ANALYSIS

Easter Island: historical anecdote or warning for the future?

Rafael Reuveny a,*, Christopher S. Decker b,1

a School of Public and Environmental Affairs, Suite 430, Indiana University, Bloomington, IN 47405, USA
b Kelley School of Business, Suite 451, Indiana University, Bloomington, IN 47405, USA

Received 5 October 1999; received in revised form 11 April 2000; accepted 16 May 2000

Abstract

Two standard solutions for the ‘Malthusian Trap’ involve institutional reforms and technological progress. Using Easter Island as an example, we investigate the hypothetical role that technological progress and population management reform might have played in preventing the collapse of the island’s civilization. The model includes a composite manufactured good and a composite harvested renewable resource. Fertility is assumed to rise with per capita income. The resource’s carrying capacity and intrinsic growth rate as well as labor’s harvesting productivity are subject to technological progress. Fertility is subject to population management reform. The model yields a system of two simultaneous, nonlinear, non-autonomous differential equations. We first study the system’s steady states. The system is then parameterized for Easter Island and its comparative dynamics are investigated in simulations. We find that technological progress can generate large fluctuations in population, renewable resources, and per capita utility, sometimes resulting in system collapse. With high fertility rates, the population and the resource vanish. None of the simulations investigated here exhibit a constantly growing per capita utility over time. Finally, we evaluate the applicability of these results to contemporary societies. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Concerns regarding the Earth’s population explosion and the pressure it places on natural resources have rekindled interest in the sustainability of economic prosperity, an issue that seems particularly relevant as we enter a new millennium. Brown and Flavin (1999) explain, “the key limits as we approach the twenty-first century are fresh water, forests, rangelands, oceanic fisheries, biological diversity, and the global atmosphere.” They go on to ask, “Will we recognize the world’s natural limits and adjust our economies accordingly, or will we proceed to expand our ecological footprint until it is too late to turn back?” These concerns can be traced back to the work of Malthus (1798), who argued that population growth would eventually lead to natural resource...
depletion, economic decline, starvation, violent conflict, and population decline. Many scholars believe that the decline of Easter Island exemplifies Malthus’s predictions (Weiskel, 1989; Ponting, 1991; Keegan, 1993; Brown and Flavin, 1999). The case of Easter Island stands at the center of our paper. A thousand years ago a civilization thrived there; by the time Europeans arrived in 1722, it had essentially disappeared and no one really knows why. While scholars have puzzled over this for years, offering many interesting theories, it was not until recently that formal economic modeling was applied to the subject. Brander and Taylor (1998) attempted to solve the mystery by modeling the island’s economy as a predator–prey system of renewable resource use in which the human population, dependent on the island’s resources for survival, overexploited them. This ultimately resulted in a dramatic population decline, a characteristic of the so-called ‘Malthusian Trap.’ Brander and Taylor assumed that island’s resources and institutional structure were not subject to change or reform over time. We build on their work by relaxing these two restrictions. We then address the relevance of our work to modern countries, particularly less developed countries (LDCs).

Two solutions to the ‘Malthusian Trap’ are typically suggested in the literature on sustainable development. The first solution involves institutional reforms. In this view, overexploitation of natural resources results from ill-defined property rights. Assigning private ownership to a resource will limit its extraction. Another kind of institutional reform involves population management efforts to reduce birth rates. The second solution to the ‘Malthusian Trap’ is technological progress. Natural resource depletion need not be a concern if technological progress improves resource yields, carrying capacity and harvesting efficiency. In a sense, technology can provide ‘substitute’ for natural resource depletion (Solow, 1997; Stiglitz, 1997). However, this approach is not without critics. In particular, Georgescu-Roegen (1971), Daly (1997) argued that capital and technology ultimately cannot provide substitute for natural resources.

Standard economic growth models emphasize the role of technological progress in securing perpetual growth. Armed with technology, population issues became tertiary to the analysis. Consequently, in these models population growth is determined exogenously, and typically is assumed either to be constant or to grow exponentially. Recently, dynamic models featuring endogenous population growth have appeared. The studies by Prskawetz et al. (1994), Milik and Prskawetz (1996), Brander and Taylor (1998) are particularly relevant to our paper. In the first two studies, a natural resource harvested under open access is combined with labor to produce a final good, but the consumption side is not modeled. In the Brander and Taylor study, a consumption side is added to a similar, but simplified, analytical framework. All of these studies yield a similar system of differential equations, which is then parameterized and simulated. The goal of Prskawetz et al. and Milik and Prskawetz is to illustrate the general mathematical properties of such a model. Therefore, their parameterization is largely without empirical underpinning. Brander and Taylor’s motivation is to study Easter Island specifically and thus their parameterization is chosen for that case.

Given the relatively primitive nature of the Easter Island civilization, it seems plausible to ignore — as Brander and Taylor do — institutional reforms and technological progress in this case. Yet, as stated earlier, the possible solutions to the ‘Malthusian Trap’ involve precisely these two elements. We can now restate the two goals of our paper more fully. First, we wish to investigate two hypothetical questions regarding Easter Island. What could have happened on Easter Island if its technology had been progressing? Similarly, what could have happened if popula-

---

2 The work of Malthus, while acknowledged, has been eclipsed by Adam Smith and David Ricardo. John Maynard Keynes sought to correct this neglect: “If only Malthus, instead of Ricardo, had been the parent stem from which nineteenth century economics proceeded, what a much wiser and richer place the world would be today (Keynes, 1933:120).” Interest in the work of Malthus grew following the work of Meadows et al. (1972).

3 For reviews of this literature, see Peman et al. (1996), Toman et al. (1995).
tion management had been adopted on the island? Our second goal is to evaluate the applicability of our findings to contemporary societies.4

Many economic growth models assume that technological progress is exogenous and universal. This approach does not explain the sources of technological progress. Beginning in the mid-1980s, endogenous growth models focused on the determinants of technological progress, emphasizing the role of human capital, innovation and economic profits.5 In this paper, we do not explain the determinants of technological progress, but rather seek to investigate the effects of technological progress. We adopt a typical neoclassical economic growth approach and assume the existence of an exogenous and universal process of technological progress.

Our analysis employs a combination of analytical model building and numerical simulations. The model includes a composite manufactured good and a composite harvested renewable resource. Fertility is assumed to rise with per capita income. The resource’s carrying capacity and intrinsic growth rate as well as labor’s harvesting productivity are subject to technological progress. Fertility is subject to population management reform. The model yields a system of two simultaneous, nonlinear, non-autonomous differential equations that, to the best of our knowledge, has no analytical solution. We first study the system’s steady states. The system is then parameterized for Easter Island and its comparative dynamics are investigated in simulations.

The simulations demonstrate that population management can guide the system smoothly toward a steady state with positive population and resource levels. Technological progress, however, tends to generate large fluctuations in population and resource stocks, and can even lead to complete human extinction. None of the simulations exhibit a constantly growing level of per capita utility over time. We conclude our paper by evaluating the implications of these results for contemporary societies.

This paper proceeds as follows. Section 2 describes the model, and Section 3 discusses its parameterization. Section 4 reports simulation results, Section 5 evaluates the contemporary implications of these results, and Section 6 concludes.

2. Analytical model

The model adopts attributes of both the Solow–Stiglitz and the Georgescu-Roegen–Daly approaches. In the spirit of Solow–Stiglitz, we assume that natural resources and man-made goods are substitutes. However, population growth is endogenously determined by the availability of natural resources. Hence, in the spirit of Georgescu-Roegen–Daly, the system is constrained by the natural environment.

2.1. Model development

Some resource models assume that agents maximize the sum of their current and discounted future utilities by choosing the amount of the resource to harvest in each period. This framework assumes that a harvesting rule could be implemented if a system of enforceable property rights is in place. We extend the work of Prskawetz et al. (1994), Milik and Prskawetz (1996), Brander and Taylor (1998). Like them, we assume that there are no enforceable property rights vis-a-vis renewable resources, which probably was true on Easter Island (Van Tilberg, 1994). Therefore, the agents in the model only maximize their current utility.

The economy is composed of two composite goods or sectors. Good $H$ is a composite renewable resource good representing an ecological complex, the components of which may include trees, soil, etc. Good $M$ is a composite product representing all other goods, the price of which is normalized to one. For the sake of simplicity, we assume that labor is the only factor of production. In each period, producers maximize profits by using a

---

4 It is also possible to analyze the property rights aspect of institutional reforms, but this mathematically complex issue merits a separate analysis.

5 For a review, see Aghion and Howitt (1998). The gain from this approach is debated (e.g. Pack, 1994; Solow, 1994). A different approach is taken by Boserup (1981), Kremer (1993), Simon (1996) who argue that progress is, in effect, caused by population growth.
linear production function in sector $M$, $M^p = \lambda L_M$, and a Cobb–Douglas production function in sector $H$, $H^p = \alpha S^\theta L_H^\psi$, where $0 < \psi \leq 1$ and $0 < \theta \leq 1$. The superscript $P$ denotes production, $S$ denotes the natural resource stock, $L_M$ denotes the labor devoted to producing $M$, $L_H$ denotes the labor devoted to harvesting, and $\lambda$ and $\alpha$ are technology parameters.\(^6\) Given our focus on Easter Island, whose economy was highly dependent on natural resources, we assume the existence of exogenous labor augmenting technological progress in harvesting, but not in the production of the composite manufacturing good. For example, a move from man-based harvesting to tools-based harvesting increases the value of $\alpha$.\(^7\)

Economic competition is assumed in both factor and output markets. Hence, the wage rate ($w$) is considered exogenous by agents and is the same in all sectors. Producers’ profit in the harvesting sector $H$ ($\Pi_H$) is $\Pi_H = p H^p - w L_H$ and profit in the manufacturing sector $M$ ($\Pi_M$) is $\Pi_M = M - w L_M$. The variable $p$ is the price of the harvested good. Since in a competitive equilibrium no profits are made, the price of the resource good is $p = w L_H / H^p$ and the wage rate is given by $w = \lambda$.\(^8\)

Using the harvesting production function, the price of the harvested good can be expressed as $p = (\lambda L_H^{1 - \theta}) / (\alpha(t) S^\psi)$.

A representative consumer is assumed to have a Cobb–Douglas utility function that increases with the quantity of both goods (superscript $C$ denotes consumption):

$$U = \left(\frac{H^C}{L^C}\right)^\theta \left(\frac{M^C}{L^C}\right)^{1 - \theta}$$

where $H^C$ and $M^C$ are the total quantities consumed of goods $H$ and $M$ respectively, $L$ is population, and $\beta$ is a taste parameter. Each consumer is assumed to be endowed with one unit of labor. Hence, his/her budget constraint is given by the equation $w = p (H^C / L) + (M^C / L)$. Standard utility optimization yields consumption values for $H^C$ and $M^C$:

$$H^c = \left(\frac{\lambda \beta \lambda}{p}\right) \quad M^c = L (1 - \beta) \lambda$$

The population is assumed to be fully employed, so that $L = L_M + L_H$. Using the production function in sector $M$, we get $L = L_H + M^p / \lambda$. Market clearing conditions are assumed to hold in each period in the $H$ and $M$ sectors. Hence, $M^C = M^p = M$ and $H^C = H^p = H$. Replacing $M^p$ with $L (1 - \beta) \lambda$ in $L = L_H + M^p / \lambda$, we derive $L_H$ in terms of $L$: $L_H = L \beta$. Substituting $L_H$ in the expression $p = (\lambda L_H^{1 - \theta}) / (\alpha(t) S^\psi)$, we arrive at the following expression for the resource price:

$$p = \frac{\lambda (L \beta)^{1 - \theta}}{\alpha(t) S^\psi}$$

Using Eqs. (2) and (3) and the equilibrium condition in both markets, we derive the equilibrium solution for $H$ and $M$ for any given period $t$:

$$H = \beta^\theta \alpha(t) L^\theta S^\psi \quad M = L \lambda (1 - \beta)$$

The natural growth of the resource is assumed to follow the commonly used logistic form with an intrinsic growth rate $r$, and a carrying capacity $K$: $G_N = r(t) S [1 - S / K(t)]$.\(^9\) This functional form implies that when $S$ equals $K(t)$, the natural resource growth rate is zero. The overall resource growth is given by its natural growth net of the harvesting rate, $G_N - H$. By substituting the equilibrium solution for $H$ into this expression, we derive the differential equation for the resource growth:

$$\frac{dS}{dt} = r(t) S \left[ 1 - \frac{S}{K(t)} \right] - \beta^\theta \alpha(t) L^\theta S^\psi.$$\(^5\)

In Eq. (5), $r$ and $K$ depend on time because they are assumed to be subject to resource augmenting


\(^7\) As noted, the efficiency of producing good $M$ ($\lambda$) is not increasing over time. Note also that in our model the dynamics of $S$ and $L$ do not depend on whether $\lambda$ grows over time. See Eqs. (6) and (7). We defer the issue of progress in $\lambda$ to future research.

\(^8\) The result $w = \lambda$ holds for a linear production function in $M$. For other production functions, the solution is more complicated. However, the added complexity does not change the qualitative nature of the model. See Prskawetz et al. (1994), Milik and Prskawetz (1996).

\(^9\) On logistic resource growth see, for example, Clark (1990).
technological progress. For example, \( r \) may increase over time due to the development of high yield seeds. Likewise, \( K \) may increase over time through the development of improved soil fertilization treatments.

Next, we define the proportional growth rate of the population, \( \zeta \), as:

\[
\zeta = \frac{dL/dt}{L} \tag{6}
\]

We assume that the population’s intrinsic birth rate, \( b \) and mortality rate, \( d \), are proportional, so that \( \zeta = b - d \).\(^{10}\) Population is made endogenous by assuming that \( \zeta = b - d + F \), where \( F \) is the fertility function. We assume \( F = \phi(H/L)^x \), where \( \phi > 0 \) and \( x > 0 \) are parameters, and \( x \) captures the notion of institutional reforms in the form of population management. Substituting \( F \) and \( \zeta \) into Eq. (6), we derive the differential equation for population growth:

\[
dL/dt = L[b + \phi(\beta z(t)S^\omega L^{\theta - 1})^x]. \tag{7}
\]

Interpreting \( H/L \) as per capita income, the expression \( F = \phi(H/L)^x \) implies that fertility grows with per capita income, but with either diminishing or increasing returns, depending on \( x \).\(^{11}\) A similar assumption is used in Sato and Davis (1971), Lane (1975), Prskawetz et al. (1994), Milik and Prskawetz (1996) and others. Brander and Taylor (1998) apply this assumption to Easter Island. As summarized by Heerink (1994), the fertility function in the model is more appropriate for societies with low per capita income. More generally, and in the spirit of Georgescu-Roegen (1971) and Daly (1992, 1997), many renewable resources supply the health and nutritional requirements necessary for procreation. Without these requirements, the population is likely to decline, regardless of its income. In this interpretation, our fertility function captures the notion that the population cannot grow forever simply by substituting man-made goods for natural resources.\(^{12}\)

2.2. Steady states

Eqs. (5) and (7) characterize the dynamic interrelationship between population \((L)\) and the renewable resource \((S)\). The solution of this system gives \( S \) and \( L \) as functions of time and the system’s parameters. There are generally two features to such a solution — the steady state (i.e. when \( L \) and \( S \) take on constant values) and the transition path to this steady state. In principle, however, a system of non-linear, non-autonomous simultaneous differential equations may not exhibit a steady state; its variables may continue to evolve over time.

To find the steady states, we let \( dS/dt = 0 \) and \( dL/dt = 0 \) in differential Eqs. (5) and (7) and solve for \( L \) and \( S \). The resulting system of equations has two corner steady states, \((L = 0, S = 0)\) and \((L = K, S = 0)\). To see this, note that Eqs. (5) and (7) can be written as \( dL/dt = LZ \) and \( dS/dt = SV \), where \( Z = b - d + \phi(\beta z(t)S^\omega L^{\theta - 1})^x \) and \( V = r(t)[1 - S/K(t)] - \beta z(t) L^\omega S^{\theta - 1} \). The points \((L = 0, S = 0)\) and \((L = 0, S = K)\) solve the system of equations \( LZ = 0 \) and \( SV = 0 \). In the steady state \((L = 0, S = 0)\), there are no people in the system and the resource is depleted. In the steady state \((L = 0, S = K)\), there are no people in the system and the resource is at carrying capacity.

The system of equations \( LZ = 0 \) and \( SV = 0 \) has no internal solutions with \( L > 0 \) and \( 0 < S < K \). To see this, note that if an internal steady state were to exist, then we must have \( Z = 0 \) for some \( L > 0 \) and \( 0 < S < K \). \( Z = 0 \) implies \( S = E(t)L^{1-\theta}/\beta \), where \( E = [(d - b)/\phi]^x/[(1/(\beta z(t)S^\omega L^{\theta - 1}))^x] \). However, the expression \( S = E(t)L^{1-\theta}/\beta \) cannot hold with constant values of \( S \) and \( L \) since \( E \) depends on time and \( \theta \) and \( \psi \) are constant parameters.

Finally, note that if \( z(t), K(t) \) and \( r(t) \) were to asymptote to constant values as \( t \) goes to infinity, or alternatively, if the growth rates of \( z(t), r(t) \) and

\(^{10}\) With a constant \( \zeta \), the solution of Eq. (6) is the familiar exponential growth of population (which is typically assumed), \( L = L(0)e^\zeta t \), where \( L(0) \) is the initial population.

\(^{11}\) It is possible to identify income per capita in the model with \((H + M)/L \) and not \( H/L \). This does not change the nature of the results since in this model \( M/L = \lambda(1 - \beta) = a \) constant.

\(^{12}\) One may argue that medical progress, which reduces mortality, is captured by manufacturing. However, many medicines come from natural resources. In fact, it is often argued that the depletion of the world’s rain forests may eliminate potential sources of cures for many diseases.
were all to asymptote at a value of zero as \( t \) goes to infinity, then the system might converge to an internal steady state. For example, if \( z(t) \), \( r(t) \) and \( K(t) \) take a logarithmic functional form, their growth rates diminish to zero as \( t \) approaches infinity. In this particular case, while never achieving constant \( L \) and \( S \) values, the system of differential Eqs. (5) and (7) might nevertheless mimic an approach to an internal steady state as the growth rates in \( a \), \( r \) and \( K \) decline over time (yet they never actually reach zero).

### 3. Parameterization

To the best of our knowledge, the system of differential Eqs. (5) and (7) does not have an analytical solution. Nevertheless, it is possible to simulate its behavior numerically, which requires parameterization. We adopt the parameterization utilized by Brander and Taylor for our base case. For our purpose, the important question is not so much the specific value of a particular parameter in the model, but whether the base case can reproduce known information about Easter Island.

Table 1 summarizes the notation, interpretation, and values of the model parameters. The initial values for \( S \) and \( L \) are set to 12 000 and 40, respectively. These are reasonable numbers for Easter Island. The value of 12 000 is also used for the initial carrying capacity, \( K(t = 0) \), to capture the situation when the first people arrived on the island (i.e. we assume that the natural resource base was fully established at that time). Next, we consider the harvesting efficiency, \( z(t) \). Given \( K(t = 0) = 12 000 \), an initial value of \( z(t = 0) = 0.00001 \) suggests that if the resource is at capacity, harvesting will initially provide just enough consumption necessary to allow the current generation to reproduce itself (i.e. zero population growth). This consumption level is often called subsistence consumption. Such an efficiency level seems a reasonable place to begin since technological progress is often motivated by the desire to grow beyond mere subsistence. Another parameter of interest is the initial intrinsic resource growth rate, \( r(t = 0) \). Brander and Taylor contend that \( r = 0.04 \) is a reasonable value for Easter Island, hence we adopt it as our starting point. The population parameter \( f \) and the net birth rate \((b − d)\) are set at 4 and \(-0.1\), respectively. The negative net birth rate implies that without undertaking some effort at survival (i.e. harvesting), the population will decline.\(^{13}\)

### 4. Simulations

We first simulate a base case without technological progress and compare the results with available historical records pertaining to Easter Island. We then conduct simulations where parameters are changed one at a time (comparative dynamics), and simulations where more than one parameter changes (combination runs). In our simulations, the resource's carrying capacity \((K)\), the resource's

\(^{13}\)The remaining parameters are as follows. The taste parameter \((β)\) is set at 0.4. With a Cobb–Douglas utility, \(β\) is the share of the labor devoted to harvesting. In many studies, the resource sector absorbs around 50% of labor, thus, \(β\) of 0.4 is reasonable. The parameters \(θ\) and \(ψ\) are set at one. This makes the harvesting function similar to the one suggested by Schaefer (1957) and used in Brander and Taylor (1998) and others (see Clark, 1990). We also tried simulations in which \(θ\) and \(ψ\) are set at less than one. This did not change the spirit of the results. The fertility parameter \(x\) in the base case is set at one.
growth rate \((r)\), and harvesting efficiency \((a)\) grow over time, and the fertility relationship takes on various values of \(x\). We use three different values of \(x\). The most common pattern for technological progress in the literature is exponential, where technology advances at a constant rate per period \((\text{Solow, 1956; Jones, 1998; Hughes, 1999})\). This assumption, implying as it does that technology will advance without bound, is not without critics \((\text{Daly, 1992})\). As an alternative pattern to exponential progress, we also inspect cases where progress proceeds at a diminishing (logarithmic) rate over time.\(^{14}\)

### 4.1. Resource and population trajectories

Fig. 1 presents the base case results for a constant technology and no population management. The horizontal axis shows 140 time periods, each representing one decade. Period zero corresponds roughly to year 400 A.D., when the first indigenous people are said to have arrived on the island. The simulation ends at period 140, roughly the time when Europeans first arrived on the island (1722 A.D.). As in \text{Brander and Taylor (1998)}, Fig. 1 generally replicates known historical data for the island. Starting in period 50, there is a decline in the resource stock. Population peaks at 10 000 during the periods 70–100 (years 1100–1400 A.D.) and then declines to 3800 around period 140. These population numbers are mid-range estimates for Easter Island.\(^{15}\)

For each of the comparative dynamic simulations, we show 200 periods. Fig. 2 presents results that occur when the carrying capacity \((K)\) increases over time, ceteris paribus. With logarithmic progress (Panel A), the population and the resource stock fluctuate over time. Logarithmic technological progress in \(K\) generates slightly more volatile fluctuations relative to the base case. With exponential progress in \(K\) (Panel B), the system exhibits a twin-peaked, highly non-linear picture that is very different from the base case. Population reaches much higher peaks in this case, compared with the logarithmic case. It jumps to 80 000, falls quickly to near-zero, jumps again to 80 000, and then again falls quickly to near-zero.

Fig. 3 presents results when the resource’s intrinsic growth rate \((r)\) increases over time, ceteris paribus. In both cases, the resource stabilizes in the long-run, but nearly half of the resource is depleted. With logarithmic progress in \(r\) (Panel A), population grows in the long run in what appears to be a linear manner. There are no oscillations, but the rate of population growth drops substantially in the middle of the simulation. With exponential progress in \(r\) (Panel B), population grows

\(^{14}\)The simulations were conducted using the mathematical package \text{MAPLE}. The numerical method used was the \text{Fehlberg fourth-fifth order Runge–Kutta}. The assumed paths of progress are \(K = 12 000 + 30 \ln (r + 1);\) \(K = 12 000 + 30e^t;\)

\(r = 0.04 + 0.1 \ln (r + 1);\) \(r = 0.04 + 0.00155 e^{0.35t};\) \(x = 0.00001 e^{0.00155 t} + 1).\) In fertility, we used \(x = 0.5,\) \(0.7\) and \(1.2.\) We also investigated the effects of linear technological progress. The results were basically similar to those obtained from logarithmic progress.

\(^{15}\)For details on Easter Island see \text{Ponting (1991), Van Tilberg (1994)}. Since the 1980s, the island has not been a closed system, and thus, the model is less applicable.
Fig. 2. Technological progress in carrying capacity, (A) logarithmic progress; (B) exponential progress.

Fig. 3. Technological progress in resource growth rate, (A) logarithmic progress; (B) exponential progress.
faster in the long run, but both the population and the resource stocks fluctuate in the short and medium runs. In both cases, technological progress in \( r \) has a persistent long-run effect on population growth; the faster the growth rate of \( r \), the faster the growth in population. These results stand in marked contrast to the base case.

Fig. 4 presents results when the efficiency of resource harvesting (\( a \)) increases over time, ceteris paribus. With logarithmic progress in \( a \) (Panel A), population peaks after about 50 periods and subsequently declines toward zero. Initially, the resource is quickly depleted but it is able to regenerate once the population begins to decline. With exponential progress in harvesting efficiency (Panel B), population peaks at about 50 periods, and then falls off quickly. By the end of the simulation, the population level is zero. Because population diminishes before the resource is completely depleted, the resource is able to regenerate. These results differ from the base case. The population peaks sooner, at a smaller level, and falls off more quickly. With logarithmic progress, the economy ends up with fewer people and exhibits larger fluctuations, and with exponential progress the population vanishes.

Fig. 5 presents results for three values of population management efforts (\( x \)), ceteris paribus. In Panels A and B, fertility is higher than in the base case (Fig. 1, \( x = 1 \)). In Panel C, fertility is lower than in the base case. We use the terms ‘fast’ to describe the fertility rate in Panel A (\( x = 0.5 \)), ‘moderate’ in Panel B (\( x = 0.7 \)), and ‘slow’ to describe the fertility rate in Panel C (\( x = 1.2 \)).\(^{16}\) In Panel A, both the resource and population vanish. In Panel B, population is depleted before the resource and the resource regenerates. With a slow fertility rate in Panel C, population does not vanish. Furthermore, relative to the base case, the population and resource trajectories are smoother, population converges at a lower level, and the resource converges at a higher level.

\(^{16}\) For the range of the values of \( S \) (0–12 000) and the values of \( a, \beta, \theta \) and \( \psi \) used here, we get \( \beta^{\psi}a^{\theta}S < 1 \). Hence, for \( x > 1 \) fertility declines with \( S \), and vice versa.
Fig. 6 considers cases where several parameters change concurrently, further demonstrating the inherent complexity of the model. The possible number of combinations of changes is large even in this relatively simple model. We consider three examples involving moderate fertility ($x = 0.7$) and logarithmic technological progress. In Panel A, $x = 0.7$ combines with progress in $K$. Population peaks at a high level but the resource diminishes quickly. Population then declines to near zero before the resource is diminished, and thus the resource replenishes itself. This result is different from the $x = 1$ case (Panel A in Fig. 2), where there were oscillations in both the population and the resource but population did not diminish to zero. Panel B in Fig. 6 considers progress in $a$. The outcomes of near zero population and resource stocks develop faster, relative to the $x = 1$ case (Panel A in Fig. 4). Population peaks at a higher level, but declines faster. Since population declines to near zero before the resource is depleted, the resource replenishes itself. In Panel C, logarithmic technological progress in $r$ also generates a different pattern when compared with the $x = 1$ case (Panel A in Fig. 3). When $x = 0.7$, the resource and the population
fluctuate, while when $x = 1$, there are no fluctuations.

4.2. Social welfare

Our results so far do not measure which scenario might be best from a public policy perspective. To address this issue, a measure of social welfare is required. However, there are no universally accepted criteria for devising such a measure (Nicholson, 1998). Consider, for example, total utility as a measure of social welfare. If it were employed, one could assert that having many people living on the edge of subsistence would be better than having fewer people living comfortably. This is difficult to justify. As an alternative, consider another popular measure, per capita utility (i.e. the utility of a representative consumer). This construct assumes that there is a harmony of interests between agents. If, on the other hand, the utility functions of agents differ, it is not possible to devise a social welfare measure that will agree with the rank ordering of all agents (Arrow, 1950). As in most economic growth
models, we have assumed the existence of a representative agent in Section 1 (i.e. all agents have the same utility function). In our case, then, per capita utility can be used as a measure of social welfare.

Figs. 2–6 illustrate various time paths of per capita utility. To evaluate these time paths, we use three criteria that account for the fact that utility changes over time. As noted above, the relative importance of these criteria, as well as their use, is subjective and ultimately depends on the society’s goals. First, we compare the value of utility at the end of the simulated time period to its initial value (initial-end criteria), an indication of whether or not society generated welfare over the simulation period. Second, we compute the mean value of utility (mean criteria), an indication of the welfare over the entire simulation period. Third, we compute the variance of the utility (variance criteria), an indication of fluctuations in per capita utility over time.

Table 2 presents the welfare effects. From the initial-end criteria, all the simulations generate a lower end-value of per capita utility compared with the initial value. A fast fertility rate generates the greatest decrease in utility, followed by the combination runs. None of the cases in Table 2 does better (and some do worse) than the base case. Hence, the notion that technological progress could lead to ever-increasing social welfare is not borne out in Table 2.

As for the mean criteria, for all types of technological progress, the highest mean per capita utility occurs in the case with logarithmic progress in \( r \). The lowest mean value occurs in the case with exponential progress in \( k \). Overall, the highest mean per capita utility occurs in the slow fertility rate case, and the lowest occurs in the fast fertility rate case. In the combination runs, the mean levels are generally lower than in the ceteris paribus simulation as well as the base case. Compared with static technology, rapid (exponential) and moderate (logarithmic) improvements in \( r \), and moderate improvements in \( k \) marginally improve welfare. In contrast, rapid increases in \( k \) spark population booms and busts, resulting in a mean per capita utility that is lower relative to the base case. The greatest improvement over the base case comes through slow fertility rates.

As for the variance criteria, the highest variability in per capita utility occurs when there is exponential technological progress in \( k \), followed by fast and moderate fertility (both alone and combined with logarithmic progress). The lowest variance occurs in the slow fertility case, followed by the logarithmic progress in \( r \) case. In the combination runs, the variances are generally higher than in the ceteris paribus cases. With the exception of the two technological progresses in \( r \) simulations, and the slow fertility rate simulation, the variances are higher than the static technology (base case) simulation. Of these three simulations, the slow fertility rate generates the smallest volatility in per capita utility.

Finally, per capita utility in the end of the simulation is generally larger when the population is smaller. For example, logarithmic technological progress in \( k \) generates higher end value per capita utility than exponential progress in \( k \). However, with logarithmic progress in \( k \), the number of people at the end of the simulation is lower than when progress is exponential. As noted, whether a smaller number of people, each with a higher per capita utility is preferred to a larger number of people, each with a lower per capita utility, is an open question.

5. Contemporary implications

Some researchers argue that Easter Island is just one of several examples of societal collapse precipitated by over-exploitation of natural resources.\(^{18}\) As noted by Weiskel (1989, p. 104), these societies evolved along a similar pattern of

\(^{17}\) In panel B of Fig. 4 and Panel A of Fig. 5, the plot of utility stops at around period 150, since population subsequently vanishes.

\(^{18}\) Other examples include the Akkadian and the Sumerian cultures of Mesopotamia, the Anasazi culture of North America, the Maya culture of South America, and the ancient Indus Valley societies. See Tainter (1988), Ponting (1991) and Kohler (1996).
| Table 2: Welfare analysis-effect on social utility from technological growth in model parameters |
|---|---|---|---|---|---|---|---|
| | Base case (static technology) | Intrinsic growth rate | Harvesting efficiency | Fertility rate | Combinations |
| | Log | Exponential | Log | Exponential | Fast | Moderate | Slow |
| Mean | 0.1810 | 0.1810 | 0.1695 | 0.0152 | 0.0801 | 0.0800 | 0.0528 | 0.1031 |
| Standard deviation | 0.0246 | 0.0126 | 0.0097 | 0.0264 | 0.0491 | 0.0503 | 0.0387 | 0.0116 | 0.0388 | 0.0573 | 0.0414 |
| Final value | −0.0423 | −0.0495 | −0.0343 | −0.0422 | −0.0338 | −0.0471 | −0.0591 | −0.2154 | −0.0670 | −0.0297 | −0.0670 | −0.1275 | −0.1281 |

---

- Initial value
“gradual emergence, brief flowering, and rapid collapse of civilization, often taking the form in the final stages of devastating military struggles over the control of arable land or essential resources.” Some scholars believe that the environmental constraints faced by those societies pose similar risks to contemporary societies, particularly in LDCs, where there are relatively high rates of population growth and great economic dependencies on renewable resources. Our results generally show that technological progress in the resource sector would have had limited ability to prevent Easter Island’s population and resource fluctuations. These results may have implications for LDCs, but one should consider them cautiously. After all, our model does not take into account the potentially mitigating effects that capital accumulation, technological progress in the manufacturing sector, property rights reforms, demographic transition, foreign aid, and trade might have on resource dependent economies. While these effects may not have applied to Easter Island, they could be more significant in LDCs.

People in LDCs generally depend more on the natural environment for their livelihoods than do people in developing countries (DCs). The accumulation of capital, the build-up of sizeable non-resource based sectors, and the implementation of technological progress in these sectors might alleviate some of the pressures that LDCs place on the resource base. However, these are costly and lengthy processes. In this respect, the population cycles in our simulations may not be an outlandish possibility for LDCs in the future.

As a general rule, property rights institutions are currently defined and enforced less rigorously in LDCs than in DCs. It is also likely that Easter Island’s society did not develop efficient property rights institutions. This does not mean that efficient property right institutions could not arise in LDCs in the future. Ostrom (1990) observes empirical cases in which such institutions arose endogenously in low-income societies. However, she also describes cases where they did not develop at all. Hence, the endogenous emergence of efficient property rights institutions in LDCs cannot be taken for granted, and may require exogenous intervention from DCs or international organizations.19

The model assumes that fertility rises with per capita income. While this assumption is used in several models, it does not allow for the possibility of demographic transition during the process of development. The theory of demographic transition argues that for states with low per capita incomes fertility rises with income, but as per capita income increases above a given threshold (typically a $1000), fertility declines (Heerink, 1994). This interpretation is not without critics, but is accepted by most demographers and economists.20 Demographic transition implies that yet another way to mitigate pressures on renewable resources in LDCs is to accelerate their economic growth. However, this approach may also entail a cost. Accelerated economic growth may well increase pressure on the environment in the form of pollution, resource depletion, global warming or deforestation. Moreover, a situation with current DCs’ per capita income applied to all countries is probably not sustainable (e.g., see Daly, 1992).

The model also assumes a closed economic system without foreign aid and trade, but of course, LDCs are not closed economies. Resource scarcities may be alleviated by foreign aid. Nevertheless, we believe the insights gained from understanding the underlying tendencies of the system without foreign aid are important, as they could assist in preventing environmental collapses that require such aid in the first place. As for trade, its effect on the social welfare of a natural resource-dependent economy is not clear. Consider a two-sector economy that has a comparative advantage in its natural resource sector. As shown by Brander and Taylor (1995) and others, trade will induce more resource harvesting. Over time, the resource is overexploited and social welfare declines relative to autarky. On the

19 Fernandez and Rodrik (1991) argue that institutions might not emerge when the distribution of benefits they may create is not clear to the actors involved.
20 Abernethy (1993) criticizes the theory of demographic transition. She argues that population declines in DCs because people believe hard times are ahead. See also Dilworth (1994).
other hand, if the economy has a comparative advantage in its non-resource based sector, trade prompts allocation of more labor to this sector, reducing natural resource harvesting. In this case, social welfare rises relative to autarky.

The discussion has, thus, far omitted the possibility of violent conflict over depleting resources. Malthus (1798) predicted that since population grows faster than food supplies, disease, starvation and violent conflict will eventually increase. These forces will provide a check on population size, resulting in fluctuations in population and resources. The typical argument made against this prediction is that it does not consider the mitigating effect of technological progress.

Much in the spirit of Malthus, our simulation results demonstrate that per capita utility and the stocks of the resource and population fluctuate widely over time, despite the presence of technological progress. It makes sense to assume that when per capita utility falls below a given threshold, people may resort to conflict in order to increase their own consumption. Such periods may also represent famines and disease. Periods when the resource is diminishing rapidly may represent resource destruction due to conflict. However, these are not the only Malthusian implications of this paper. Violent conflict, disease, and famines may also limit the physical and mental capabilities of the population, thus reducing its ability to generate technological progress. This point, however, is controversial. For example, Boserup (1981) and Simon (1996) argue that since necessity is the mother of invention, these same adverse forces will generate more innovation.

It is interesting to note that during its decline, Easter Island did experience increased violence (Keegan, 1993). To what extent are these disrupting and violent political forces with us today? Myers (1993), Homer-Dixon (1994) and others present supporting evidence that environmental decay may well give rise to violent conflict in LDCs. Moreover, a 1998 report of the World Watch Institute in Washington, DC finds that current population levels in Africa are lower than the levels predicted a few years ago. In line with our discussion, the report attributes the lower observed population levels to environmental degradation, increases in disease (e.g. AIDS), and violent conflict.22

6. Conclusion

We have investigated the interaction between renewable resources and population assuming hypothetical technological progress and population management on Easter Island. In the majority of our simulations, the population and the resource fluctuated widely over time; technological progress would not necessarily have generated a ‘golden path’ of economic growth on Easter Island. Institutional reform in the form of fertility management had a positive effect on the system, allowing for relatively smooth population and resource trajectories. A constantly growing per capita utility was not observed in any of the simulations. We did not investigate whether a different parameterization of the model would allow for constantly growing per capita utility. It may be that allowing for demographic transition would permit continuous growth in welfare to occur. However, we defer this interesting question to future research.23

Our results suggest that policies designed to alleviate the Malthusian predicament must deal with certain fundamental questions. Should society attempt to increase social welfare even if it results in wider social welfare fluctuations over time? Should society encourage social welfare stability even if it means lower levels of welfare? Should society promote high social welfare at the

---

21 This statement also applies, to varying degrees, to other historical societies whose collapses are said to be related to environmental degradation.

22 In principle, such conflicts could also occur in DCs. Choucri and North (1975), for example, argue that World War I was largely the result of a competition over natural resources in colonial areas due to an increasing European population. The competition induced arms races and the system became unstable. Recall also the fish wars between DCs since the 1970s (e.g. Iceland–UK, Spain–Canada).

23 We wish to thank an anonymous reviewer for this suggestion.
expense of a larger population? We believe it is reasonable to support policies that minimize population fluctuations while attempting to keep more people in the system, even at the expense of having lower per capita utility. However, as with other normative choices, this goal is subjective.

Since we have employed a relatively simple model, there are several ways in which the analysis could be developed further. Future research may make agents forward-looking. It is not clear how the dynamics would be altered in this case. Demographic transition might also be incorporated into the model. However, we believe the assumption that below a given renewable resource stock fertility decreases with resource depletion, regardless of per capita income, should be maintained. Another avenue of future research involves Monte Carlo simulations whereby one draws parameter values from assumed distributions. Similarly, one could try other technological trajectories, as well as lengthen the time horizon for the simulations to learn more about the model’s dynamics. Finally, it would be worthwhile to endogenize technological progress. For instance, one could make progress a function of population growth or, alternatively, a function of resource scarcity.

At the end of the day, we would like to revisit the following question — to what extent are the simulation results applicable to contemporary LDCs? Given the model’s simplicity, we need to be careful. While the model’s base case replicates what is understood to have happened on Easter Island, there is clearly some distance between even the poorest LDC and Easter Island. At the same time, we agree with those scholars who argue that the Easter Island case is important. Technological progress is often viewed as the main engine of sustainable development, assuring ever-increasing welfare over time. This view is not supported here. Whether contemporary societies evolve along paths similar to those presented here also depends on their choices. However, we believe the Easter Island story does serve as a clear warning of what the future might hold should nations choose policies similar to those chosen on “our” Easter Island.

References


24 We wish to thank an anonymous reviewer for these two suggestions.


