# Chapter 17
# Economic Causes and Consequences of Deforestation on Easter Island

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## 1 Introduction

One approach to understanding the deforestation of Easter Island is based on economic and ecological modeling (EEM) of the interaction between the forest stock and the human population. The objective of the EEM approach is to estimate and explain the temporal pattern of deforestation and of the human population on Easter Island using a mathematical model incorporating relevant economic and ecological principles.

An early EEM approach to Easter Island deforestation, developed by Brander and Taylor (1998) (BT from now on), is related to the "predator-prey" models originally proposed and analyzed by Lotka (1925) and Volterra (1926). As applied to Easter Island, the forest is the "prey" and the human population is the "predator." Predator–prey models may or may not give rise to a "boom-and-bust" pattern depending on parameter values—that is, depending on the precise relationships in the model. The BT model for Easter Island is consistent with a boom-and-bust pattern and identifies the key factors underlying this pattern.

This chapter provides an extension and modification of the BT model that allows for a more detailed and more accurate representation of Easter Island's economy and also incorporates new information that has emerged since the BT model was published in 1998. The result is a model that tracks the known information more accurately and more clearly identifies the important economic factors underlying Easter Island's deforestation and population rise and fall. This chapter also shows how alternative assumptions about important but uncertain factors, such as the extent of soil erosion, affect the estimated trajectories of population, deforestation,

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and standard of living on the island. In addition, as a contribution to a book on multidisciplinary approaches to studying Easter Island, this chapter also describes the role of economic principles in understanding Easter Island's evolution.

This chapter is not the first extension of the BT model. Other valuable extensions and general contributions to the EEM approach include Anderies (2000), Basener and Ross (2004), Dalton and Coats (2000), Good and Reuveny (2006), and Pezzey and Anderies (2003) among others. This general line of research has been reviewed by Merico (2017).

Relative to this literature, the model developed here contains several significant innovations. First, the BT model, like many economic models, is a "two-sector" model in that it separates the economy into two components, a resource sector and a service sector that represents "everything else." The BT resource sector encompasses both the forest and the agricultural sector, and the underlying resource is referred to as a "forest-soil complex." This chapter uses a three-sector model in which the resource sector is sub-divided into a forestry sector and an agricultural sector and therefore allows a more detailed estimation of the forest stock trajectory.

In addition, the growth of the forest is represented by a generalization of the logistic model to include a "threshold level" of the forest stock below which it is not viable, and the production functions in both forestry and agriculture are generalized from a "Shaefer" form to a "Cobb-Douglas" form. These extensions and generalizations are possible because the current paper relies on numerical methods to solve the model, in contrast to BT, who sought to develop a model simple enough to allow for closed-form analytical solutions.

One motivation for using the economic-ecological modeling (EEM) approach is that it incorporates economic information and ecological information in a way that may yield insights not readily obtained using other approaches. For example, Brander and Taylor (1998) show that the interactive trajectory of a renewable resource stock and a typical pre-modern population in a closed system, such as Easter Island, would depend crucially on the "intrinsic growth rate" (or regeneration rate) of the resource stock. A relatively slow-growing resource stock naturally gives to a boom-and-bust pattern, whereas a sufficiently fast-growing resource would yield monotonic convergence to a steady state. The evidence suggests that the palm forest on Easter Island was composed primarily of the slow-growing *Jubaea chilensis* palm (Grau 2001) or a similar species, whereas other Polynesian islands, such as Tahiti, had much faster-growing palm species. Therefore, the EEM approach can explain not only why Easter Island had a boom-and-bust pattern of development, but can also explain why it differed from most other major Polynesian islands, which did not exhibit a boom-and-bust cycle.

Another important motivation for the EEM approach is that it allows the modeler to "fill in" the full dynamic trajectory of the resource based on fitting the model to a few known data points. In the case of Easter Island, it is known that most of the island was covered by a dense palm forest prior to colonization by Polynesians and that the forest was essentially gone by 1722 at the time of first European contact. In addition, significant information regarding the intervening period is available from sediment cores from several locations on the island. The EEM approach allows us to put together these pieces of information in a consistent way to estimate the overall temporal pattern of deforestation and human population dynamics.

Providing a meaningful EEM quantification of Easter Island (or any other environment) requires reasonably accurate information about important functional relationships between variables. For example, the assumed "production functions" that show the relationships between inputs such as labor and output such as forest products need to be reasonable approximations. Good estimates of specific parameter values are also needed. This includes information about the forest, the people, and the economy. If the functional relationships or parameter estimates are highly uncertain, then the accuracy of the model is also highly uncertain. However, the model can, at a minimum, show the implications of different plausible assumptions for the trajectory of population, the forest stock, and other key variables.

Sections 2 summarizes important information about the forest, Section 3 reviews demographic and other information about the Rapa Nui population on Easter Island, and Sect. 4 provides key facts about the economy. These sections also specify the proposed functional relationships in each of these areas. Section 5 describes the parameter values used in the base-case simulation and illustrates that simulation diagrammatically. Section 6 shows the effects of using different parameter values and different assumptions about the model. Section 7 discusses the major economic themes and principles in the analysis, and Sect. 8 contains concluding remarks.

## 2 The Easter Island Forest

Our knowledge of Easter Island's forest is due mainly to paleo-ecological studies of the pollen content of sediment cores taken from several locations on the island, first reported by Flenley and King (1984) and Dransfield et al. (1984). As emphasized by Rull (2020b), these core-based pollen studies are limited, consisting of cores taken from only three specific locations on the Island, Rano Raraku, Rano Aroi, and Rano Kao.

The three source locations for cores exhibit quite different temporal patterns, although virtual extinction of the palm forest by about 1600 CE is evident at all three sites. Based on Figure 7 in Rull (2020b, p. 133), the Rano Raraku cores exhibit a sharp deforestation pulse starting just before 1200 CE, followed by slow decline until another deforestation pulse starting about 1450 CE. The Rano Kao record indicates marked deforestation periods around 1050 CE and 1350 CE, with significant regeneration in the intervening period. The Rano Aroi record shows significant expansion of the forest between about 1400 CE and 1520 CE, after which deforestation begins. Thus, significant deforestation began at markedly different times at the three locations and deforestation pulses occurred at different times. And, most notably, two of the three sites experienced forest expansion over significant periods.

As these three locations account for only a small part of the island, it is far from clear what the overall temporal pattern of deforestation was, or when it began.

However, core sample evidence has been augmented by root imprints obtained by Andreas Mieth and Hans-Rudolf Bork and others, as described by Mieth and Bork (2017, Ch. 2, pp. 39–41). This includes obtaining root imprints in edges of gullies, corresponding to significant depth and therefore to considerable age, but without the need for drilling cores. This evidence suggests that about 75% of the island was covered by a dense palm forest of close to 20 million individual palm trees prior to colonization. Mieth and Bork (2017, p. 39) also assert that evidence for the Jubaea palm is "conclusive," although it may have been a variant of the Jubaea genus other than the *Jubaea chilensis*. These giant palms typically grow to a height of over 20 meters and a diameter on the order of 2 meters (Grau 2004).

In addition to the dominant palm species, the forest also included many other species of smaller trees and shrubs, most of which were also harvested to extinction well before first European contact. One shrub that survived was the Toromino shrub, which was apparently extinguished except for a single plant from which all known current cultivated specimens descend (Mieth and Bork 2017). The forest was also home to many species of land-based birds that also went extinct as their habitat disappeared.

There is a general agreement that the great majority of the deforestation occurred between 1250 CE and 1600 CE. This is sometimes taken to imply that first colonization occurred shortly before 1250 CE, However, as pointed out by Mieth and Bork (2017), this conclusion is implausible. First, the "great majority" is not the same as "all." Some significant deforestation occurred well before 1250 CE, and no later than about 1050 CE (Rano Kao). In view of the variety in deforestation times exhibited by the three well-studied locations, it is likely that other parts of the island had still different starting times for deforestation. Given the large number of other locations, it is therefore possible that some areas began significant deforestation before 1050 CE.

One further point about deforestation to be considered is the "rat hypothesis" advanced by Hunt (2007), that rats brought to Easter Island by Polynesians consumed or at least damaged the nuts of the palms and therefore prevented growth of new trees, converting the forest into a non-renewable resource. My reading of the evidence is against this hypothesis. First, as noted by Vogt and Moser (2010) and others, most of the preserved nutshells from Easter Island do not show gnawing marks, although a few do show damage, suggesting that the rats had only a small impact on the forest. Second, two of the three sources of cores exhibited significant periods of forest regeneration well after initial colonization of Easter Island. These observations seem to conclusively reject the hypothesis that rats stopped new forest growth. It is possible that rats might have slowed the regeneration rate slightly, and it is possible that drying on the island in the early colonization period, as indicated in Rull (2020b, Fig. 7), might have slowed regeneration, but my reading of the evidence is that these effects were likely of minor significance.

The model component used here to represent growth of the forest stock is the logistic model with a threshold, as described by the following forest growth equation:

$$G(F) = rF\,(1 - F/\mathrm{K})\,(1\text{–}M/F) \tag{17.1}$$

In this equation, $G$ is the growth of the forest stock in a given period, $F$ is the size of the stock at the beginning of the period, $r$ is the intrinsic growth rate, $K$ is the carrying capacity (maximum possible stock size), and $M$ is the minimum viable stock. Initially, when $F = K$, the forest stock is at its maximum size and therefore the growth, $G(F)$, is zero, as with the standard logistic growth function.

If $M = 0$, then the forest growth equation reverts to the standard logistic form used in BT and in many other studies. If $M$ is positive, and if the stock falls below $M$, growth is negative and the stock follows a path toward extinction. See Bascompte (2003) for a discussion of this growth equation and related approaches.

There are several reasons why $M$ would exceed zero. One reason is soil erosion. A large stand of trees provides a windbreak and retains water and soil through its root system. If most of the stand is cleared, beyond some point topsoil is readily lost from wind erosion and from runoff when rains occur. Depending on conditions, erosion could render such small isolated stands unsustainable.

A second reason relates to the loss of an "insurance" effect as the stock gets small. A large forest can survive localized disasters such as lightning, localized fires, a localized temporary drought, sabotage of trees due to internecine human conflict, other human error, disease, etc., as losses in one area can ultimately by replaced by expansion of healthy stands of trees elsewhere. But a stock that is reduced to just a few small stands is just a few small localized negative shocks away from an extinction path.

## 3 Easter Island's Human Population

Easter Island's indigenous human population, the Rapa Nui, was Polynesian in origin. As reported in Rull (2020a, Ch. 2, p. 59), some DNA studies of modern indigenous Rapa Nui indicate a contribution of about 8% of the genome from Native Americans dating from somewhere between 1280 CE and 1495 CE. However, gene-based research by Fehren-Schmitz et al. (2017) finds no evidence of any Native American contribution predating first European contact with Easter Island. The Native American contribution, if there is one, may have arisen due to Native Americans being brought from South America to Easter Island by Rapa Nui sailors or by other Polynesians, or from independent Native American contact with the island after the Rapa Nui were well-established.

One unresolved question about Easter Island is the date of first Polynesian colonization. Early study of Easter Island suggested a date as early as 400 CE.

However, at present the (rather broad) range of 800 CE to 1200 CE suggested by Flenley and Bahn (2003) is widely accepted.

Some observers, particularly Wilmshurst et al. (2011) suggest an even later date based on carbon dating of artifacts (and assert relatively late colonization dates for much of Polynesia). However, Mulrooney et al. (2011) note a number of flaws and some outright errors in this work that bias the implied date of colonization upward (later in time). Furthermore, as pointed out by multiple authors, the date when the population was sufficiently large and sufficiently established to leave a significant number of artifacts is very likely later than the date of first colonization, possibly much later. Carbon dating is not precise but, even assuming that we have accurate carbon dating of some artifacts, that date is an upper bound on first colonization, not a "best estimate" of when colonization first occurred. It is likely that initial colonization was by a small group of perhaps 50 to 100 individuals, arriving on one to three ocean-going canoes traveling together (See, for example, Martinsson-Wallin and Crockford (2001)). Given the broad dispersion of artifacts and other indicators of human population dating from the late 1200s CE onward, it is unlikely that a small initial group arriving only two or three generations earlier (assuming about 20 to 25 years per generation) could have grown sufficiently quickly.

In addition, the pattern of deforestation is itself important evidence and, as noted in Sect. 2, there is evidence of significant deforestation by about 1050 CE. It is sometimes suggested that such deforestation could be the result of natural causes such as climate change or disease, but climate change on Easter Island was mild over this period and, if climate change such as general drying or general cooling was the explanation, then it should have affected all parts of Easter Island, not just Rano Kao. And, while climate change might have slowed forest regeneration, it would be unlikely to cause actual deforestation over the relevant time horizon. Similarly, while plant disease or parasites are possible, there is no actual evidence to support this possibility. It would be a remarkable coincidence if such natural deforestation just happened to occur at the same time when other evidence, plausibly interpreted, suggests contemporaneous human colonization.

If significant human-based deforestation was occurring by about 1050 CE, the implied date of first colonization would be no later than 1050 CE. I take 1050 CE as the starting point of human colonization, although the correct date could well be earlier. Moving the date of first arrival back in time by 50 years or so would not affect the qualitative nature of model, as everything would just be moved 50 years (or more) earlier and the resulting forest stock and population trajectories would still be generally consistent with known evidence. If the date of first arrival was even earlier, that would imply lower (but still plausible) natural fertility than I assume in the base case in this chapter.

Based on Polynesian demographic patterns as described by Kirch and Rallu (2007) and the recent study of New Zealand by Brown and Crema (2019)), an early population growth rate of 3% per year would be a very high estimate. Even 2% to 2.5% per year would be high, although plausible if the ratio of resources to population is high and life is neither difficult nor dangerous. Kirch and Rallu (2007) state that the long run average population growth rate in most of Polynesia was probably less than 1% per year. My model allows for a maximum possible population growth rate of 2.5% but fertility falls and mortality rises in response to declines in per capita food availability.

The base model uses the following fertility and mortality functions.

$$br = b_1\left(1 - \frac{b_2 L}{C}\right) \tag{17.2}$$

$$mr = m_1\left(1 + \frac{m_2 L}{C}\right) \tag{17.3}$$

In these equations, $L$ is the human population, $C$ is consumption of food and other goods that contribute to fertility and survival. The model assumes that $C = H + Q$, the sum of agricultural output and forest output. The other sector (the "everything else" sector) consists largely of statue carving and movement and associated religious functions that do not contribute directly to nutrition and other basic physical needs. The demographic parameters are $b_1$, $b_2$, $m_1$, and $m_2$, all of which are taken to be positive. Like BT and much of the literature on pre-industrial demography (such as Fernihough 2013; Klemp and Møller 2016) these functions assume that fertility and mortality are linearly related to some measure of either real income or its inverse ($L/C$ in this case).

If the food supply is very large relative to population, then the birth rate, $br$, is $b_1$ and the mortality rate, $mr$, is $m_1$. In this situation, the overall population growth rate, $pr = br - mr = b_1 - m_1$, would be at its maximum level. As population $L$ rises relative to food supply $F$, the birth rate falls and the mortality rate rises (given that parameters $b_2$ and $m_2$ are positive), reflecting a Malthusian structure.

The most striking feature of the Rapa Nui society was the creation of large statues or "*moai*." These statues were carved from the Rano Raraku quarry and moved to various locations on the island. Creation of statues is related to the question of deforestation as it is very likely that wood from the forest was used to create rollers or sleds on which statues could be moved (Van Tilburg 1996). The forest was also a source of material for implements such as levers that would have been necessary for moving and positioning statues. Various time periods have been suggested for the start of *moai* carving, with the earliest being some time shortly before 1200 CE. The end period was probably between about 1625 CE and 1650 CE, although both earlier and later times have been suggested.

The other main cultural point to note is the dramatic social shift from the ancestor worship centered on the moai to the Birdman cult. The dates of the Birdman cult are also uncertain but carbon dating and other evidence described by Robinson and Stevenson (2017) strongly suggests Birdman cult activity in the early 1600s.

## 4 The Economy of Easter Island

The forest sector had a variety of outputs although, for modeling purposes, all forest output is aggregated into a single category. One very important use of the forest would have been to harvest trees (other than palms) to make canoes and other sea craft that could be used for fishing. Therefore, fish is one important output of the forest. In addition, the forest was home to various species of land-based birds that would also have contributed to the food supply. It has also been suggested that the Rapa Nui might have taken sap from harvested trees for drinking (Mieth and Bork 2017, p. 48). Thus, the forest would have contributed significantly to food production.

In addition, wood from the forest was used to build dwellings and for various tools and implements, including rollers for moving statues. Wood was also used for fires for cooking and for other purposes, although much of that wood for cooking would have come from other (smaller) tree species and undergrowth on the island, as implied by the analysis of charcoal remains.

### *4.1 Production Functions*

Production in both the forest sector and the agricultural sector is modeled using Cobb–Douglas production functions, as is common in economic analysis. Also, agricultural output in pre-industrial societies is typically taken to exhibit constant returns to scale in labor and land as in, for example, Klemp and Møller (2016). The agricultural production function is

$$Q = \alpha L_a^q A^{(1-q)} \tag{17.4}$$

where $Q$ is agricultural output, $\alpha$ is a productivity parameter, $L_a$ is agricultural labor, and $A$ is agricultural land. The exponents $q$ and $1 - q$ are "elasticities." Each elasticity shows (approximately) the percentage increase in output if the associated input (labor or land) increases by one percent, holding the other input constant. It follows that if the elasticities sum to one, as assumed in this case, the production function has constant returns to scale, which implies that there is no particular advantage or disadvantage to greater scale: Doubling both inputs would double output. However, the marginal product of labor is declining in that, if we hold agricultural land fixed, the extra output obtained by adding more labor declines as the labor input increases.

In the forest sector, the production function is

$$H = \beta L_f^h F \tag{17.5}$$

where $H$ (for “harvest”) is forest output, $\beta$ is a productivity parameter, $L_f$ is labor used in forestry, and $F$ is the forest stock. This production function is similar to the Shaefer production function used in BT except that the labor input has an exponent or elasticity, $h$, that is assumed to be less than one, which implies diminishing (instead of constant) marginal productivity of labor and is more realistic. This production function overall exhibits increasing returns to scale in that proportionate increases in labor and the forest stock would increase output more than proportionately. It is important to emphasize that the “forest sector” is taken to include the entire “downstream” output of forestry. In particularly, cutting down trees, making canoes and going fishing, and building dwellings from wood are all part of “forestry output” in this structure. Increasing returns to scale (advantages of scale) in forestry are plausible for several reasons, including the advantages of greater specialization at greater scale.

The forest sector competes with the agricultural sector for land. In the island’s initial state at first colonization, most of the land was covered by the palm forest. Units of land can be defined such that the initial forest stock, $K$, is the same as the initial land area occupied by the palm forest, which is therefore also $K$. Some of the land, while unsuitable for palms, would have been available for agriculture, and some land was suitable for neither a palm forest nor for agriculture. I denote the initial agricultural land as $A_0$. It follows that the total amount of land usable for forestry and agriculture is $A_0 + K$. As time goes on, the forest stock is depleted and agricultural land increases accordingly, but the total amount of useable land does not change. Therefore, at any given time, the combined agricultural land, $A$, and forest stock, $F$, equals the amount of land available, $A_0, + K$ as expressed in Eq. 17.6.

$$A + F = A_0 + K \tag{17.6}$$

An interesting interaction between the agricultural and forest sectors is that burning of the forest cover would, in the short run, fertilize the soil and increase agricultural productivity, causing $\alpha$ in eq. (17.4) to increase. Even if most of the wood were used for other purposes, the roots and undergrowth would still be burned and there would be some other harvesting residue, creating some fertilizer effect. However, over time the loss of forest cover would lead to increased soil erosion that would gradually have a negative effect on agriculture, causing $\alpha$ to fall (See Zheng (2006) for an example of the dramatic increase in soil erosion caused by deforestation). These two effects are incorporated in the model through the following equation:

$$\alpha_t = \alpha_0 + \frac{zH_{t-1}}{A_t} - eA_t/K \tag{17.7}$$

The subscript $t$ denotes time, $\alpha_0$ is the initial productivity parameter, $z$ shows the increase in short run productivity caused by last year’s forest removal, $H$, and $e$ shows the negative effect due to soil erosion as agricultural land, $A$, increases and deforestation therefore occurs. If we wish to ignore these two effects, we can set $z$ and $e$ to zero.

In addition to forestry and agricultural sectors, the model allows for a third sector that represents "everything else." This sector includes statue carving and various services including religious, domestic, governance, and security (military) services. This is a constant returns to scale sector in which the only scarce input is labor. Output $V$ (for "ser*v*ices") is given by

$$V = vL_v \tag{17.8}$$

where $v$ is a productivity parameter and $L_s$ is labor used in this sector.

## 4.2 Demand, Utility, and Well-being on Easter Island

As with any economy, one important component of the Easter Island economy is the structure of preferences and demands (or "wants and needs") for different products. Economists often start by specifying a utility function from which demand functions can be derived. In that case, the utility function can also be used as a measure of well-being as higher values of the utility function reflect greater success in fulfilling the wants and needs of the population. BT use a Cobb–Douglas utility function. The model in this chapter uses a quadratic utility function, which is the other commonly used utility function and which is better if complete loss of one sector is possible, as is true of the forestry sector in this case. Specifically, the utility function has the following form.

$$U = u_1 Q - \frac{1}{2}u_2 Q^2 + u_3 H - \frac{1}{2}u_4 H^2 + V \tag{17.9}$$

where $u_1, \ldots, u_4$ are utility function parameters. This utility function is quadratic in $Q$ (agricultural output) and $F$ (forestry output) and linear in the service sector output. The service sector acts as a residual sector that provides a product with constant marginal value. It is therefore convenient to treat the service sector good as a numeraire good whose "price" is normalized to be one and the prices of the other two goods are the rates at which they can be exchanged for the service good. It follows from (9) that the demand functions for forest output and agricultural output are linear functions of their prices.

## 4.3 Allocating Labor

One important aspect of Easter Island's economy (or any other economy) is the system that allocates labor to different tasks. The most common assumption is that workers flow to the occupation where the value of their current marginal product is highest. The marginal product is approximately the extra output obtained by adding one unit of labor (one worker) to the production process. More formally, the marginal product is the derivative of the production function with respect to labor. Thus, for example, the marginal product of labor in forestry is $\mathrm{d}H/\mathrm{d}L_f = \beta h {L_f}^{(h-1)}F$. The value of marginal product in forestry is this marginal product multiplied by the price of forestry output. The value of marginal product in agriculture is derived in the same way. The value of marginal product in the service sector is always $v$.

The assumption that workers flow to the sector with the highest marginal product makes sense if workers themselves are able to keep the value of what they produce (their value of marginal product). It would also be expected in a system where someone else, such as a clan chief, makes the labor allocation decision and receives a share of the worker's value of marginal product.

If the value of marginal product is the same in all sectors, the labor market is in equilibrium. If not, adjustment occurs. Workers would leave sectors with a low value of marginal product and move to higher productivity sectors. This process would continue until an equilibrium was reached in which the value of marginal product is equalized across all sectors. Such adjustment may be fast or slow.

One aspect of the forest sector is that adding workers depletes the resource more quickly and reduces future productivity for all workers. This is a negative externality. An individual worker will work in forestry if the current value of marginal product is high. The externality is that when a worker decides where to work, that worker does not consider the costs (external effects) imposed on future workers in the form of reduced future productivity. In contrast, if a far-sighted manager controls access to the forest, that manager will limit access to the resource to prevent such over-harvesting. In the model, the agricultural sector is not subject to this dynamic negative externality. In practice, any such externality in agriculture is small relative to the forestry externality. The service sector is also not subject to any such negative externalities as it does not make use of any underlying resource base.

BT assume instantaneous labor market adjustment and an open-access forestry sector, leading to over-harvesting and ultimate depletion of the resource. This chapter uses a similar approach, assuming that the forest is an open-access resource and that, at any given time, workers flow to the sector where the value of marginal product is highest. However, this chapter assumes a more realistic adjustment process rather than instantaneous adjustment. Specifically, all new workers entering the labor force enter the sector with the highest marginal product of labor at that time, but old workers in other sectors remain in those sectors and the labor forces in those sectors decline only as old workers retire or die.

## 5 Parameterizing and Simulating the Base Model

The model consists of eqs. (17.1) through (17.9) and is dynamic in the sense that variables evolve over time. The model starts at the time of first colonization of Easter Island by Polynesians and each variable is at its initial value. The initial harvest is determined by production function (5), with the forest stock equal to its initial carrying capacity, *K*. Growth in the forest stock occurs according to growth function (1), although growth in the first period is zero because $F = K$ initially. In the next period, the forest stock equals the initial stock minus the prior harvest and in later periods the forest stock equals the previous stock minus the difference between the harvest and forest growth. Therefore, the harvest will change from year to year, as will other variables. The model uses discrete time periods (of one year) rather than continuous time and is therefore a difference equation model rather than a differential equation model as in BT, but that change has no substantive effect.

The objective of the modeling exercise is to choose parameter values and starting values of variables that are realistic and that generate a dynamic pattern consistent with known facts. This approach is an example of the dynamic "computable general equilibrium" (CGE) method, although most CGE models are much more complicated. There are enough parameters to provide considerable flexibility in fitting the model to known data. Even so, it is not necessarily true that any set of plausible parameter values and initial values can capture known facts. Such a situation would imply that one or more assumed functional relationships is not a good enough approximation to reality. In this case, however, the model can replicate known facts well.

All parameters have to be assigned values. Those parameters, such as the intrinsic growth rate, *r*, or the fertility parameters do not change over time. Variables do vary over time. For example, the actual growth of the forest in any year is calculated within the model and varies over time. Some of the variables need to be assigned starting values. For example, the initial population must be specified. In all years after the first, the population is determined by the model. Some variables are calculated by the model in the first year and all subsequent years, such as the first-year agricultural output or the first-year birth rate. Table 17.1 shows the parameters, any variables that require estimated starting values, and most of the other variables of interest.

The parameters and initial sources are derived in several ways. First, some parameters are just a matter of scaling. I have set the initial forest stock (and the carrying capacity) at 20,000 in view of estimate of Mieth and Bork (2017) of about 20 million palm trees (so one unit of forest stock represents about 1000 trees) and because that is a convenient scale for diagrams. However, it could have been scaled to any value (such as 100), although that scaling would have to be consistent with the scaling of other variables, such as the productivity parameter and agricultural land.

Some parameters are taken from outside sources. In particular, the demographic parameters are based on my reading of Kirch and Rallu (2007) and other sources.

**Table 17.1** Parameters and variables

| Parameter | Name | Value | Variable | Name | Initial value |
|---|---|---|---|---|---|
| $b_1, b_2$ | fertility parameters | 0.035, 0.01 | $A$ | agric. land | 1000 |
| $\beta$ | forestry productivity | 0.00002 | $\alpha$ | agric. productivity | 0.012 |
| $e$ | erosion parameter | 0.005 | $br$ | birth rate | cm[a] |
| $h$ | forestry elasticity | 0.8 | $F$ | forest stock | 20,000 |
| $K$ | forest carrying cap. | 20,000 | $G$ | forest growth | cm |
| $m_1, m_2$ | mortality parameters | 0.01, 0.01 | $H$ | forest harvest | cm |
| $M$ | min. viable forest stock | 2000 | $L$ | population | 50 |
| $q$ | agriculture elasticity | 0.5 | $mr$ | mortality rate | cm |
| $r$ | intrinsic growth rate | 0.004 | $Q$ | agricultural output | cm |
| $u_1, \ldots, u_4$ | demand parameters | 100, 1200, 2 | $S$ | service output | cm |
| $z$ | fertilizer parameter | 1.0 | $U$ | utility | cm |

[a] cm = calculated by the model. This table shows the parameters values used in the base-case model along with the required initial values for some variables

The initial amount of agricultural land is taken to be 1000, reflecting the finding of Mieth and Bork (2017) that the forest covered about 75% of the island. The remaining 25% must have been unsuitable for forest growth and most of it would, presumably, also be unsuitable for agriculture mainly due to basalt outcrops. However, some land would have been suitable for agriculture even though it was not suitable for palm trees. The value of 1000 is 5% of the initial forest stock and therefore 5% of the initial land devoted to the forest.

The initial population is taken to be 50, and the model makes no distinction between the population and the labor force. That is, the model does not include a population category corresponding to young children who cannot work. If we were to introduce such a category, we would just allow the population to exceed the labor force by some percentage to account for those children and the model would be otherwise unaffected.

The value of the intrinsic growth rate (0.004) is taken from BT and the sources cited there. This means that the forest stock would expand at the rate of about 0.4% per year or about 4% per decade. This is slow growth, as is characteristic of the Jubaea palm. The agricultural elasticities are typical for estimates obtained for pre-industrial agricultural production functions. The other parameters, particularly the productivity parameters and the forest elasticity parameter, are chosen to make the model fit the known data, subject to plausibility.

Some of the parameters and initial values do not have important effects in the sense that they can be changed substantially without having much impact on the model trajectories. For example, the assumed initial stock of agricultural land is in this category. Whether the initial value is 500 or 2000 (instead of 1000) has little impact. The fertilizer effect and erosion effect also do not have much impact at the levels I have assumed and the model is similar if those effects are eliminated, but they do have some impact that is worth noting. The size of the initial population also does not have much impact (within the reasonable range).

The minimum viable forest stock is taken to be 2000, which is 10% of the initial stock. This is a fairly high value. But this variable also is not particularly important in that the qualitative behavior of model is not affected much if different choices are made. A low value of 500 or even 0 has little effect on the overall trajectory of the main variables, except that the forest stock does not go fully extinct but stabilizes at a low level.

The most important parameters are, as is consistent with BT and other EEM work in this area, the demographic parameters and the intrinsic growth rate. Those parameters determine the basic character of the model. The production function parameters are also important. Changing these parameters by modest amounts can change the qualitative behavior of the model, as illustrated in the next section. Figure 17.1 shows the base-case simulation of the model, using the values shown in Table 17.1.

The simulation in Fig. 17.1 tracks known facts about Easter Island reasonably well. In particular, the period of rapid deforestation (about 1150 CE to about 1450 CE) followed by extinction of the forest shortly after 1600 captures the path of deforestation. The population peak is somewhat lower than in BT but, at close to 7000, is still much higher than the estimated population of between 2000 and 3000 at first European contact. However, the decline in per capita utility or well-being is much sharper than the decline in population.

This decline in per capita utility or well-being reflects basic economic principles. In the absence of epidemics (which were almost certainly absent from Easter Island before European contact), conditions have to become very difficult to induce a decline in population. Without getting into a discussion of whether the Rapa Nui suffered a "collapse" or merely a "decline," the model implies a very steep drop in standard of living. This sharp decline is consistent with other economic evidence,

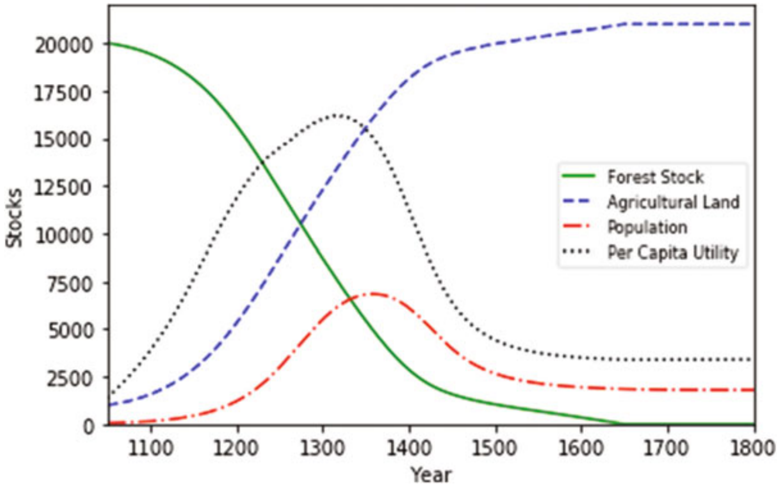

**Fig. 17.1** Easter Island simulation base case

such as the use of stone chicken houses, which implies a high level of concern about security and is indicative of a serious decline in economic fortunes. I also note the frequency of an implement that might be regarded as a weapon (the “mata’a”) in the archeological record during the period of decline, although some scholars argue that the mata’a is just a tool with many possible uses.

## 6 Alternatives

One value of the model is that it allows experimentation with alternative parameter values. This section provides four alternatives or “scenarios” that illustrate which aspects of Easter Island were of major significance and which had only minor effects. The first scenario eliminates the minimum viable stock consideration, the fertilizer effect of harvesting, and the erosion effect of lost forest cover. Figure 17.2 shows the effects.

Figure 17.2 is not very different from Fig. 17.1, indicating that the minimum viable stock constraint, the fertilizer effect, and the soil erosion effect do not change the basic character of how Easter Island evolved. Nevertheless, there are meaningful differences between Figs. 17.1 and 17.2. Most importantly, long-run sustainable per capita well-being (“utility”) is substantially higher after Year 1500 in Fig. 17.2. The most important reason for this is eliminating the soil erosion effect. In other words, the base model implies that soil erosion due to lost forest cover had a significant negative impact on long-run well-being on the island, even though the overall dynamic pattern of the major variables is similar in both figures. My reading of the evidence suggests that soil erosion is important enough that it should

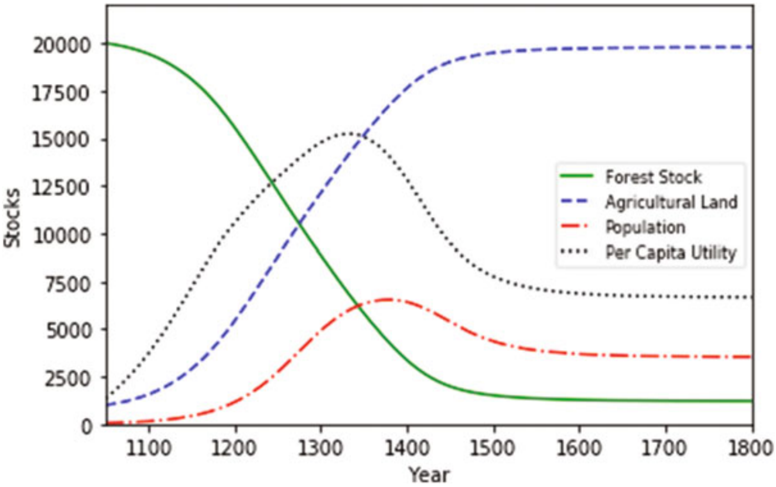

**Fig. 17.2** Effect of eliminating minimum viable stock, erosion, and fertilizer effects

be included in the model. Some scholars have suggested that soil erosion was a localized phenomenon and not significant in coastal regions.

The second major difference is that, in Fig. 17.2, the forest stock is never completely extinguished, although it is reduced to less than 10% of its original size. This effect is due to dropping the minimum viable stock feature. Without this feature, when the forest is very small, it grows faster than when it is larger. In addition, the trees are sufficiently dispersed and, presumably, inferior in quality, that the cost of harvesting the last few trees is high enough to prevent complete extinction. This may be unrealistic and is one reason for including the minimum viable stock feature of the model.

The second alternative scenario to consider is an alternative considered by BT. As noted by multiple authors, the Jubaea palm is very slow-growing. The assumed base-case intrinsic growth rate of 0.4% per year is taken from Brander and Taylor (1998), who calculated this estimate based on horticultural information on the Jubaea palm. However, we can estimate what would have happened if the intrinsic growth rate of the palm forest had been similar to the coconut palms on Tahiti, about 3.5% per year (instead of 0.4% per year). Figure 17.3 shows the results of keeping all the base-case parameter values except for this one change.

This scenario is not intended to represent a realistic possibility for Easter Island, as the assumed intrinsic growth rate is much too high. The scenario is intended to show the importance of the intrinsic growth rate in explaining the difference between Easter Island and other Polynesian islands. As in BT, this alternative completely changes the character of the model's trajectory. The boom-and-bust cycle disappears, per capita utility is much higher, and both population and the forest stock converge on a steady state. It is no surprise that, other things equal, an economy is much better off with a fast-growing resource than with a slow-

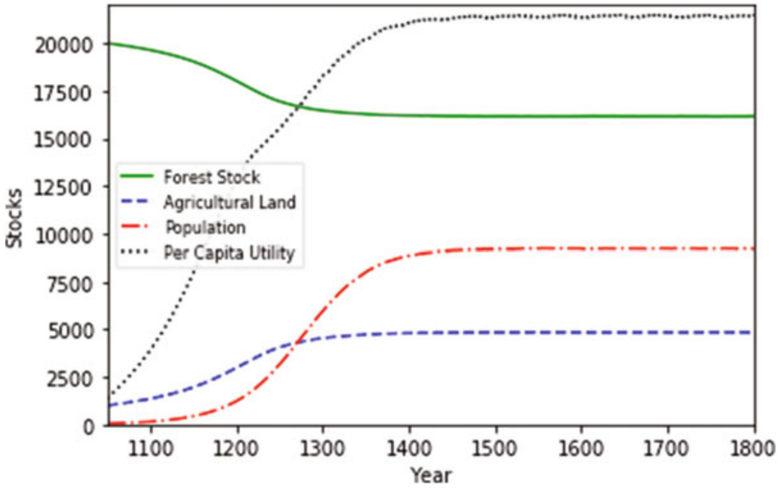

**Fig. 17.3** Fast forest growth

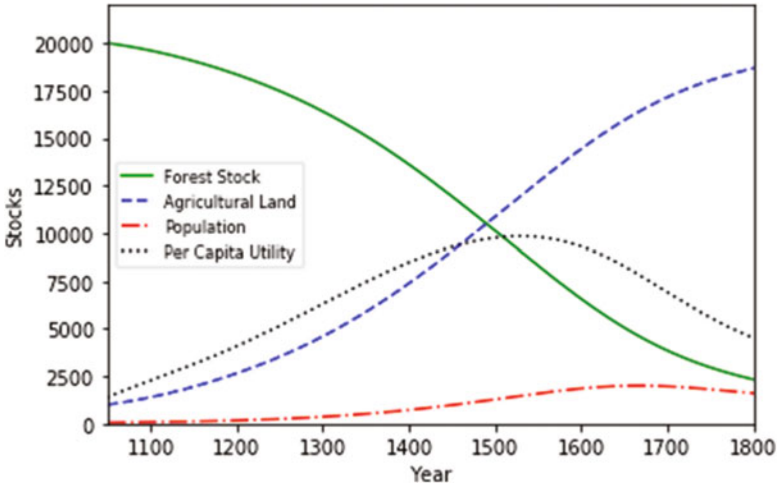

**Fig. 17.4** The effect of a lower maximum birth rate

growing resource. The more surprising finding is that the dynamic adjustment on the model is completely transformed even though underlying preferences and behavioral assumptions are unchanged.

Figure 17.4 illustrates the effect of alternative demographic assumptions. Figure 17.4 has the same parameter values as Fig. 17.1 except that the demographic parameters are adjusted so that the maximum possible population growth rate falls from 2.5% to 1.5%.

Reducing the maximum birth rate has the natural effect of slowing down but not eliminating depletion of the forest and expansion of agriculture. In addition, the overall boom-and-bust pattern, while still present, is muted as the maximum population is much lower and the long-run level of per capita utility is significantly higher. Some scholars view a trajectory of this type as being a good representation of the current understanding of the actual trajectory of Easter Island.

The final alternative to consider is the "optimal management" scenario. This scenario asks what would have happened if the forest had been optimally managed instead of being subject to open access. The specific policy rule considered is as follows. The model proceeds exactly as in the base case up to the time when the forest stock is reduced to the size that provides the maximum sustainable yield, which occurs where forest growth per year is maximized. (This maximum yield forest stock is much less than the carrying capacity, where the annual growth of the stock is zero.) At this time, the labor force in forestry is reduced to the level that would generate the maximum sustainable yield from forestry. This requires a significant reduction in the forestry labor force to prevent further depletion of the forest and therefore lowers per capita income sharply at that point. Net fertility also falls sharply due to the decline in forest output. However, per capita utility and population reach a steady state soon after and remain at that level.

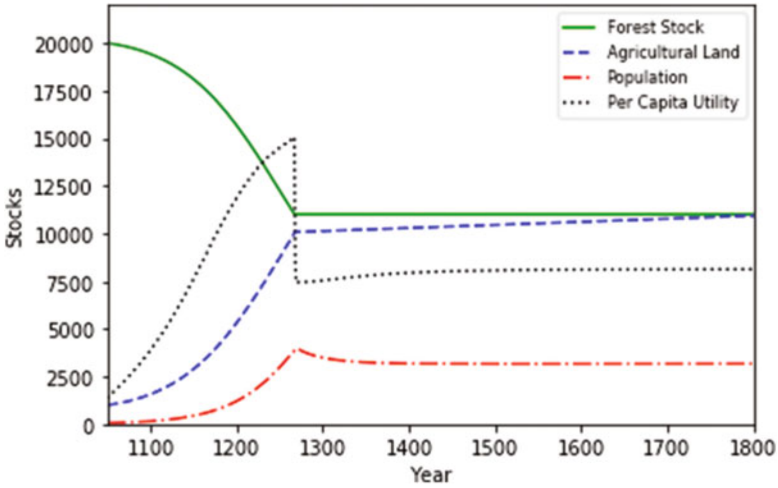

**Fig. 17.5** Optimal management of the resource

Figure 17.5 shows that this path provides the highest possible steady state per capita utility given the low underlying intrinsic forest growth rate of 0.004 (0.4%) per year. This is not nearly as good as having a faster-growing resource (as in Fig. 17.3) but it provides a much better long-run outcome than the base case as measured by per capita utility.

## 7 Economic Principles and Easter Island

This section reviews two major economic themes in the analysis. First, economic analysis focuses on individual economic incentives—the desire to enjoy as high a standard of living as possible. In many pre-industrial situations, for the majority of people this amounts to trying to obtain enough food and other basic necessities on a day-to-day or year-to-year basis to stay alive. Reproductive incentives, which may support longer term well-being if children are expected to make net contributions to family welfare, are also very important.

So how would basic economic incentives explain the large investment in food and labor required to build and transport the moai? There are two possible answers. First, it is possible that people placed high value on such statues—that they obtained utility or well-being from the creation or existence of the moai. Second, a more likely explanation is that labor allocation decisions may have been made largely by leaders who perceived status or other benefits from maoi production and who therefore had incentives to promote high levels of such activity.

Individual incentives may act in the collective interest, which is the main theme in Adam Smith's foundational 1776 treatise, the "Wealth of Nations." But sometimes individual incentives do not serve the collective interest. Open-access resources provide one such counterexample, as first clearly shown in a formal model by Gordon (1954). In the Easter Island model, decisions made by individual workers or others controlling them leads to over-harvesting of the forest stock that ultimately reduces per capita well-being on the island. In addition, individual incentives regarding fertility lead to population growth at a level that also contributes to resource depletion and a reduction in per capita well-being, consistent with the classic work of Malthus (1798).

Over-harvesting due to individual economic incentives is a property of the model that may or may not closely reflect actual behavior on Easter Island. Possibly non-economic factors are of more relevance. But economics emphasizes the possible role of open-access resources and of underlying economic demography.

A second economic theme implicit in this chapter is the importance of economic and ecological fundamentals in explaining differences between societies. If we want to compare Easter Island with Tahiti, economists would not attribute the dramatically different outcomes to differences in motivation, in sensitivity to the environment, in social custom, or in ethical, moral, or religious belief. Such things might be important, but economists would start by considering economic and ecological differences. In the case of Easter Island and Tahiti, the difference in the intrinsic growth rates of the different palm forests on the two islands is an economically satisfying explanation that does not rely on unexplained differences in social organization or social custom.

Economists of course recognize that cultural institutions and economic fundamentals interact in a complex system of co-evolution. However, to a first approximation, economists are likely to view unusual or unique aspects of the culture on Easter Island as consequences of Easter Island's underlying economic fundamentals rather than as causes of economic phenomena. For example, the elaboration of the ancestor worship and moai manufacture was largely due to the existence of suitable resources for carving and moving the statures and to the wealth derived from an abundant forest resource that allowed a fairly large share of labor force to be diverted into an activity (statue construction and movement) that did not contribute directly to food production. When the resources needed to move the statues became scarce and the level of wealth in the society fell, the emphasis on moai ended and a new dominant culture (the "Birdman" culture) was more reflective of a poorer and more competitive society.

## 8 Concluding Remarks

The modern understanding of Easter Island's pre-history changed dramatically when examination of sediment cores, first reported in by Dransfield et al. (1984), Flenley and King (1984), and a few others, became possible. Although deforestation had previously been speculated, suddenly deforestation became accepted fact and the story of Easter Island become one of ecological catastrophe as popularized by Diamond (2005), among others.

In recent years, there has been some resistance to the ecological catastrophe description. Rull (2020a, Chap. 11 this volume) reports that, although there is no doubt that nearly complete deforestation occurred prior to European contact, several papers have questioned whether a corresponding cultural and demographic crisis occurred.

The EEM model presented in this chapter is consistent with a dramatic decline in well-being on Easter Island well before first European contact. The basic economic logic contained in the equations of the model runs as follows.

Easter Island was colonized by a small group about or before 1050 CE. The group was too small to fully realize economies of scale (due largely to the inability to get the full benefits of specialization). However, the island was still very hospitable and population grew rapidly, probably at close to 2% per year, doubling every 30 to 40 years, for about 200 years, implying a population of about 3000 or more by 1250 CE and still growing fairly rapidly.

In this early period, the output of forest was very important in providing food, although there was some agricultural activity. The equations of the model do not specify that this output was fish, but the natural interpretation is that trees from the forest were used to create canoes and other craft that could be used for fishing. Initially, fishing and forest birds would have much more important sources of protein than the limited alternatives available from agriculture, although the Rapa Nui did bring chickens with them to Easter Island.

During this period, per capita living standards rose as the Rapa Nui obtained the benefits of economies of scale in forest-related activities and developed specialized skills. Wealth increased to the point where the society was able to support a large class of service workers. The model does not specify the nature of this service activity but we understand that a significant part of it consisted of building and moving statues and the associated religious and organizational activity.

Initially, forest depletion was slow and the forest would have seemed like an inexhaustible resource, but the pace of deforestation increased to the point where most of the forest had gone by about 1400 CE. The forest resource was replaced by agricultural land and the model allows a short run beneficial effect on agricultural productivity due to fertilization from tree harvesting residue, but this is more than offset in the long run due to increased soil erosion arising from loss of forest cover. Also, agriculture is taken to be a constant returns to scale activity that displaces an increasing returns activity (forestry), which has a negative effect on per capita productivity and per capita well-being.

The decline in per capita availability of food and other resources increases mortality and reduces fertility in a standard Malthusian pattern. The model does not specify to what extent the increase in mortality is due to declining nutrition directly and to what extent it reflects violent internecine conflict, but either is consistent with the model. Population peaks at just under 7000 shortly before 1400 CE, after which population growth turns negative. Ultimately, as the forest was extinguished, *moai* carving stopped and agriculture took up most of the available land. Population and per capita well-being stabilized at the relatively low levels observed by Europeans at first contact.

This description is the way the model works, not necessarily what actually happened but, as documented throughout the paper, this pattern is consistent with the empirical evidence. The decline of population, living standards, and *moai*-carving activity is perhaps too slow to be called a "catastrophe," but it is certainly a dramatic decline.

In modern terms, it is as if Europe or the United States lost more than half its population over the space of a few generations and had real incomes fall to pre-WWII depression era levels. The key difference between Easter Island and the modern world is the role of technological progress. The model contains economies of scale but abstracts from technological progress although some technological progress did occur, such as the development of the rock garden. Incorporating a small amount of technological progress would not affect the general properties of the model. If the modern world is to avoid a comparable ecologically-based decline, the combination of technological progress and a demographic transition to sustainably low fertility will likely be the main reasons.

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