M < \hat{I}_2^T$ and $\frac{d\hat{I}_1}{dp} < 0$. That is, higher probability of new technology reduces the expected total development.

Given $c_0^+ = 0$, $\hat{I}_2^T$ is always positive since if $\hat{I}_2^T \leq 0$, then $\hat{I}_2^M < 0$, and reducing $\hat{I}_1$ can reduce the overall two period cost. However, we cannot rule out the possibility that $\hat{I}_2^M$ is negative when the new technology is very advanced (i.e. when A^M is high).

A.3 Transformation Patterns With Fixed Costs

Now we show how the transformation patterns depend on the probability of new technology when there are fixed costs of transformation. Similar to the no-fixed cost case, we know $\hat{I}_2^T$ cannot be negative. But it can be zero due to the fixed development cost. $\hat{I}_2^M$ can take positive, zero or negative values, with $\hat{I}_2^M \leq \hat{I}_2^T$. Then there are five possible resource transformation schemes[8] in period two: (S1) develop with both traditional and modern technologies $\hat{I}_2^T > 0$, $\hat{I}_2^M > 0$; (S2) develop with traditional and stay-put with modern technologies $\hat{I}_2^T > 0$, $\hat{I}_2^M = 0$; (S3) develop with traditional and restore with modern technologies $\hat{I}_2^T > 0$, $\hat{I}_2^M < 0$; (S4) stay put with traditional and modern technologies $\hat{I}_2^T = 0$, $\hat{I}_2^M = 0$; and (S5) stay put with traditional and restore with modern technologies $\hat{I}_2^T = 0$, $\hat{I}_2^M < 0$. Which scheme actually happens depends on the fixed costs

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[8] *We use "scheme" to represent second period transformation decisions to differentiate from the overall transformation "pattern."*

and the level of $\hat{I}_1$, which in turn depends on the probability and level of the new technology. As p changes from 0 to 1, there may be a (finite) number of switches of development schemes.

Remark 4 *If higher $\hat{I}_1$ causes a change in the transformation scheme, it either reduces development or causes restoration. Thus, there are two possible general trends of scheme switch if $\hat{I}_1$ rises: (S1)-(S2)-(S3)-(S5) and (S1)-(S2)-(S4)-(S5).*

$\hat{I}_1(p)$ jumps at a switch point but otherwise is continuous. Equation (4) is thus defined for the range of p exclusive of the jump points. As we will show later on, $\hat{I}_1(p)$ is not monotonic in p. Thus Remark 4 does not lend a lot of help in characterizing the scheme switches as p changes. However, we can rule out cycles of schemes as p changes: the same scheme can only appear once on a *connected* segment of p.

Lemma 1 *As p rises from 0 to 1, if a certain transformation scheme is switched out, it will not be switched back.*

Proof Imagine the determination of $\hat{I}_1$ by the crossing point of the marginal cost and marginal benefit functions of I_1. For a fixed resource transformation scheme, the marginal benefit function is continuous and monotonic in p. So is the level of $\hat{I}_1$ since the marginal cost function is fixed (i.e. independent of p).

Suppose scheme (Si), $i \in \{1,2,3,4,5\}$, is switched out at p_1 but is switched back at $p_2 > p_1$. Then $\hat{I}_1(p_1) \neq \hat{I}_1(p_2)$. Thus the transformation scheme at $\hat{I}_1(p_1)$ and $\hat{I}_1(p_2)$ are the same, but are different from the schemes associated with I_1 between $\hat{I}_1(p_1)$ and $\hat{I}_1(p_2)$. Then as I_1 changes from $\hat{I}_1(p_1)$ to $\hat{I}_1(p_2)$, the scheme switch violates the two general switch trends listed in Remark 4. QED

Lemma 1 suggests a simple starting point of checking the possible schemes as p changes: we can first check the schemes at the two endpoints, $p = 0$ and $p = 1$.

Proposition 3 *If the transformation schemes at $p = 0$ and $p = 1$ are different, there must be a finite number of switch points for $p \in [0,1]$. There is no switching if the schemes at $p = 0$ and $p = 1$ are the same.*

For a fixed transformation scheme, both $\hat{I}_1(p)$ and the expected total development $\hat{TI}(p)$ are continuous and monotone in p. In particular,

Proposition 4 *Both $\hat{I}_1(p)$ and $\hat{TI}(p)$ are decreasing in p when the transformation scheme is (S1), (S3), (S4) or (S5), They may be increasing or decreasing in p when the scheme is (S2), and they are more likely to be increasing if A^M is low.*

Proof For scheme (S1), the fixed cost of transformation does not matter because the development is positive. From Remark 1, we know $\hat{I}_1(p)$ and $\hat{TI}(p)$ are strictly decreasing in p.

Under schemes (S3) and (S5), $\frac{dQ_2^M}{dI_1} < 0$ since $\hat{I}_2^M < 0$. Since $\frac{dQ_2^T}{dI_1}$ is always positive, (4) then indicates that $\hat{I}_1(p)$ decreases in p. It is straightforward to show that $\hat{TI}(p)$ also decreases in p.

Under scheme (S4), $\pi_{KA} < 0$ and (4) indicate $\hat{I}_1'(p) < 0$. Again, it is straightforward to show that $\hat{TI}'(p) < 0$.

Under scheme (S2), substituting in $\hat{I}_2^M = 0$, we get

$$\frac{dQ_2^M}{dI_1} = \pi_K(K_0 + I_1, A^M) - V'(S - K_1 - I_1) \tag{6}$$

Since $\hat{I}_2^T > 0$, envelope theorem gives

$$\frac{dQ_2^T}{dI_1} = \pi_K(K_0 + I_1 + \hat{I}_2^T, A^T) - V'(S - K_1 - I_1 - \hat{I}_2^T) \tag{7}$$

The relative magnitude of $\frac{dQ_2^M}{dI_1}$ and $\frac{dQ_2^T}{dI_1}$ is thus ambiguous, depending on the difference between A^M and A^T, and the magnitude of $\hat{I}_2^T$. If A^M is low, it is more likely that $\frac{dQ_2^M}{dI_1}$ is high, or $\hat{I}_1'(p) > 0$. QED

While both $\hat{I}_1(p)$ and $\hat{TI}(p)$ are continuous in p for a fixed transformation scheme, they jump (either up or down) at a switch point. Since in some cases we do not know the specific scheme associated with a certain A^M and p, we do not know the corresponding properties of $\hat{I}_1(p)$ and $\hat{TI}(p)$. To understand the impacts of a new technology A^M, it is important to identify both the schemes associated with probability p and the nature of the switches as p changes.

Now we try to identify the possible transformation schemes for each level of A^M. If $A^M \in \mathcal{A}_{11}$, both $\hat{I}_1$ and $\hat{I}_2$ are positive for $p = 0$ and $p = 1$. Propositions 3 and 4 then indicate that the scheme is (S1) for all p and both $\hat{I}_1$ and $\hat{TI}$ are decreasing in p. For $A^M \in \mathcal{A}_{31}$, we know from Figure 2 that $\hat{I}_2^T > 0$ and $\hat{I}_2^M = 0$ at $p = 0$ and $\hat{I}_2^M = 0$ at $p = 1$. However, since $I_1^*(A^M) < I_1^*(A^T)$, we know $\hat{I}_2^T > 0$ at $p = 1$. Thus, the scheme is (S2) for all p and $\hat{I}_1$ and $\hat{TI}$ are decreasing in p. For other levels of technologies, the transformation patterns become more complicated and there might be several switches.

References

Abel, Andrew B. and Janice C. Eberly, "A Unified Model of Investment Under Uncertainty," *American Economic Review*, 1994, *84* (5), 1369–1384.

Arrow, Kenneth J. and Anthony C. Fisher, "Environmental Preservation, Uncertainty, and Irreversibility," *Quarterly Journal of Economics*, 1974, *88*, 312–319.

Dixit, Avinash K. and Robert S. Pindyck, *Investment Under Uncertainty*, Princeton, New Jersey: Princeton University Press, 1994.

Fisher, Anthony C., John V. Krutilla, and Charles J. Cicchetti, "The Economics of Environmental Preservation: A Theoretical and Empirical Analysis," *American Economic Review*, 1972, *62*, 605–619.

Henry, Claude, "Investment Decisions Under Uncertainty: The Irreversibility Effect," *American Economic Review*, 1974, *64*, 1006–1012.

Reisner, Marc P., *Cadillac desert : the American West and its disappearing water*, New York, N.Y.: Viking, 1986.

Zhao, Jinhua and David Zilberman, "Endogenous Investment, Restoration, and Nature of Irreversibility," Presented at the AAEA Annual Meeting, Indianapolis, Department of Agricultural and Resource Economics, University of California at Berkeley 1995.