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The Simple Economics of Easter Island: A Ricardo-Malthus Model of Renewable Resource Use

By JAMES A. BRANDER AND M. SCOTT TAYLOR*

This paper presents a general equilibrium model of renewable resource and population dynamics related to the Lotka-Volterra predator-prey model, with man as the predator and the resource base as the prey. We apply the model to the rise and fall of Easter Island, showing that plausible parameter values generate a "feast and famine" pattern of cyclical adjustment in population and resource stocks. Near-monotonic adjustment arises for higher values of a resource regeneration parameter, as might apply elsewhere in Polynesia. We also describe other civilizations that might have declined because of population overshooting and endogenous resource degradation. (JEL Q20, N57, J10)

The world of the late twentieth century is much more heavily populated and has much higher average living standards than any previous period in human history. However, widely publicized concerns have been expressed over whether per capita real income can continue to increase or even be maintained at current levels in the face of rapid population growth and environmental degradation. Economists normally tend to be skeptical about such claims, largely on the basis of the historical record. At various times in the past, people have worried about overpopulation and environmental degradation, yet the past, at least as we imagine it, seems to provide a record of impressive progress in living standards.

The application of modern science to archaeological and anthropological evidence is,

however, producing interesting new information on the role of natural resource degradation. Specifically, a pattern of economic and population growth, resource degradation, and subsequent economic decline appears more common than previously thought. A major question of present-day resource management is whether the world as a whole, or some portion of it, might be on a trajectory of this type. A first step in addressing such concerns is to construct a formal model linking population dynamics and renewable resource dynamics.

The primary objective of this paper is to construct such a model. The second objective is to apply this model to the very interesting case of Easter Island which, until recently, has been one of the world's great anthropological mysteries. Our model contains three central components. The first component is Malthusian population dynamics, following Thomas R. Malthus (1798). Malthus argued that increases in real income arising from productivity improvements (or other sources) would tend to cause population growth, leading to erosion and perhaps full dissipation of income gains. He also suggested that population growth might overshoot productivity gains, causing subsequent painful readjustment.¹

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¹ Malthus was not a fatalist. He believed that enlightened public policy could reduce population growth, contemplating both contraception and "moral restraint" as

The second component of the model is an open-access renewable resource. Malthus asserted (Ch. 10 pp. 82–83) that the negative effects of population growth would be worse in the absence of established property rights. Property rights are a particular problem with renewable resources such as fish, forests, soil, and wildlife. Thus, if we are to observe Malthusian effects anywhere, we are perhaps likeliest to see them where renewable resources are an important part of the resource base. The extreme version of incomplete property rights is an open-access resource, where anyone can use the resource stock freely. Malthus did not provide a clear formulation of open-access renewable resources, but we can take this step, drawing on the modern theory of renewable resources.

The third component of the model is a Ricardian production structure at each moment in time. Thus the model might reasonably be referred to as a Ricardo-Malthus model of open-access renewable resources. The components of the model are relatively simple. Even so, the model exhibits complex dynamic behavior. For example, one possible outcome of the model is a dynamic pattern in which, starting from some initial state, population and the resource stock rise and fall in damped cycles. A change in parameters, however, can shift dynamic behavior toward monotonic extinction of the population or might lead to monotonic convergence toward an interior steady state.

The model provides a plausible explanation of the rise and fall of the Easter Island civilization. Applying the model to larger and more complex modern resource systems would require an expanded model structure, but the simple model presented in this paper provides, at the very least, insights that should be considered in evaluating current renewable resource management practices.

mitigating factors. He noted that reduced fertility arising from social responses (such as increased age of marriage) was the major check on population in Western Europe. Other checks included reduced fertility and increased mortality arising from poor nutrition and increased incidence of disease. Famine, in his view, was only nature's last resort, and he noted that in much of Europe "absolute famine has never been known" (Malthus, 1798 p. 61).

The main intellectual precursors to our analysis are Malthus (1798), David Ricardo (1817), and the pioneering work on renewable resources of H. Scott Gordon (1954) and M. B. Schaefer (1957). Resource dynamics have been studied by many scholars, and a particularly valuable overview of this material (with considerable original work) is Colin W. Clark (1990). The particular resource model used here is due to Brander and Taylor (1997), and is also related to Anthony D. Scott and Clive Southey (1969). Detailed modeling and estimation of particular renewable resource stocks has been carried out by many scholars including, for example, Jean-Didier Opsomer and Jon M. Conrad (1994). Careful studies of Malthusian population dynamics include Maw-Lin Lee and David J. Loschky (1987) and George R. Boyer (1989). The claim that environmental constraints are impinging negatively on living standards is a central theme in Richard B. Norgaard (1994) and Lester R. Brown (1995).

Applying formal economic analysis to an archaeological mystery is an unusual activity for economists, but is not without precedent. In particular, Vernon L. Smith (1975) used a formal model of hunting to explain the extinctions of large mammals during the late Pleistocene era and more recently (Smith, 1992) suggested using formal economic models to explain human prehistory more generally. This idea parallels evolution in the field of archaeology itself, where mathematical models are increasingly used as aids to interpreting physical evidence. A valuable overview of this rapidly changing field is Kenneth R. Dark (1995).

Section I provides a brief description of Easter Island's past. This past is fascinating in its own right, as are the methods by which it has been uncovered, but our main goal is to provide background to our approach. Section II presents our general equilibrium model of resource use and Malthusian population dynamics. Section III analyzes population and resource interactions, and states the main propositions characterizing the dynamic behavior of the system. Section IV applies the model to Easter Island and Section V describes other cases where the model might apply. Section VI discusses the role of institutional

change, and Section VII contains concluding remarks.

I. Easter Island

Easter Island (also called Rapa Nui) is a small Pacific island over 2,000 miles (3,200 km) from the coast of Chile, with a population (as of the early 1990's) of about 2,100. For the past two centuries, Easter Island has been regarded as a major archaeological and anthropological mystery. In particular, the Polynesian civilization in place at the time of first European discovery in 1722 is known to have been much poorer and much less populous than it had been a few hundred years earlier. Thus the economic record in Easter Island is one of rising wealth and rising population, followed by decline.

The most visible evidence of Easter Island's past glory consists of enormous statues (called "moai"), carved from volcanic stone. Many statues rested on large platforms at various locations on the island. The largest "movable" statues weigh more than 80 tons, and the largest statue of all lies unfinished in the quarry where it was carved, and weighs about 270 tons. The puzzling feature of the statues and platforms is that the late stone age Polynesian culture found on Easter Island in 1722 seemed incapable of creating such monumental architecture. First, the culture seemed too poor to support a large artisan class devoted to carving statues, and certainly no such group existed in the eighteenth century. Also, the statues were moved substantial distances from the island's lone quarry to their destinations, but the population, estimated at about 3,000 in 1722, seemed too small to move the larger statues,² at least without tools such as levers, rollers, rope, and wooden sleds. However, the island in 1722 had no trees suitable for making such tools. Local residents had no knowledge of how to move the statues, and believed that the

statues had walked to the platforms under the influence of a spiritual power.

Various theories have been advanced to explain these statues and other aspects of Easter Island. The most well-known theory is due to Thor Heyerdahl (1950, 1989), who argued that native South Americans had inhabited Easter Island (and other Pacific islands), had built Easter Island's statues, and had subsequently been displaced by a less advanced Polynesian culture. To support his thesis, Heyerdahl traveled on a balsa raft, the *Kon-Tiki*, from off the coast of South America to the Pacific islands. A more exotic theory of the "Atlantis" type, proposed by John Macmillan Brown (1924), is that Easter Island is the tiny remnant of a great continent or archipelago (sometimes called "Mu") that housed an advanced civilization but sunk beneath the ocean. A still more exotic theory, proposed by Erich von Daniken (1970), is that the statues were created by an extraterrestrial civilization. Two recent books describing the current understanding of Easter Island are Bahn and Flenley (1992) and Van Tilburg (1994). This understanding does not support the Heyerdahl, "Atlantis," or extraterrestrial theories of Easter Island, but fits well with the Ricardo-Malthus model of open-access resources.

Recently discovered evidence suggests that Easter Island was first settled by a small group of Polynesians about or shortly after 400 A.D. The pollen record obtained from core samples and dated with carbon dating methods shows that the island supported a great palm forest at this time. This discovery was a major surprise given the treeless nature of the island at the time of first European contact. In the years following initial settlement, one important activity was cutting down trees, making canoes, and catching fish. Thus the archaeological record shows a high density of fish bones during this early period. Wood was also used to make tools and for firewood, and the forest was a nesting place for birds that the islanders also ate. The population grew rapidly and was wealthy in the sense that meeting subsistence requirements would have been relatively easy, leaving ample time to devote to other activities including, as time went on, carving and moving statues.

² There is a significant literature devoted to methods of monument construction and movement. Even 3,000 people could not have moved the larger statues without the benefit of wooden sleds and levers. See Paul Bahn and John Flenley (1992) and Jo Anne Van Tilburg (1994) for a discussion of statue transportation.

Noticeable forest reduction is evident in the pollen record by about 900 A.D. Most of the statues were carved between about 1100 and 1500.³ By about 1400 the palm forest was entirely gone. Diet changed for the worse as forest depletion became severe, containing less fish (and thus less protein) than earlier. Loss of forest cover also led to reduced water retention in the soil and to soil erosion, causing lower agricultural yields. Population probably peaked at about 10,000 sometime around 1400 A.D., then began to decline.⁴ The period 1400 to 1500 was a period of falling food consumption and initially active, but subsequently declining, carving activity.

Carving had apparently ceased by 1500. At about this time, a new tool called a "mataa" enters the archaeological record. This tool resembles a spearhead or dagger and is almost certainly a weapon. In addition, many islanders began inhabiting caves and fortified dwellings. There is also strong evidence of cannibalism at this time. The natural inference is that the island entered a period of violent internecine conflict. However, at first European contact in 1722 no obvious signs of warfare were noted. This visit (by three Dutch ships) lasted only a single day, however, and much may have gone unnoticed.

The next known contact with the outside world was a brief visit from a Spanish ship in 1770, followed in 1774 by a visit from James Cook, who provided a systematic description⁵ of Easter Island. There had been some change between 1722 and 1774. Most noticeably, almost all of the statues had been knocked over, whereas many had been standing in 1722. Statue worship, still in place in 1722, had disappeared by 1774. Population was apparently

less numerous than it had been in 1722, and was estimated at about 2,000.⁶

Thus Easter Island suffered a sharp decline after perhaps a thousand years of apparent peace and prosperity. The population rose well above its long-run sustainable level and subsequently fell in tandem with disintegration of the existing social order and a rise in violent conflict. Kirch (1984 p. 264) suggests that "Easter Island is a story of a society which—temporarily but brilliantly surpassing its limits—crashed devastatingly."

The mystery of Easter Island's fall is regarded by many as solved. In simple form, the current explanation is that the islanders degraded their environment to the point that it could no longer support the population and culture it once had. However, Polynesians almost always dramatically altered the environments of the islands they discovered. Why did environmental degradation lead to population overshooting and decline on Easter Island, but not on the other major islands of Polynesia? Furthermore, there are 12 so-called "mystery islands" in Polynesia. These islands were once settled by Polynesians but were unoccupied at the time of European discovery. All these Polynesian islands represent pieces of "data" that should be consistent with whatever theory is proposed as an explanation for Easter Island.

II. The Ricardo-Malthus Model

A. Renewable Resource Dynamics

The resource stock at time t is $S(t)$. For Easter Island it is convenient to think of the resource stock as the ecological complex consisting of the forest and soil. The change in the stock at time t is the natural growth rate

³ Radiocarbon dates are available in Van Tilburg (1994 p. 33). These dates are attributed to unpublished work of W. S. Ayres.

⁴ This population estimate appears several places in the literature and is often attributed to W. Mulloy. Others have suggested that the reasonable range for the population maximum was between 7,000 and 20,000, with most favoring about 10,000.

⁵ Cook had a Tahitian crew member who could communicate quite easily with the Easter Islanders, as Tahitian and the Easter Island language were similar. See P. V. Kirch (1984 Chs. 3 and 11).

⁶ In 1862 the population was reliably estimated at about 3,000. In 1862 and 1863, slave traders from Peru invaded the island and took about one-third of the population as slaves. Many of these slaves died of smallpox. A few returned to the island, inadvertently causing a smallpox epidemic that killed most of the remaining Islanders. In 1877 the population reached its low point of 111, from which it subsequently increased by natural increase and by immigration from Tahiti and Chile.

$G(S(t))$, minus the harvest rate, $H(t)$. Dropping the time argument for convenience,

$$(1) \quad dS/dt = G(S) - H.$$

We use the logistic functional form⁷ for G , which is perhaps the simplest plausible functional form for biological growth in a constrained environment.

$$(2) \quad G(S) = rS(1 - S/K).$$

K , the "carrying capacity," is the maximum possible size for the resource stock, as $S = K$ implies that further growth cannot occur. Variable r is the "intrinsic" growth (or regeneration) rate.

The economy produces and consumes two goods. H is the harvest of the renewable resource, and M is some aggregate "other good." In the case of Easter Island, we think of the (broadly defined) harvest as being food (i.e., agricultural output from the soil and fish caught from wooden vessels made from trees), while good M would include tools, housing, artistic output (including monumental architecture), household production, etc. Good M is treated as a numeraire whose price is normalized to 1. Aside from resource stock S , the only other factor of production is labor, L . We make the inessential simplification that labor force L is equal to the population. Good M is produced with constant returns to scale using only labor. By choice of units, one unit of labor produces one unit of good M . Since the price of good M is 1, the wage (denoted by w) must equal 1 if manufactures are produced.

We assume that harvesting of the resource is carried out according to the Schaefer harvesting production function (proposed by Schaefer [1957]) as follows,

$$(3) \quad H^P = \alpha SL_H$$

where H^P is the harvest supplied by producers. (The superscript P stands for "production".) L_H is the labor used in resource harvesting and

α is a positive constant. Letting $a_{LH}(S)$ represent the unit labor requirement in the resource sector, (3) implies that $a_{LH}(S) = L_H/H^P = 1/(\alpha S)$. Production in both sectors is carried out under conditions of free entry. Because of open access there is no explicit rental cost for using S , and the price of the resource good must equal its unit cost of production.

$$(4) \quad p = wa_{LH} = w/(\alpha S).$$

A representative consumer is endowed with one unit of labor and is assumed to have instantaneous utility given by the following Cobb-Douglas utility function

$$(5) \quad u = h^\beta m^{1-\beta}$$

where h and m are individual consumption of the resource good and of manufactures, and β is between 0 and 1. Maximizing utility at a point in time subject to instantaneous budget constraint $ph + m = w$ yields $h = w\beta/p$ and $m = w(1 - \beta)$. Since total domestic demand is L times individual demand, we have

$$(6) \quad H^D = w\beta L/p; \quad M^D = w(1 - \beta)L$$

where superscript D represents demand.

At a moment in time the resource stock is fixed, the population (and labor force) is fixed, and the economy's production possibility frontier is given by the following full-employment condition.

$$(7) \quad H^P a_{LH}(S) + M = L.$$

A linear production structure of this type is referred to as a Ricardian production structure (after Ricardo, 1817). The Ricardian temporary equilibrium can be determined algebraically by substituting (4) into (6) (i.e., the supply price equals the demand price) to obtain temporary equilibrium resource harvest, H .

$$(8) \quad H = \alpha\beta LS.$$

The equilibrium output of M is $M = (1 - \beta)L$, implying that manufactures will always be produced and therefore that wage $w = 1$. At a Ricardian temporary equilibrium, the

⁷ Our major results can be extended to the case of a general compensatory growth function. See Appendix B.

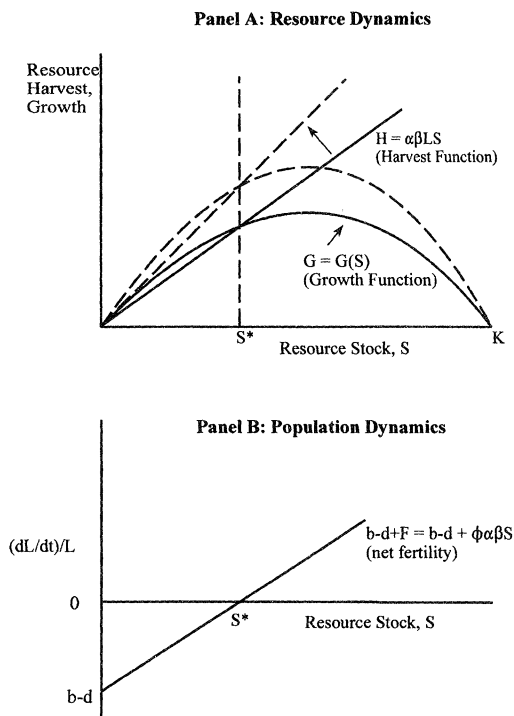


FIGURE 1. A RICARDO-MALTHUS STEADY STATE

harvest will not necessarily equal the underlying biological growth rate of the resource. If, for example, temporary equilibrium harvest H exceeds biological growth G , then the stock diminishes. Substituting (2) and (8) into (1) yields the following expression for the evolution of the resource stock.

$$(9) \quad dS/dt = rS(1 - S/K) - \alpha\beta LS.$$

If the resource stock falls, then labor productivity in the resource sector falls, the Ricardian production possibility frontier shifts in, and this establishes a new temporary equilibrium with a lower harvest.

Panel A of Figure 1 illustrates a typical steady state (i.e., where $dS/dt = 0$) using the harvest function (8) and the resource growth function (2). (Ignore the dashed lines for now.) As shown in the figure, stock S^* implies that harvest $H = \alpha\beta LS^*$ just matches resource growth $G(S)$ at $S = S^*$. Thus S^* is a steady state if the actual population level is L .

B. Malthusian Population Dynamics

Our discussion of Figure 1 so far implicitly treats population as fixed at size L , allowing us to focus purely on resource dynamics. We now consider population dynamics. We assume an underlying proportional birth rate, b , and an underlying proportional death rate, d . Thus the base rate of population increase is $(b - d)$, which we assume to be negative, implying that without any forest stock or arable soil the population would eventually disappear. However, consumption of the resource good increases fertility and/or decreases mortality, and therefore increases the rate of population growth.⁸ In particular, the population growth rate is given by

$$(10) \quad dL/dt = L[b - d + F]$$

where $F = \phi H/L$ is the fertility function, and ϕ is a positive constant. Thus higher per capita consumption of the resource good leads to higher population growth. It is in this sense that population dynamics are “Malthusian.”⁹ Noting from (8) that $H/L = \alpha\beta S$, equation (10) can be rewritten as

$$(11) \quad dL/dt = L(b - d + \phi\alpha\beta S).$$

III. Population and Resource Interactions

Equations (9) and (11) form a two-equation system of differential equations characterizing the evolution of the Ricardo-Malthus model. These equations are a variation of the Lotka-Volterra predator-prey model.¹⁰ Human population, L , is the “predator” and the resource

⁸ One might let net fertility depend on total consumption rather than on resource consumption, although the case could be argued either way and has little effect on the analysis.

⁹ Among modern high-income societies, population growth is negatively correlated with income at both the country and individual level. Most premodern societies appear to exhibit Malthusian population dynamics, in that higher consumption causes higher population growth.

¹⁰ Predator-prey systems have sometimes been studied in renewable resource economics. See, in particular, David L. Ragozin and Gardner Brown (1985) and Philip Neher (1990).

stock, S , is the “prey.” We concentrate first on steady-state analysis, then turn to the system’s dynamic behavior.

A. Steady-State Analysis

The system given by (9) and (11) will have a steady state if dL/dt and dS/dt are simultaneously equal to zero. There are three solutions, as expressed in Proposition 1.

PROPOSITION 1: *The Ricardo-Malthus model exhibits three steady states. Steady state 1 is a corner solution at $(L = 0, S = 0)$. Steady state 2 is a corner solution at $(L = 0, S = K)$. Steady state 3 is an interior solution at*

$$(12) \quad L = [r/(\alpha\beta)] \\ \times [1 - (d - b)/(\phi\alpha\beta K)], \\ S = (d - b)/(\phi\alpha\beta).$$

PROOF:

The proof follows immediately from simultaneously setting equations (9) and (11) to zero and can be seen by inspection. To obtain steady state 3, one can solve for S from expression (11), then substitute this value in (9) to obtain L . Note that steady state 3 implies positive values for L and S as $d > b$, and r , α , β , and ϕ are all positive. The steady-state stock, S , must be less than carrying capacity K . In steady state 3, $S = (d - b)/(\phi\alpha\beta)$ so this consistency requirement can be written as

$$(13) \quad (d - b)/(\phi\alpha\beta) < K.$$

If (13) comes to equality or reverses direction, then steady state 3 collapses to steady state 2.

We focus on the interior steady state. As shown in Proposition 4, when (13) holds, the interior steady state is stable whereas steady states 1 and 2 are saddlepoints. The interior steady state can be illustrated graphically by using the two panels of Figure 1. Panel A represents the resource dynamics conditional on population L . Panel B captures the population dynamics given in (11) by graphing the percentage rate of change of the population (dL/dt)/ L on the vertical axis, and the resource stock on the horizontal. The upward-sloping line is net fertility $(b - d + F)$, which is linear in S as $F = \phi\alpha\beta S$ [substituting (8) into the definition of F].

At any stock $S < S^*$, there is an excess of deaths over births and the population shrinks; at any stock greater than S^* the population grows. At stock S^* population growth is zero and the population level is stationary. We denote this level as L^* . Therefore, at resource stock S^* , the population is stabilized at L^* and the harvest of the resource is just equal to its underlying growth rate, implying that S is also stationary. The two panels together therefore illustrate an interior steady state. Using expression (12), or Figure 1, we can determine how changes in exogenous parameters affect interior steady-state resource stocks and population. Proposition 2 follows by inspection, and Proposition 3 is obtained by differentiating L as given in (12).

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PROPOSITION 2: *The steady-state resource stock*

- (i) *rises if the mortality rate rises, the birth rate falls, or fertility responsiveness falls;*
- (ii) *falls if there is technological progress in harvesting; and*
- (iii) *is unaffected by changes in the intrinsic resource regeneration rate, r , or carrying capacity, K .*

PROPOSITION 3: *The steady-state population level*

- (i) *rises equiproportionately with an increase in the intrinsic rate of resource growth, r ;*
- (ii) *falls when harvesting technology improves if $S < K/2$ and rises if $S > K/2$;*
- (iii) *falls when the taste for the resource good rises if $S < K/2$ and rises if $S > K/2$; and*
- (iv) *rises if the carrying capacity of the environment rises.*

It follows from (8) and (12) that per capita steady-state resource consumption, h , is $(d - b)/\phi$. Per capita consumption of the other

good is $(1 - \beta)$. Thus steady-state resource consumption is determined by demographics, and rises if the birth rate falls or if fertility responsiveness falls.¹¹ It is instructive to see how population growth dissipates gains from resource productivity improvements. Suppose the economy is at the steady state in Figure 1 and r rises. The growth curve will shift up as shown by the dashed line in Panel A. At stock S^* , the harvest is then less than resource growth and the resource rebuilds. Per capita consumption of the resource good rises, causing population growth, and the harvest function in Panel A rotates upwards (as L rises). Since nothing has altered the demographic steady state in Panel B, the resource stock must return to S^* , but with a higher population and unchanged per capita real income.

B. Dynamics

We now characterize the dynamic behaviour of the system. We assume that parameter restriction (13) is met, implying that an interior steady state exists.

PROPOSITION 4: *When an interior steady state exists, the local behavior of the system is as follows.*

- (i) *Steady state 1 ($L=0, S=0$) is an unstable saddlepoint allowing an approach along the $S = 0$ axis.*
- (ii) *Steady state 2 ($L = 0, S = K$) is an unstable saddlepoint allowing an approach along the $L = 0$ axis.*
- (iii) *Steady state 3 ($L > 0, S > 0$) is a stable steady state and a "spiral node" with cyclical convergence if*

$$(14) \quad r(d-b)/(K\phi\alpha\beta) + 4((d-b) - K\phi\alpha\beta) < 0.$$

¹¹ Another easily derived point of interest is that a decline in the birth rate causes steady-state resource output to rise if $S < K/2$. This possibility is unusual for Malthusian models, but arises here because of the resource dynamics.

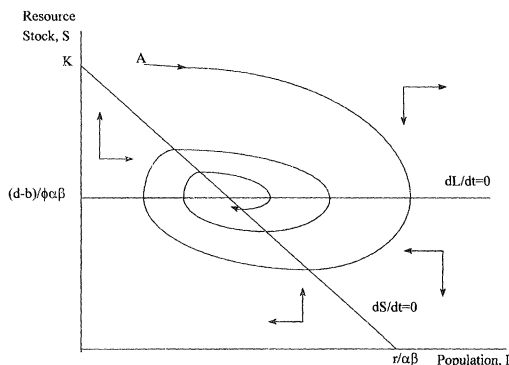


FIGURE 2. TRANSITION DYNAMICS

- (iv) *Steady state 3 is a stable steady state and an "improper node" allowing monotonic convergence if the inequality in (14) runs in the other direction.*

PROOF:

See Appendix A.

Proposition 4 is based on the fact that the dynamic system is locally linear in the neighborhood of a steady state. Since Proposition 4 shows that the interior steady state is locally stable, our earlier comparative steady-state exercises (Propositions 2 and 3) are meaningful in that small perturbations in parameters will lead to small changes in steady-state values and allow convergence to a new steady state.

Condition (14) is central in understanding the model's local dynamics. It can be rewritten as $r < 4K\phi\alpha\beta(K\phi\alpha\beta - (d-b))/(d-b)$. Noting from (13) that the right-hand side of this inequality must be positive, one interpretation of (14) is that a slow enough rate of intrinsic resource growth insures a locally cyclical trajectory. Conversely, given r , (14) indicates that cyclical dynamics will occur if fertility is very responsive to per capita consumption (represented by ϕ) or if the harvesting technology is very efficient (i.e., if α is high).

To examine the global properties of the model, consider the phase diagram in Figure 2. Population L is on the horizontal axis and resource stock S is on the vertical axis. The horizontal line labeled $dL/dt = 0$ derives from

expression (11), which implies that $dL/dt = 0$ if $S = (d - b)/\phi\alpha\beta$. If the system is above this line, then $dL/dt > 0$, and if the system is below it, then $dL/dt < 0$. The other line, labeled $dS/dt = 0$, is obtained from expression (9), which implies that $dS/dt = 0$ if $S = K - (K\alpha\beta/r)L$. Above this line, $dS/dt < 0$ and below it, $dS/dt > 0$. The intersection of these lines is the interior steady state. The directions of motion for each of the four regions in the diagram are shown by the right-angle arrows.

Consider, for example, point A, which might represent "first arrival" (i.e., a small population and the resource at carrying capacity). Point A is above the $dS/dt = 0$ line, implying that the resource stock must be falling, and is also above the $dL/dt = 0$ line, implying a rising population. The figure shows one possible adjustment path toward the steady state, but other types of adjustment are also consistent with the arrows of motion, including monotonic adjustment toward the steady state. Proposition 5 characterizes the global approach to steady state conditional on different starting points.

PROPOSITION 5: *When an interior steady state exists, the global behavior of the system is as follows.*

- (i) *If $L > 0$ and $S = 0$, the system approaches steady state 1 with $L = 0$ and $S = 0$.*
- (ii) *If $L = 0$ and $S > 0$, the system approaches steady state 2 with $S = K$ and $L = 0$.*
- (i) *If $S > 0$ and $L > 0$, then the system converges to the interior solution in steady state 3.*

PROOF:

See Appendix A.

It is striking that the system converges to an interior steady state from any interior starting point. There are two important parameter restrictions underlying this property. The first is inequality (13). If this inequality is not satisfied, the system crashes toward zero population. In this case, steady state 2 becomes a globally stable improper node. Thus, if (13) is not satisfied, our model implies extinction of

the human population and a restoration of the resource base to carrying capacity.

The second parameter condition is given by (14) which, as shown in Appendix A, determines whether the linearized system in the neighborhood of the interior steady state has complex or real roots. If the linearized system has complex roots, then all trajectories exhibit cyclical adjustment sufficiently close to the steady state. If the linearized system has real roots, then all trajectories approach the interior steady state along a path increasingly close to the dominant eigenvector of the system. Such a trajectory may be globally monotonic and must be locally monotonic.

If we start far away from the steady state, then it is more difficult to describe the paths of the system completely, but many qualitative features of the global system follow from an understanding of the local analysis. For example, suppose the system is perturbed from an initial steady state by the instantaneous disappearance of some fraction of the predator population. Cyclical behavior arises if the predator grows quickly in response to this shock while the resource grows slowly. In this case, the quick growth of the predator causes it to overshoot its new long-run level. The now overabundant predator then reduces the prey below its steady-state level, and this in turn causes a decline of the predator population below its steady-state level. But when the predator declines, the prey rebuilds and overshoots the steady state, leading to a resurgence of the predator, which again overshoots, etc., tracing out a damped cycle with an overshooting predator population chasing a slowly adjusting prey toward the steady state. This interpretation is consistent with condition (14), which shows that adjustment must be cyclical if r (the intrinsic growth rate of the prey) is sufficiently low or if $\phi\alpha\beta$ (the growth response of the predator to a change in the resource stock S) is sufficiently high.

This description describes the forces affecting the local behavior of the system near a steady state, but it also applies to global behavior. A complete analytical characterization of all possible trajectories as a function of parameters is difficult to develop, but the limiting case in which the resource stock adjusts instantaneously to its steady-state

value is instructive. In this case the economy would always operate on the $dS/dt = 0$ locus. As the founding population is (by assumption) smaller than its steady-state value, the economy would move down the $dS/dt = 0$ locus until it reached the steady state. In this case, when the predator adjusts slowly and the prey adjusts infinitely quickly, both the resource stock and the population level adjust monotonically toward their steady-state values.

Technically, we can use the condition $dS/dt = 0$ to solve for S as a function of L [from (9)] then substitute this in (11) to get a one-variable differential equation in L . The solution is logistic: population grows fast at first then levels off, as in the standard description of Polynesian islands.

IV. Applying the Ricardo-Malthus Model to Easter Island

In this section we use simulations of the Ricardo-Malthus model to make two points. First, by choosing parameters that are consistent with our knowledge of Easter Island, Polynesian civilizations generally, and other Neolithic populations, we are able to generate a time series for population size and resource stocks that appears to (approximately) replicate Easter Island's past. We take this as tentative support for our theory of the rise and fall of the Easter Island civilization. Second, parameter changes can change the time pattern of population and resource stock evolution from extreme cyclical overshooting to monotonic adjustment toward the steady state.¹² We take this feature of the model as a possible explanation as to why Easter Island appears to be different from other Polynesian islands.

A. Parameter Choice

Some parameter values are simply a matter of scaling, such as the carrying capacity of the

forest/soil resource complex. It is convenient for the stock to be similar in magnitude to the population, so we let the carrying capacity of the resource stock be 12,000 units. This is the starting value of the stock when Polynesian colonization first occurred. (The forest had been in place for approximately 37,000 years before first colonization, so carrying capacity had certainly been reached.)

The next parameter to consider is α , labor harvesting productivity. The productivity of a unit of labor is αS . One unit of labor corresponds to the amount of labor one person can provide in one period. It is convenient to let ten-year intervals be periods. If we let $\alpha = 0.00001$, this means that if $S = K$, a household could provide its subsistence consumption (the amount just necessary to reproduce itself) in about 20 percent of its available labor time. Accordingly, there is considerable surplus on the island when the resource stock is large. This seems roughly consistent with known information.

Parameter β reflects the "taste" for the output of the harvest good. One way of trying to get some idea of β is to recall that β is equal to the share of the labor force devoted to harvesting the resource. The other sector includes manufacturing and service activities. Various pieces of evidence suggest that the resource sector probably absorbed somewhat less than half the available labor supply. A value of 0.4 for β is probably in the reasonable range.

Another important parameter is r , the intrinsic growth (or regeneration) rate of the resource. We initially assume an intrinsic growth rate of 0.04, implying that, left to itself, the forest/soil complex would increase by 4 percent per decade in the absence of congestion effects (i.e., if the stock were small compared to the carrying capacity). The remaining key parameters are the demographic parameters. Let $(b - d) = -0.1$ and let $\phi = 4$. The value for $(b - d)$ means that the population would decrease by 10 percent per decade in the absence of the resource stock. Letting $\phi = 4$ implies that there would be positive population growth if the stock were approximately 50 percent of its carrying capacity, and negative population growth otherwise. Throughout the simulation period annual population growth never exceeds 1 percent per year, which is

¹² The key parameter difference that we consider in explaining the difference between Easter Island and other Polynesian islands is substantial. The model also implies bifurcations (in parameter space) around which major changes in predictions arise.

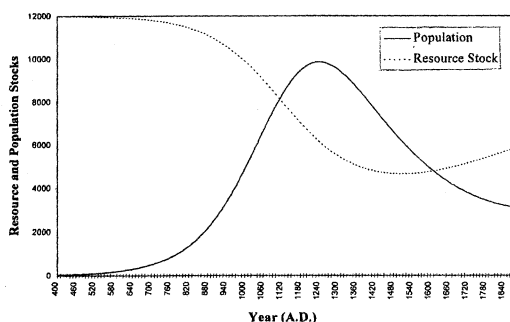


FIGURE 3. EASTER ISLAND BASE CASE

consistent with the demographic literature on Neolithic populations. The range of estimates for the founding population ranges from 20 to 100 or more, with 40 being commonly used as a plausible estimate. We take the starting value to be 40, but varying this estimate makes little difference to the results. These parameters yield the time-series pattern shown in Figure 3.

Figure 3 shows an interesting dynamic pattern. For the first 300 years, humans have little impact on the resource. Population then begins to increase rapidly and the resource stock falls precipitously for the next 800 years. About 900 years after discovery the initial population of 40 has grown to about 10,000. The period of high population (and high labor supply) in the simulation corresponds to the period of intense carving in the archaeological record. The simulated resource stock reaches its trough about 250 years later, close to 1500 A.D., as does per capita resource consumption. Recall that a new weapon (the "mataa") appears in the archaeological record at about this time, evidence of cannibalism also appears, and there is movement to fortified structures and caves as dwellings. The simulated resource stock begins its recovery but population continues to fall, implying a 1722 population of approximately 3,800 to meet the Dutch ships, not far from the 3,000 actually estimated. The simulated 1774 population is about 3,400, again somewhat more than the 2,000 Cook estimated. In the 1800's there is substantial outside intervention so our model would no longer hold.

B. Why Is Easter Island Unusual?

Our model allows both cyclical and monotonic behavior so it offers the potential to explain both the cyclical overshooting that occurred on Easter Island and the monotonic behavior apparently observed on the major Polynesian islands. There is no reason to believe that Easter Island was an outlier in its underlying demographics, its tastes, or its technology. However, it was an outlier in one very important respect. The palm tree that grew on Easter Island happened to be a very slow-growing palm. This palm (which was the single most significant component of the forest/soil complex on Easter Island) is now known (due to J. Dransfield et al., 1984) to have been a species of *Jubea Chilensis* (the Chilean Wine palm). This palm tree grows nowhere else in Polynesia, and it is perhaps the only palm that can live in Easter Island's relatively cool climate. An authoritative text (Alexander M. Blombery and Tony Rodd, 1982 p. 110) reports that "Cultivation presents few problems in a suitable temperate climate, but growth of these massive palms is slow and it is generally later generations who get the benefit from their planting." Under ideal conditions, the *Jubea* palm requires about 40 to 60 years before it reaches the fruit-growing stage, and can take longer.¹³

In contrast, the two most common large palms in Polynesia are the Cocos (coconut palm) and the *Pritchardia* (Fiji fan palm). Neither of these palms can grow on Easter Island, and both are fast-growing trees that reach fruit-growing age in approximately seven to ten years. For a resource based on these palms, it would be more reasonable that the intrinsic growth rate would be about 0.35 or 35 percent per decade.¹⁴ Figure 4 shows a simulation that

¹³ This information is based on private communication with palm growers. Easter Island was also an outlier in rainfall and temperature, contributing to slow growth of the resource.

¹⁴ Translating "time-to-fruit" into intrinsic growth rate r is difficult, as trees continue to grow well after first yielding fruit and we are interested in the entire forest/soil complex in any case. Associating a 40-year time-to-fruit with $r = 0.04$ and a seven-ten-year time-to-fruit with $r = 0.35$ is plausible but very rough. Also, the trees were not

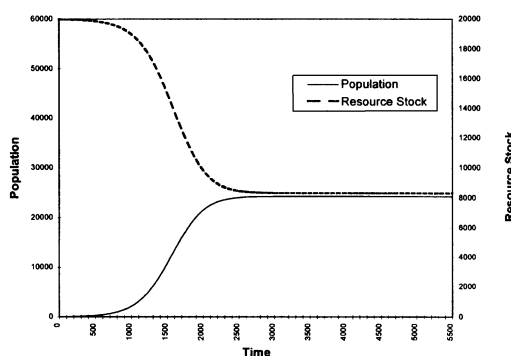


FIGURE 4. POPULATION AND RESOURCE DYNAMICS WITH FAST REGENERATION

is identical to Figure 3 except that the growth rate is raised from 0.04 to 0.35.

The higher intrinsic resource growth rate causes the population to adjust more smoothly. In fact, this simulation is technically cyclical, but the cycle is so muted that the adjustment path is virtually monotonic, as the population peaks at 42,245 before leveling out at its steady-state value of 41,927. The population trajectory would not become strictly monotonic unless the intrinsic growth rate exceeded 0.71, but even at moderate growth rates of 0.15 or 0.2, the population "crash" would be too small to be evident to archeologists. Low growth rates, on the other hand, produce dramatic cyclical fluctuations.

Thus an island with a slow-growing resource base will exhibit overshooting and collapse. An otherwise identical island with a more rapidly growing resource will exhibit a near-monotonic adjustment of population and resource stocks toward steady-state values. Even if everything else were similar across islands, this one fact would allow the Ricardo-Malthus model to be consistent with both the spectacular overshooting and collapse on Easter Island and the far less dramatic development exhibited on other major Polynesian islands.

The model is also consistent with the 12 so-called "mystery islands" that were once set-

tled by Polynesians but were unoccupied at European contact. All but one of these islands have relatively small carrying capacities. Applying our model, we observe that if K is sufficiently small then condition (13) will not be satisfied and there will be no "interior" steady state. A colonizing population could arrive, but would eventually drive the resource stock down to a level that would cause extinction of the human population.

Another noteworthy Polynesian settlement is New Zealand's South Island. The South Island had a high concentration of large flightless birds (up to 10 feet tall and 500 pounds in weight) called "Moas." First Polynesian settlement is thought to have occurred around 1000 A.D. (although it may have been later). Following settlement the South Island Maoris (or "Moa-hunters") lived "high on the bird" by hunting Moa, along with fishing and agriculture. Over this period there was substantial deforestation and the Moa were driven to extinction. It is not clear exactly when the Moa became extinct, but the larger species disappeared first, possibly lasting as little as 200 years following settlement. There is some disagreement over whether population overshoot then declined, or whether it merely stagnated as the Moa disappeared.¹⁵ However, the South Island was more densely settled than the North during the Moa-hunting period, but at European contact (about 1700) settlement was denser in the more temperate and warmer North. Thus it is possible that the South Island exhibited population overshooting, as would be consistent with the slow-growing resource base (consisting of Moa and slow-growing forests).

While Easter Island and Polynesia more generally offer interesting applications of our model, the significance of our analysis would be greatly expanded if the basic approach were also relevant for other cases. In the following section we ask whether population growth and

the only element in the forest/soil complex, which further complicates the problem of estimating the intrinsic growth rate for different hypothetical situations.

¹⁵ Peter Bellwood (1987 p. 157) contends that a population overshoot did occur, stating that "the picture is one of ultimate population decline, with a gradual decrease in cultural energy owing to an insurmountable decrease in resources." A good reference on the Moa is Atholl Anderson (1989).

endogenous resource degradation have played an important role in the decline of other civilizations.

V. Other Applications

Our model might be consistent with the Mayan collapse which, like Easter Island, was long regarded as a mystery. The Mayan empire occupied what is now the Yucatan Peninsula of Mexico; and parts of Guatemala, El Salvador, and Honduras. The empire reached its peak in the period 600–830 A.D., then suffered a rapid decline in both population and cultural sophistication over the following 100 years. The civilization was partially rebuilt in an outlying area but this later Mayan civilization went into decline about 1200 A.D. Only fragments of the Mayan people and civilization still existed at the time of Spanish conquest in 1521.

Recent evidence (including T. Patrick Culbert [1988] and Sarah L. O'Hara et al. [1993]) shows the key role of environmental decline in the Mayan collapse. As on Easter Island, much of the evidence is from carbon-dated core samples showing deforestation, drying, soil erosion and contamination, and reduced crop yields in major agricultural areas. By the early ninth century, agricultural output could no longer support the dense population in the region, leading to out-migration, a sharp decline in population, and a collapse of the sophisticated civilization that had developed. The main unresolved question concerns the extent to which drying and erosion were the endogenous result of human activity rather than arising from exogenous climate changes. The evidence suggests that both factors were important. The following quotes from Culbert (1988 pp. 99–101) provide a now widely accepted interpretation.

All available data show that populations in the Southern lowlands rose rapidly to a Late Classic peak. Not only was the population unusually dense (200 per sq. km.), but it covered an area too large to allow adjustment through relocation or emigration. ...Maya agriculture became increasingly intensive as population rose... Overextension—overshoot in systems terminology—often afflicts complex systems during a period of ex-

pansion... In the Maya case, the overextension was ecological and consisted of a population system dependent upon maximal results from a subsistence system that made no allowance for long-term hazards.

Culbert's description of Maya seems similar to the operation of our model. Maya achieved high population density through intensive agriculture that, at best, left no margin of safety when climatic conditions changed marginally for the worse and, at worst, created an endogenously determined agricultural shortfall arising from deforestation and soil erosion.

Resource degradation also played an important role in the decline of the ancient Mesopotamian states (in what is now Iraq). Various civilizations and empires rose and fell in parts of this region between the period 2350 B.C. and 600 A.D. The first true empire was the Akkadian Empire (2350–2150 B.C.). Soil samples from the Akkadian region indicate increasingly intensive agricultural land use until about 2200 B.C., when the soil in the northern part of the empire became too dry to support the population (H. Weiss et al., 1993). The entire northern portion of the empire was abandoned, causing a major migration into the South, which in turn strained food and water supplies in the South to the point of civic collapse and breakdown of central authority (Ann Gibbons, 1993). By 2150 B.C. the empire had degenerated into a group of independent city states.

Later civilizations made extensive use of irrigation. Joseph Tainter (1988) writes "In this area, agricultural intensification and excessive irrigation lead to short-term above-normal harvests, with increasing prosperity ... [but] the rise of saline ground water erodes or destroys agricultural productivity." By the end of the third dynasty of Ur (about 2000 B.C.), agricultural yields per unit of land had fallen by about 50 percent since the first dynasty (about 300 years earlier), and about twice as much seed per unit of land was required even to achieve this lower yield. (See Robert McCormick Adams, 1981 p. 151.) Declining agricultural productivity was an important contributing factor to the decline of Ur.

Other major Mesopotamian civilizations, including the Assyrians, the Babylonians, and

the Sumerians suffered the same salinization problem suffered by the Ur. Gradually, through successive empires based in different parts of the region, nearly the entire area became infertile. According to Tainter (1988), by about 1200 A.D. the total occupied area in the region had fallen to perhaps 5 or 6 percent of its earlier peak, and most previously fertile land was uninhabitable. Furthermore, while climate has fluctuated in the region over the past few thousand years, there is no discernable trend in precipitation (as described by Adams, 1981 pp. 12–13). Therefore, while the relative contribution of natural climate change and human activity to the destruction of a major agricultural region cannot be precisely determined, human agricultural practices seem to have been the dominant factor.

A less well-known example concerns the Chaco Anasazi in the southwestern United States. Between about 1000 A.D. and 1150 A.D. the Chaco Anasazi built an impressive system of roads, settlements, and “great houses.” As described in Stephen H. Lekson and Catherine M. Cameron (1995), the largest great houses had about 700 rooms and are thought to have been administrative centers for a complex trading system. In this period, population grew rapidly, probably through immigration as well as natural increase. This region is prone to significant rainfall variations, and a dry period began in 1134, lasting until 1181. After 1134 no new great houses were built, much of the land was abandoned, and the elite culture of the Chaco Anasazi disappeared. The puzzle here is that this drought was no more severe than droughts of the previous century that had been weathered without strain. Tainter (1988) suggests that Chacoan Anasazi economic organization had already been pushed beyond its limits by population growth and that the moderate drought of 1134 pushed an already overloaded system into collapse.

The Maya, the Anasazi, and the ancient Mesopotamian civilizations all show a similar pattern. In each case, decline of the resource base, particularly soil degradation, was the main factor precipitating a population crash and the decline of a complex civilization. While exogenous climate fluctuations may have played a significant role in these cases, population growth and endogenous resource

degradation were also important, making them similar to Easter Island.¹⁶

Overall, evidence on soil change and crop information recently obtained from core samples has significantly changed the way modern archaeologists interpret the past. Resource degradation is now understood to be common in major civilizations. The role of warfare and violent conflict is also being reinterpreted. Rather than being the cause of decline, violent conflict is commonly the result of resource degradation and occurs after the civilization has started to decline, as on Easter Island.

VI. Institutional Adaptation

A critic might object that our analysis underestimates institutional adaptation. We assume an open-access resource, but perhaps we should expect more efficient resource management institutions to evolve. This is primarily an empirical question.¹⁷ Elinor Ostrom (1990) has studied the historical record on common property problems and argues persuasively that efficient institutional reforms sometimes occur in primitive (and advanced) societies, but sometimes do not. (See also Ostrom et al., 1994.) In Ostrom (1990 p. 21) she writes “some individuals have broken out of the trap inherent in the commons dilemma, whereas others continue remorsefully trapped into destroying their own resources.” She also observes (1990 p. 210) that “we cannot [adopt] ... a presumption that appropriators will adopt new rules whenever the net benefits of a rule change will exceed net costs.”

The main objective of Ostrom (1990) is to determine the factors that favor efficient institutions and those that impede efficient in-

¹⁶ It is also possible that exogenous climate change may have affected Easter Island, as emphasized to us in private communication by Grant McCall. See also J. Flenley et al. (1991).

¹⁷ Various theoretical arguments can also be advanced to explain why a society may not undertake an efficiency-enhancing policy change. Raquel Fernandez and Dani Rodrik (1991) model a status quo bias against such reforms that arises when individual gainers and losers from reform cannot be readily identified *ex ante*. Similarly, Alberto Alesina and Allan Drazen (1991) provide a model in which reforms are delayed if different groups can attempt to shift the burden of adjustment to other groups.

stitutional response. The most important favorable factor is an agreed-upon and correct understanding of the problem. If a soil exhaustion problem is falsely attributed to low rainfall, then the response might be more rain dances rather than restructured property rights. To use a modern example, it was not possible to settle on an effective response to ozone depletion until there was substantial agreement that a problem existed and on the mechanism causing the problem. Even then, obtaining consensus was difficult, and several major countries have refused to participate in the resulting international agreement.

It is also helpful if proposed rule changes affect relevant parties in a similar way rather than generating winners and losers. Other favorable factors include low discount rates and low enforcement costs. It is also helpful if the affected group is small and if the group has a high level of initial trust and sense of community. Thus, for example, if there are existing ethnic or social divisions that dominate the way people perceive issues, this makes appropriate institutional change difficult to achieve. These conditions follow from the general principle that institutional change is more likely to occur when the individuals who must make the change are confident that they will be among the beneficiaries.

Easter Island did not present a favorable environment for efficient institutional change. It is unlikely that the Islanders understood the biology of the forest-soil complex or the likely incentive effects of alternative institutional arrangements. It is even possible that individual islanders did not recognize that depletion was taking place. Although the forest disappeared rapidly by archaeological standards, change was slow over the course of an individual life span. Typical life spans for those who survived infancy would have been on the order of 30 years, and even during most rapid depletion, the forest stock would have declined by no more than 5 percent over a typical lifetime. Even if the problem had been recognized, the 40 to 60 years taken for a tree to mature would exceed the working life of virtually all islanders.¹⁸ Thus a program of replanting and caring

for seedlings would almost never have been of direct benefit to the cultivators.

The Easter Islanders did make some institutional changes in response to resource scarcity. One major change was that at some point the Easter Islanders abandoned the system of statue worship and apparently pushed over almost all of the statues (usually facedown). Institutional changes of this type, amounting to religious revolution, are clearly very costly and, while they are understandable responses to declining circumstances, they are unlikely to have helped the underlying resource-use problem.

The other kind of institutional reform suggested by our model is population control. There is a large and fascinating literature on social institutions affecting fertility. Perhaps the main point is simply that the range of such institutions is very large. Some societies adopted practices that directly limited population growth, including infanticide and genital mutilation. More subtle and benign approaches involving marriage customs and crude contraceptive methods were also used. Such population controls tend to be density dependent. For example, as crowding increases and resources become more scarce, it is more difficult for young men to acquire sufficient wealth to marry, and both infanticide and contraception would be practiced more frequently. This was the pattern elsewhere in Polynesia and was probably true of Easter Island as well. This is consistent with our model, as it means that net fertility falls when per capita resource consumption falls.

However, in societies that lack a clear scientific understanding of their world, institutional adaptation involving fertility, property rights, and other matters is likely to be a "trial and error" process. Efficient institutions would probably be achieved only after a long period of time and many trials. It would be difficult for a society like Easter Island to adapt efficiently in a single boom and bust cycle.

¹⁸ These longevity estimates are derived from the four major skeletal series available for prehistoric Polynesia.

We have used the life tables in Kirch (1984 pp. 112–14) to calculate that life expectancy at age 5 is slightly less than 30 years, and that the percentage surviving until their mid-forties would be approximately 5 percent.

The other declining civilizations also seem to be poor candidates for efficient institutional reform. We do not have space to discuss each case in detail, but anticipation and understanding of the ecological problem would have been limited, and conflict between competing groups would have delayed reform. Even in sophisticated societies like Maya and Mesopotamia, where property rights may have been relatively secure, the complex array of externalities involved in soil erosion, salinity and declining water tables would have been hard to address successfully.

We recognize, however, that modern knowledge of institutions in preliterate civilizations is very limited. In considering Polynesia, we know there was substantial variation across the different islands. Therefore, one alternative hypothesis to ours is that institutional variation across societies within Polynesia might be the explanation for contrasting growth experiences.

VII. Concluding Remarks

This paper presents a simple model of renewable resource growth and population dynamics and employs this model to provide a plausible account of the rise and fall of the Easter Island civilization. For reasonable parameter values, the model generates a boom and bust cycle in which population grows, the resource base is degraded, and population ultimately falls. This cycle arises because the resource base has a slow regeneration rate. A faster-growing resource would allow monotonic convergence toward the steady-state population. Thus the model can explain the difference between Easter Island and other Polynesian islands based on known differences in resource growth rates.

Our analysis has several lessons for the modern world. First, the model implies that changes in technology, the environment, or human behavior can create feast and famine cycles that may be a recipe for violent conflict over apparently diminishing resources. Easter Island may be only one case of many where unregulated resource use and Malthusian forces led to depletion of the resource base and social conflict. Identifying countries at risk in the modern world may be difficult, but our model provides some guidance as it identifies

the key parameters that make cyclical downturns more likely.

A modern case that might be consistent with our model is Rwanda, which entered the news during 1994 because of a violent civil war. This war was normally attributed to ethnic tensions between Hutus and Tutsis, but more careful analysis suggests the possibility that Malthusian population growth, resource degradation, and resulting competition for resources was at the root of the conflict. Between 1950 and 1994, population in Rwanda quadrupled. The boom began in the 1950's when advances in health care and agricultural practice led to increasing real incomes and rising net fertility. By the 1980's what had been an open frontier was "filled up," and real living standards started to fall. Conflict over land between Hutus and Tutsis became increasingly severe, culminating in a civil war in which a significant fraction of the population was killed and a very large fraction (perhaps 25 percent) became refugees. Thomas Homer-Dixon (1994) describes several other modern cases where resource degradation driven by population growth has caused violent conflict and local decline of living standards. Models of the Easter Island type, with explicit resource and demographic dynamics, might be helpful in understanding such situations.

A second lesson of our analysis is that it provides one of the first formal empirical examples in which the cycles that arise in nonlinear models appear relevant in analyzing long-run economic development. In short, it suggests that nonlinear dynamics are likely to be relevant in studying economic growth, especially in situations where renewable resources are important.

Third, our analysis of Easter Island and the other cases suggests that economic decline based on natural resource degradation is not uncommon. Institutional change could potentially have averted collapse in many of these societies but it was not undertaken (or at least was not undertaken fast enough). Institutional failure in renewable resource use does happen, and it has been fatal for several societies. Recent events in the world's major fisheries suggest that institutional change remains difficult. An extreme case is the (Canadian) Newfoundland cod fishery which was closed in 1992, as

cod stocks were down to less than 5 percent of their 1960 levels. Our work offers support for the position that it is both important and difficult to reach efficient institutional arrangements in renewable resource use.

Finally, despite our model's rather gloomy implications, we do not wish to embrace the pessimism of modern neo-Malthusians. First, in considering the modern world, one would introduce nonlinearity in the response of fertility to consumption so as to allow for a demographic transition of the type observed in modern high-income societies. Specifically, net fertility declines with income at sufficiently high-income levels. In our model, cyclical dynamics arise only when fertility has a strong enough positive response to per capita consumption, so incorporating a demographic transition would probably allow the possibility of escape from cyclical dynamics if a high enough income could be reached.

In addition, our model abstracts from technological progress, which is the main force emphasized by growth optimists. Abstracting from technological progress is reasonable for our discussion of Easter Island, and perhaps for most of the other examples we have discussed, but it would clearly be a serious omission in considering the modern world. The model can, however, be readily augmented in this direction. Both the r parameter (resource growth) and the α parameter (harvesting efficiency) could be viewed as susceptible to either exogenous or endogenous technical progress. Furthermore, progress in the form of further scientific understanding may also facilitate institutional adaption in resource use. This would require a larger modification in the model as it implies a different characterization of temporary equilibrium in the resource sector. On the other hand, the possibility of demographic transition notwithstanding, net fertility (particularly declining mortality) is affected by technical progress, and increases in net fertility driven by improvements in medical technology may well lead to population overshooting.

Finally, while technical progress has been the dominant force in the growth process since the beginning of the industrial revolution, this last 300 years is a small fraction of the time that

humans have harvested from the earth and built complex, but ultimately fragile, societies. It is, for that matter, shorter than what might be regarded as the "golden age" of Easter Island.

APPENDIX A

PROOF OF PROPOSITION 4:

Let (L^*, S^*) represent a steady state. Define the vector $\mathbf{u} = (u_L, u_S) = (L - L^*, S - S^*)$. Thus \mathbf{u} is the vector of deviations in L and S from a particular steady state. It follows that $du_L/dt = dL/dt$ and $du_S/dt = dS/dt$, where dL/dt and dS/dt are given by (11) and (9). Using a Taylor series expansion for du/dt around $\mathbf{u} = 0$ [i.e., around (L^*, S^*)], it can be shown (as in William E. Boyce and Richard C. DiPrima, 1992 pp. 450–51) that du/dt can be expressed as follows.

$$(A1) \quad du/dt = \mathbf{J}(L^*, S^*)\mathbf{u} + R(L, S)$$

where \mathbf{J} is the Jacobian matrix of first-order partial derivatives of dL/dt and dS/dt with respect to L and S , and $R(L, S)$ is a remainder of higher-order terms that can be ignored near $\mathbf{u} = 0$. \mathbf{J} is evaluated at (L^*, S^*) . Denoting the components of \mathbf{J} as J_{11} , J_{12} , etc., in the obvious way, we can write this linear system as

$$(A2) \quad du/dt = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} u_L \\ u_S \end{bmatrix}.$$

A two-equation system of linear differential equations [as in (A2)] has a general solution of the form

$$(A3) \quad \mathbf{u}(t) = c_1 E_1 e^{z_1 t} + c_2 E_2 e^{z_2 t}$$

where c_1 and c_2 are constants, z_1 and z_2 are the eigenvalues of coefficient matrix \mathbf{J} , and E_1 and E_2 are the corresponding eigenvectors. The dynamic behavior of the system depends on whether z_1 and z_2 are real, complex, or imaginary, and on whether any real part of these eigenvalues is positive or negative. The system is explosive if z_1 and z_2 are positive real numbers, and converges monotonically to the steady state if z_1 and z_2 are negative. If z_1 and z_2 are complex numbers then cyclical behavior emerges. The coefficients of \mathbf{J} can be

determined by taking partial derivatives of (9) and (11).

$$(A4) \quad J_{11} = (b - d) + \phi\alpha\beta S; J_{12} = \phi\alpha\beta L;$$

$$J_{21} = -\alpha\beta S; J_{22} = r - 2rS/K - \alpha\beta L.$$

(i) For steady state 1 ($L = 0, S = 0$), coefficient matrix \mathbf{J} becomes

$$(A5) \quad \mathbf{J}(0, 0) = \begin{bmatrix} b - d & 0 \\ 0 & r \end{bmatrix}.$$

The eigenvalues are the diagonal elements $b - d < 0$ and $r > 0$. This combination of one negative real eigenvalue and one positive real eigenvalue implies that steady state (0, 0) is an unstable saddlepoint.

(ii) and (iii) For steady state 2 ($L = 0, S = K$) and steady state 3 ($L = (r/\alpha\beta)(1 - S/K)$, $S = (d - b)/\phi\alpha\beta$) we proceed in the same way, making the appropriate substitutions in matrix \mathbf{J} using (A4) and calculating the associated eigenvalues of \mathbf{J} . For steady state 2 the eigenvalues are $-r$ and $(b - d) + \phi\alpha\beta K$ [which is positive by (13)]. As with steady state 1, the combination of positive and negative real eigenvalues implies that steady state 2 is an unstable saddlepoint. For steady state 3, matrix \mathbf{J} has nonzero off-diagonal elements, so the eigenvalues cannot be seen by inspection but must be obtained as the roots of the characteristic equation. Letting S^* denote the steady-state value of S , the characteristic equation is $z(rS^*/K + z) - (d - b)r(1 - S^*/K) = 0$, which is quadratic in z and has roots

$$(A6) \quad z = \left[-rS^*/K \pm ((rS^*/K)^2 - 4(d - b)r(1 - S^*/K))^{1/2} \right] / 2.$$

If the discriminant of (A6) is positive (or zero), then both solutions for z must be negative real numbers and the steady state is a stable node with monotonic convergence. A negative discriminant implies complex eigenvalues with a negative real part, and the steady state is a stable spiral point. The system then exhibits damped cycles that converge on the steady state. Noting that equation (14) given in the proposition is simply the discriminant

of characteristic equation (A6), the proof is complete.

PROOF OF PROPOSITION 5:

- (i) Proposition 4 establishes that steady state 1 ($L = 0, S = 0$) is a saddlepoint allowing a local approach along the horizontal axis, and we can tell from inspection of the full nonlinear system that steady state 1 is reached from any point along the horizontal axis. If $S = 0$, and $L > 0$, then L must fall to zero. Thus one trajectory of our full nonlinear system is given by the horizontal axis in Figure 2.
- (ii) We know from Proposition 4 that steady state 2 ($L = 0$ and $S = K$) is a saddlepoint allowing a local approach along the vertical axis, and we can tell from inspection that steady state 2 is reached from any point along the vertical axis. That is, if $L = 0$, and $S > 0$, then S must raise toward level K , hence another trajectory of our full nonlinear system is given by the vertical axis in Figure 2.
- (iii) As the differential equation system is autonomous and continuously differentiable, no two trajectories of the system can intersect. Any trajectory that starts from a point strictly interior in Figure 2 must remain strictly interior. (Otherwise it would touch one of the axes, which we know is impossible, as the axes themselves are trajectories.) We can then divide equation (9) by (11) to obtain the slope of any system trajectory as $dS/dL = [rS(1 - S/K) - \alpha\beta LS] / [L(b - d + \phi\alpha\beta S)]$. Inspection of this slope in each region of the phase diagram in Figure 2 implies that the direction of any trajectory must eventually be inward towards the interior steady state. Limit cycles can be ruled out by applying a theorem due to Kolmogorov as provided by Robert M. May (1973 pp. 85–89). Therefore, the trajectory must approach the steady state.

APPENDIX B

The paper uses the logistic growth function, but the analysis is readily generalized

to a general compensatory (bent over) growth function provided that $G(0) = G(K) = 0$ and that $G(S)/S$ is strictly decreasing in S . In this case we let $r = \lim_{S \rightarrow 0} G(S)/S$. Equation (9) becomes $dS/dt = G(S) - \alpha\beta LS$. Equation (11) is unchanged. Proposition 1 follows immediately, except that in steady state 3, the steady-state value of L is expressed as $L^* = G(S^*)/(S^*\alpha\beta)$, where $S^* = (d - b)/(\alpha\beta\phi)$ as before. Proposition 2 follows immediately. To obtain an analog of Proposition 3, we need to replace the experiment of increasing r by an overall increase in $G(S)/S$ and, instead of focussing on whether $S < K/2$ or $S > K/2$, we focus on whether $G(S)$ is increasing or decreasing. Figures 1 and 2 have the same general form as before. In Proposition 4, parts (i) and (ii) are unchanged, and (iii) follows as before except that condition (14) becomes $H(S^*)^2 - 4(d - b)G(S^*)/S^* < 0$, where $H(S^*) = G'(S^*) - G(S^*)/S^*$. Proposition 5 is unchanged. To carry out the Easter Island simulation we, of course, require some specific functional form. The logistic form works well, but it is clear from this brief discussion that other forms would also work. More general analysis of general functional structures is difficult, although methods along the lines of those used in Peter Howitt and R. Preston McAfee (1988) could perhaps be applied.

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