Collapse of Easter Island:
A Study to Understand the Story of a Collapsing Society

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Abstract

This study aims at explaining the collapsing behavior of collapsing populations using system dynamics methodology and using Easter Island as a case study. This work is triggered by Jared Diamond's (2005) popular book and Brander and Taylor's (1998) economic model of Easter Island. A system dynamics model representing the resource and population sectors of Easter Island has been built based on allocation of labor. First, base cases have been considered for the hunter/gatherer society and the agricultural society. Later, sensitivity analyses have been run to see the behavioral changes with respect to the parameters used in the model. It is found out that the erosion is the main natural process yielding the collapsing behavior. An interesting finding of the study is that differentiation between a forest and an agricultural sector is crucial while studying the decline of agricultural societies because the dynamics implied by their replenishment rates differ considerably.

Introduction

Easter Island has always been an attractive topic for the popular culture thanks to its several-story high statues on its barren land. It was so inexplicable for such a "primitive" society to have built such statues that it was a common source for attributing the extraterrestrial involvement on Earth. It was one of the lifelines of the theory of Erich von Daniken (1968) along with the Pyramids. When I first read his book as a small kid, somehow it made sense with all these fascinating structures.

Currently, less emphasis is put on the extraterrestrial "implications" of Easter Island but more on its natural and societal implications with the increasing awareness for collapsing societies drawing parallelisms with the current global picture. Popular TV channels show a documentary about some version of its story based on some archeologists. Jared Diamond's 2005 book could become a best-seller.

The problem that this study strives to address is best summarized by the title of Jared Diamond's 2005 book *Collapse: How Societies Choose to Fail or Succeed*. To expand the title, the problem is that during the course of history many societies have failed to sustain themselves and vanished. Diamond (2005) describes the collapse of a society as the drastic decrease in society's "human population size and/or political/economic/social capacity over a considerable area over an extended time" (p.3). So, this study tries to address the issue of reasons and the story behind the collapse of an agricultural society.

Audience for this paper is anyone who is interested enough to think about the sustainability of our societies. Although this should include everyone, given the level of awareness of people it is not possible to reach everyone with such a study. So, the main audience is the people who are working on sustainability in different levels.

As a separate society the audience is anyone who is interested in system dynamics methodology. Especially, the approach that I take in this study is more based on the allocation of resources rather than working on the changes in aggregate desired values.

Prior Modeling Work on Easter Island

Modeling of Easter Island's dynamics found some popularity in the beginning of this century in the field of economics mostly due to the work of Brander and Taylor (1998) published in The American Economic Review. By using a very simple but well-calibrated and well-explored second order differential equation system, they were able to explain the collapsing behavior of Easter Island population.

Brander and Taylor (1998) model was built on Malthusian assumption of increase in adequacy of resources increase the births in the population and Ricardian production structure. The determination of resource good harvest amount was based on rational households maximizing a Cobb-Douglas utility function based on resource and non-resource good with respect to the labor constraint that they have. The resulting second order differential equation system could explain the behavior:

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

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

where, L is population, S is resource stock, r is regeneration fraction of the resource stock, K is carrying capacity, β is the taste for the resource good, α is the productivity of unit labor in terms of fraction of forest, ϕ is the effect of each unit of resource good on growth rate of population, b is normal birth fraction, and d is normal death rate. See that $rS(1 - S/K)$ is the logistic growth of the resource stock, $\alpha\beta LS$ is the harvest rate found by the household's optimization of its utility, and $\phi\alpha\beta S$ is the fertility function, which increases or decreases the net birth fraction according to the amount of resource harvested. *Figure 1* is the dynamics Brander and Taylor (1998) find by their simulation of the model:

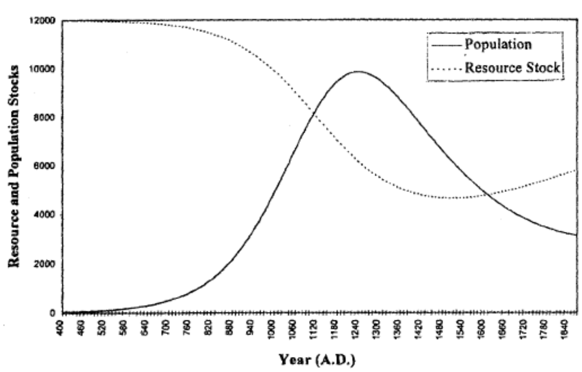


Figure 1: Behavior of Brander and Taylor (1998) model (from Brander and Taylor (1998))

They argue that the regeneration fraction of forest/soil complex is the limiting factor, which determines the collapse by comparing Easter Island with the other Polynesian islands, some of which faced monotonically increasing and then settling population, i.e. S-shaped growth.

Anderies (2000) modified this model to allow for a subsistence level of resource good, below which people would only attempt to attain the resource good. For this end, he used a Stone-Geary type utility function instead of a Cobb-Douglas function, which allows for infinite substitution:

$$U(h,m) = (h - h_{\min})^{\beta} m^{1-\beta}$$

where h is the resource good, m is the non-resource good, $h_{\min}$ is the subsistence level of resource good. Maximization of this utility function with all the other assumptions of the Brander and Taylor (1998) model Anderies (2000) finds the following labor allocation:

$$L_H = \begin{cases} \dfrac{L(1-\beta)h_{\min}}{\alpha S} & \text{if } h_{\min} \le \alpha S \\ L & \text{otherwise} \end{cases}$$

$$L_M = \begin{cases} (1-\beta)L(1-\dfrac{h_{\min}}{\alpha S}) & \text{if } h_{\min} \le \alpha S \\ 0 & \text{otherwise} \end{cases}$$

This suggests that people first think about satisfying their subsistence needs and then allocate the leftover labor according to their taste of that good. These modifications imply the behavior in *Figure 2*:

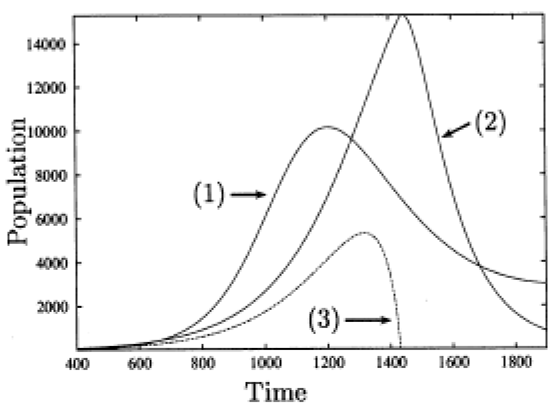


Figure 2: Behavior of (1) Brander and Taylor (1998) model (2) Anderies (2000) model and (3) manufactured goods in Anderies (2000) (from Anderies (2000))

Anderies (2000) suggests that the further emphasis on production extracts more from the resource good stock makes the collapse much more severe.

Reuveny and Decker (2000) use the same model as Brander and Taylor (1998) but makes further experiments with the parameters of the model to represent technological change in those parameters. They insert exogenous logarithmic and exponential changes into the constants to see if a monotonic increase is possible with increasing technology in any of the parameters but they found out that it is not possible with the cases they considered. In each case the population overshot its capacity usually with fluctuations with high amplitudes.

Reference Mode and Dynamic Hypothesis

There is actually a debate about when the Polynesians first settled on the island and what the peak population was. Most of the modeling work done previously in the field of economics cites the time of settlement as of around 400 AD following Brander and Taylor (1998). These studies are based on earlier archeological and linguistic studies. However, Diamond (2005) suggests that newer and more convincing archeological studies based on radiocarbon dating of specific sites and relative layering of the earliest human remains suggest that the first settlement has been around 900 AD. So, this seems to be more plausible to use in this study.

The peak population amount is also a matter of debate in the literature. Diamond (2005) mentions that the estimates vary between 6000 and 30000 people. He proposes that about 15000 peak population is not surprising given the fact that at the time of its discovery by the Europeans, the population was estimated to be around 6000 and 8000 considering the 2000 left after epidemics brought by the ships in 1700s. The economic literature takes the peak population as 10000. So, a population between 10000 and 15000 is adequate to consider for this study.

The timing of the maximum population is suggested by Diamond as somewhere between 1400 and 1600. After that a severe decline came that continued until 1700s when the Europeans first set foot on the island.

Thus, the reference pattern based on the description of Diamond is in *Figure 3(a)*. This diagram is just my approximation as exact numbers are not given. In Figure 1(b), the reference mode presented by Croix and Dottori (2008), which reflects the reference modes used for prior studies.

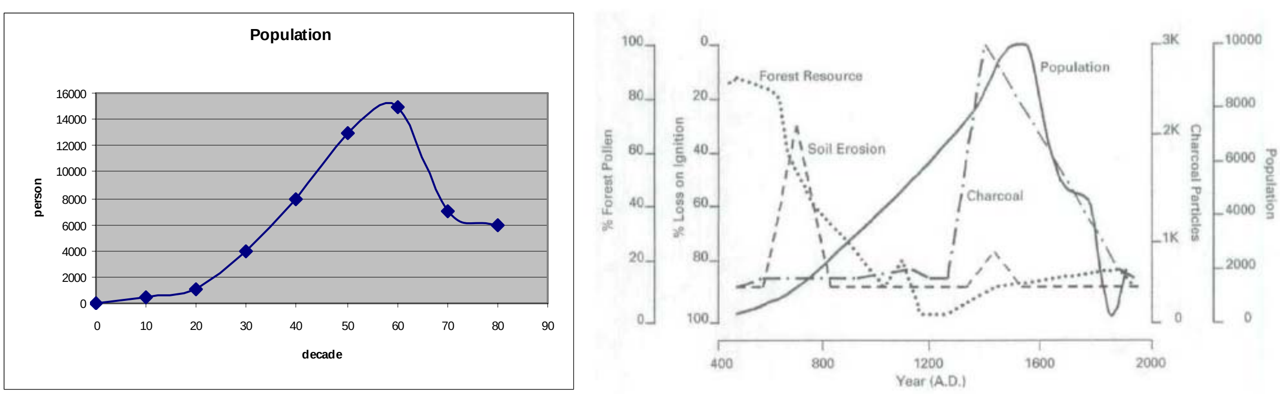


Figure 3: The trajectory of population according to (a) Diamond (2005) (b) Croix and Dottori (2008) with other variables (taken from Croix and Dottori (2008) cited to be tekn from Bahn and Flenley (1992))

The dynamic hypothesis behind this behavior is that is that Easter Islanders grew as they found the resources abundant in the environment but to meet their increasing needs for resources, they cleared the forest increased the intensity of farming, which lead to environmental damage. As this happens with a delay, the population overshoots found itself over its capacity and collapsed.

This problem is a society's problem of managing its carrying capacity in its essence. As the carrying capacity can be diminished, the society can fall into a trap that it created. So, even if the state of the system, i.e. the population may seem increasing fairly normally, actually it might be going towards its crash due to the endogenous dynamics involved with the population and the resources, i.e. forest and soil. So, this problem and the hypothesis behind it is an example of the well-known and studied overshoot-than-collapse archetype (Sterman, 2000, p.123).

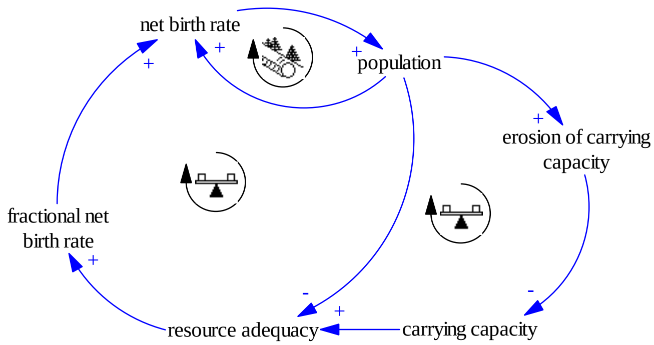


Figure 4: Overshoot-than-collapse structure in sytem dynamics (Reproduced based on Sterman 2001)

Model Structure

Overview

Population is effected by two needs: food and shelter. The model assumes Malthusian dynamics, i.e. there is a direct relationship between self-sufficiency and population increase or decrease. On top of that, the need for shelter regulates the average lifetime where lack of shelter decreases the average lifetime of the population. Shelter is made by using wood, which is extracted from the forest.

There are two different food sources. First is gatherable food that is gathered from the forest such as fruits or caught by using the forest such as fishes that can be caught from the sea by using canoes. The second is agricultural food. Agricultural food comes from the cultivated portion of the arable land. The society strives to allocate its labor force between loggers and food workers to have protection and not to starve.

If there is not enough food to feed the population and there is not capacity left to accommodate farmers, then the society tries to create additional resources by opening up new arable land through clearing the forest or developing marginal land, or by increasing the productivity of unit land.

However, forest clearing and increasing productivity of the land induces the side effect of erosion. If there is not enough forest coverage, the land is not protected against wind or landslides. Also, if more technology, which is done by using rocks and mulch in Easter Island, is applied to the land, the nutrients in the land is exhausted faster and the land gets eroded faster (Lightfoot, 1996). This leads to overshooting of the carrying capacity as the productive arable land will go down with less forest and more intensive farming.

There is another assumption in the model which states that people get used to the food amount that they consume over some time. So, their decision actually depends on the food that they deem as normal. There is actually a similar relationship between logging rate and desired logging rate that imposes another assumption about their behavior. The assumption is that if the desired logging rate gets very close to zero, the relevance of it while making allocation decisions is eliminated.

The explanation above is summarized in *Figure 5*. Please beware that not all causal relationships ae depicted in this diagram, just the relevant ones to the overall view explained above.

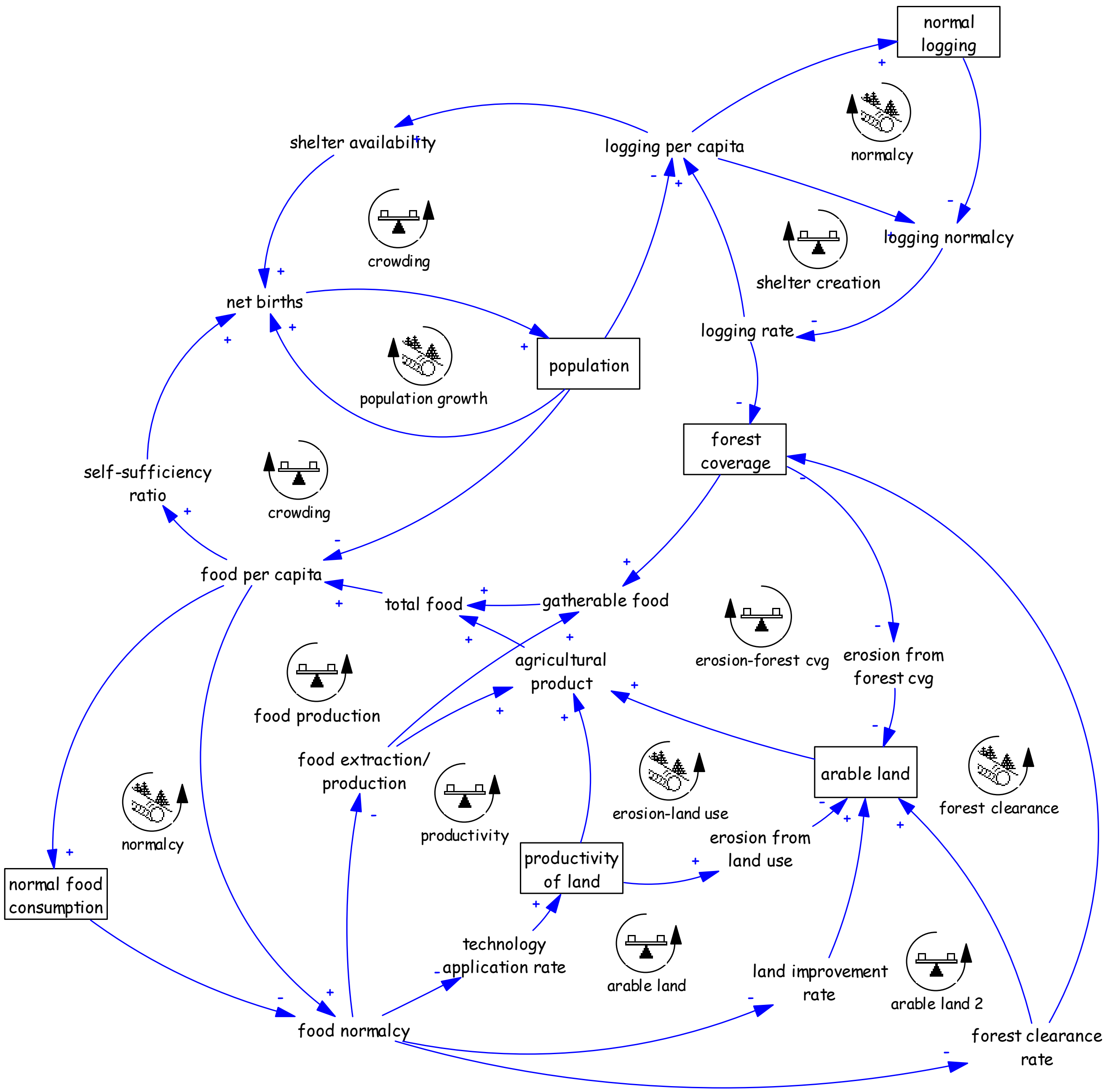


Figure 5: The causal-loop diagram of the whole model with the important relationships and loops idetified.

Flow of Land

Land management is the main problem of a civilization that lives out of it. The dynamics of the model are realized through the conversions among different types of land. There are four different types: forest coverage, logged area, arable land and eroded land. Forest coverage is the source of shelter and wild food resources. Arable land is the land that can be cultivated for agricultural food. Logged area is the land that is nutritious but further work on it is needed to be done to be used for farming. Eroded land is the land which has been rid of nutrients and agriculture cannot be done on it.

The flows between the states of land can be natural processes or human-activity processes. Natural processes are forest regeneration, arable to logged conversion, land replenishment and erosion. Forest regeneration signifies the creation of more forest by reproduction of trees. Arable to logged conversion is the degrading of barren land into logged area. Land replenishment is the process of eroded land's attaining its nutrients back. Finally, erosion is the loss of arable land's nutrients. Although it is primarily a natural process, erosion is highly dependent on human activities as mentioned in the previous part. It is aggravated by lack of forest coverage which is logged or cleared and by the increased application of intensive agricultural methods as it increases the usage rate of the nutrients in the soil. *Figure 6* shows the flow of land and they are dependent on:

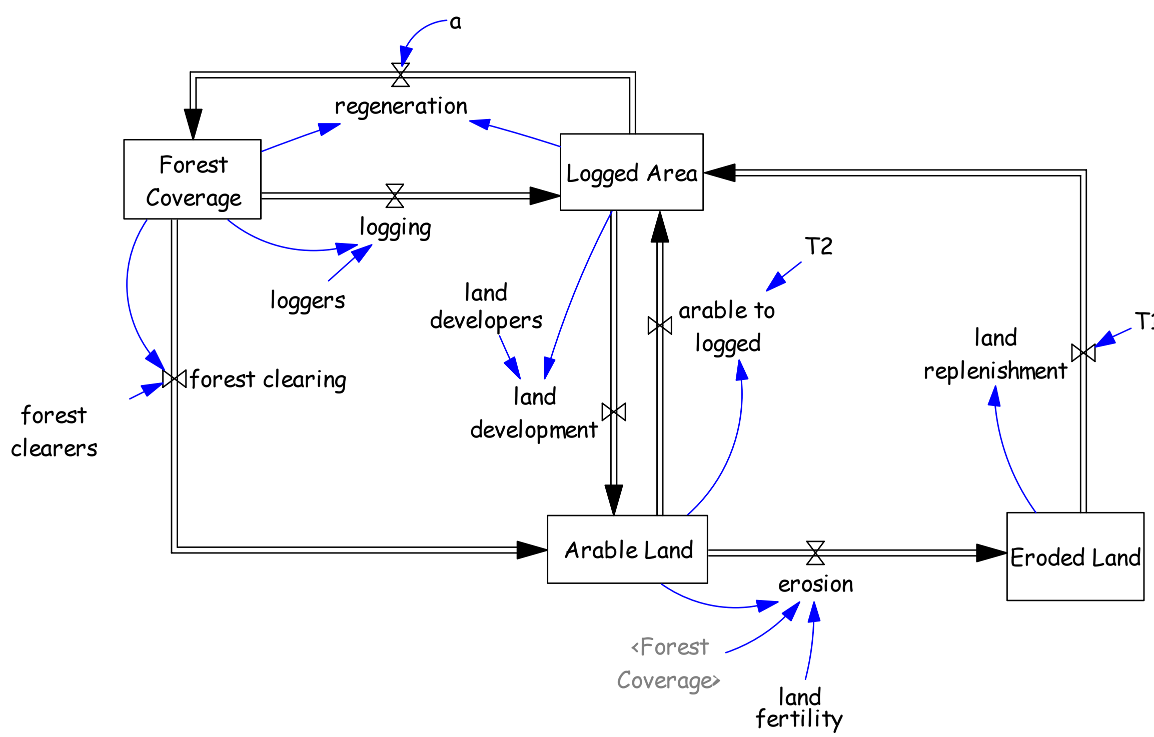


Figure 6:Flow of land (for demonstration purposes only, not exactly how the model is)

There are three types of important extractive human activities: logging, forest clearing and land development. Logging is done to provide shelter to people and forest clearing and land development are done to provide the society with more arable land when people run out of it.

Determination of Human Activities

Extractive Activities

The formulation of extractive human activities (an activity that takes out of a stock) is based on the behavioral conclusion of Brander and Taylor (1998). In their work, they end up with some behavior of resource extraction based on a utility function and a production function. In *Figure 7* the stock-flow representation of their implied behavior can be seen (refer to discussion prior modeling work above and Brander and Taylor (1998) for the details):

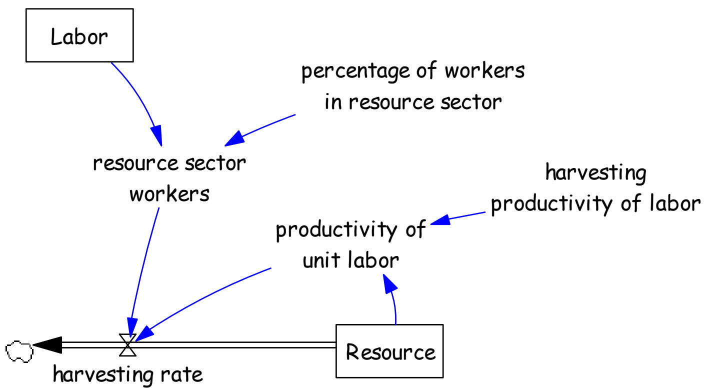


Figure 7: The stock-flow representation of the harvesting funtion of Brander and Taylor (1998)

So, the rate is the multiplication of the productivity of unit labor and the relevant sector workers. This formulation is modified to enable a nonlinear relationship between the resource and productivity of labor.

Production Activities

A similar approach in terms of productivity and labor are used in the production processes of food. As there is no first-order control, the limits of the There is a slight difference between the formulations of gatherable food and agricultural food production but both make use of nonlinearity in the productivity of laborers. The formulation of agricultural production is in *Figure 8*. The formulation of gatherable food is somewhat more straight-forward using a fuzzy min formulation between desired and available food (Please see the model).

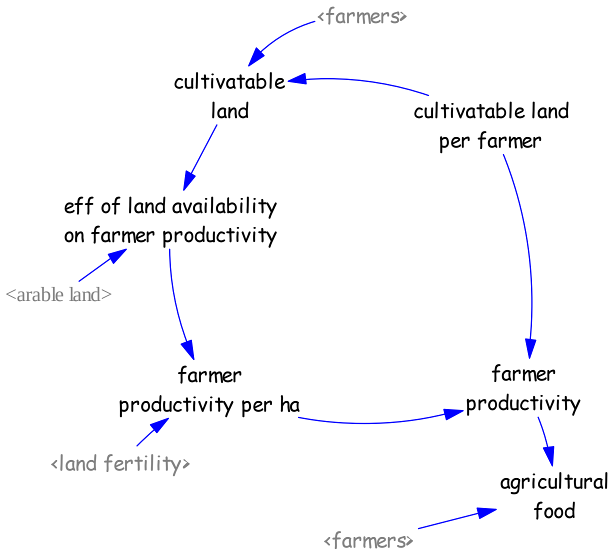


Figure 8: The production of agricultural food.

This formulation transforms land fertility into farmer productivity by taking the land utilization into account. Every additional farmer can produce some amount more but when the land is fully utilized, the productivity of a farmer is less than the fertility. Also in the formulation, cultivatable land per farmer is the amount of land a farmer can cultivate to attain the land fertility.

Land Fertility

Land fertility stands for the average productivity of unit land. As people try to get more from unit land they increases the land fertility by applying some level of technology to it and this is formulated by a goal seeking structure which is accelerated or decelerated by the amount of workers in increasing productivity.

Additionally, as new land comes in the average productivity falls down seeking simple land productivity in the rate of new land creation as the fertility of the older land might have been increased by prior work on the older land. *Figure 9* shows the relationship.

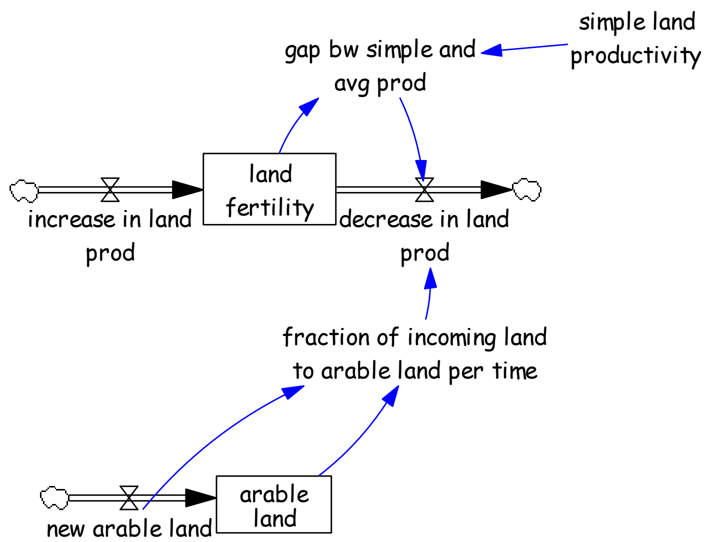


Figure 9: Relationship between the land fertility and arable land

Allocation of Labor

The model operates on allocation of labor as all the extent of the human activities is determined by how many laborers are allocated for each work. *Figure 10* is a tree that shows the hierarchy of the allocation process in the model. The heads and tails are different types of laborers and the phrases in between the arrows show the criteria of allocation between the two.

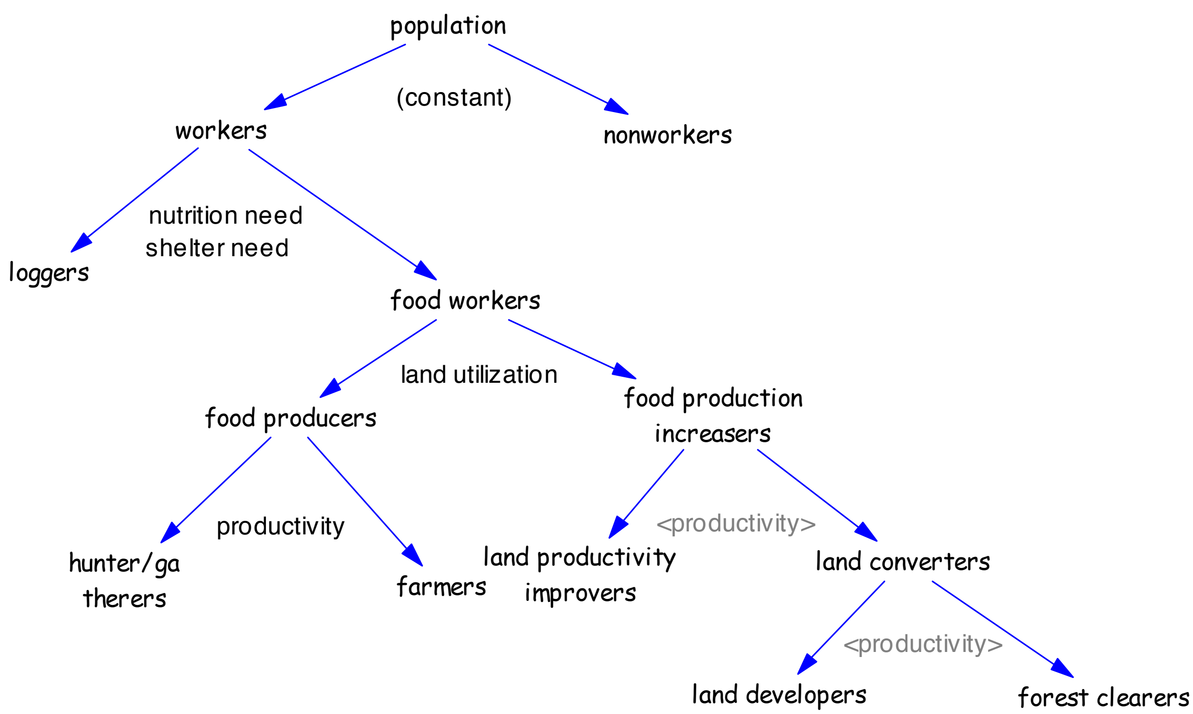


Figure 10:Allocation of labor

The whole population is divided into workers and non-workers with a constant percentage (taken as 40% in the model). This allocation takes children, chiefs and artisans out of the working population.

Loggers and food workers are allocated according to the competing pressures of nutrition need and shelter need. Nutrition need is the reciprocal of the maximum of self-sufficiency ratio and food normalcy. When it goes below 1, which means that less food than normal is available and this exerts a pressure to allocate more food workers.

Shelter need is the reciprocal of shelter normalcy adjusted with an effect of relevance of the floating goal of desired logging. The relevance depends on the comparison of the goal and the absolute amount of logging needed to attain zero effect of shelter on death rate. Otherwise, the society tries to allocate a lot of people to logging while logging is not worthwhile anymore and starve to death as they do not produce food with these people. This is not consistent with the actual behavior.

Food production increasers and food producers are allocated according to the pressures from the utilization of land because if the land is not utilized fully, the society would not want to create more land or to increase the productivity it could rather add more workers.

The allocation of all other labor is based on comparisons between the productivities of unit labor. For example, hunter/gatherers and farmers are allocated according to how much they can produce in a decade. Similarly, the land developers and forest clearers are allocated according to how much land they can convert in a decade.

As can be inferred from the discussion above, this somewhat resembles an economic allocation but one in which implementing the allocation decision takes time and is based on a feedback process of pressures. The society would increase the amount of some type of laborer until the goal is achieved for the pressure based formulations.

Determination of Natural Processes

Population Dynamics

Population formulation is very similar to Forrester's World Model (1971), where fractions have been used based on how people react to their food availability and shelter availability. Food availability can increase the birth rate and reduce the death rate but shelter availability only has a significant impact on the death rate as shelter would reduce the average lifespan as more people get weaker and people may not be protected from the environment.

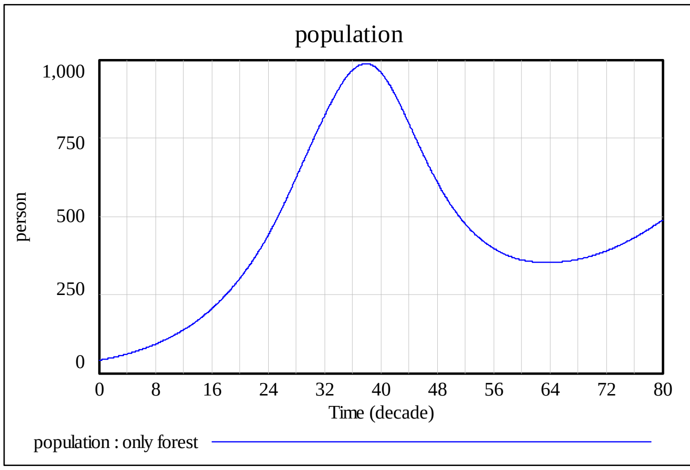
Land Dynamics

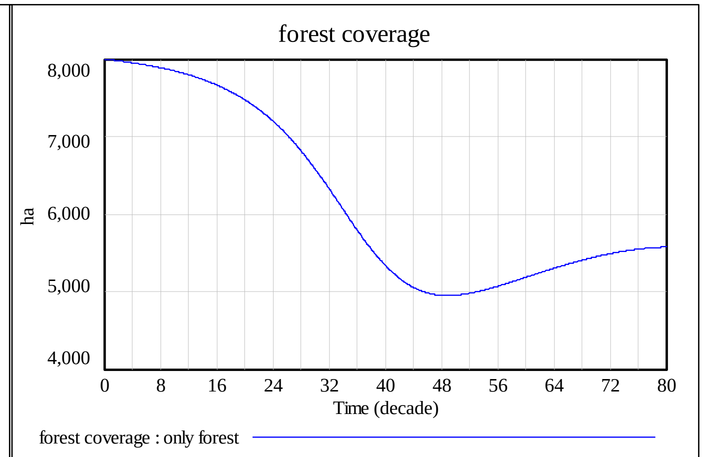
Regeneration rate is determined by a logistic function which can only grow forest into the logged area. Arable to logged conversion and land replenishment times are simple time delays based on the uncultivated land and eroded land respectively. Erosion rates from land use and deforestation are fractional changes that are modified by the fertility and forest coverage respectively.

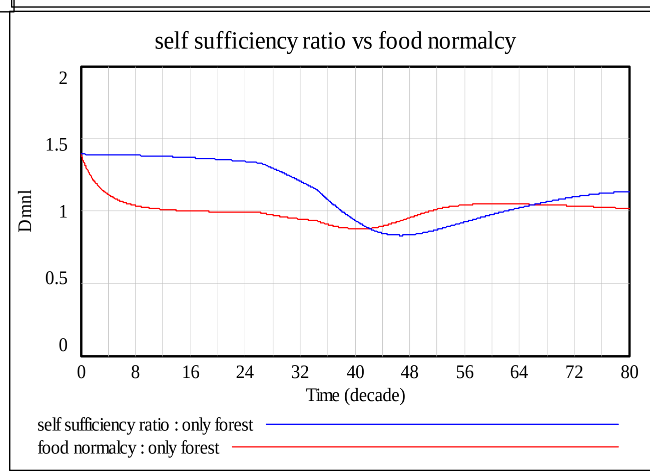
III. Model Behavior

A. Hunter-Gatherer Society

The first model that I will consider is the model of a hunter-gatherer society where the society does not to know about agriculture. Thus, the percentage of hunter/gatherers in workers is 1 throughout the model. The reason of including this model is to compare it with the behavior of n agricultural society. *Figure 11* shows the behaviors of population and forest coverage.







The story of the behavior is that population increases as more food is hunted/gathered but around time=38, the population starts to decline following the decline in hunted/gathered food. The reason for the decrease in food production is that as the forest coverage went down productivity for hunting/gathering more food declines. As a result the population starves as the food gathered or hunted is not enough to cover the need of the population so; decline in population is the result.

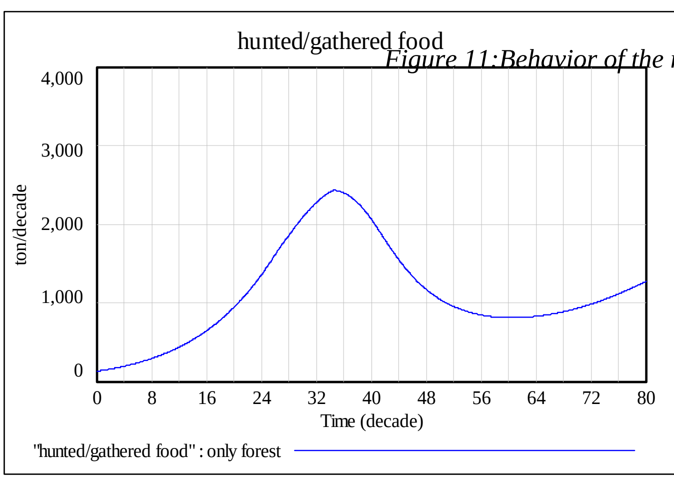


Figure 11:Behavior of the model with only hunter-gatherers

The critical variable turns out to be the forest regeneration fraction for such a society as it increases the amount of food that they can catch and the shelter they need by increasing the forest regeneration rate. The regeneration fraction used for the base run is 0.04 per decade. *Figure 12* shows the sensitivity analysis based on regeneration fraction=RANDOM UNIFORM (0.01-0.5):

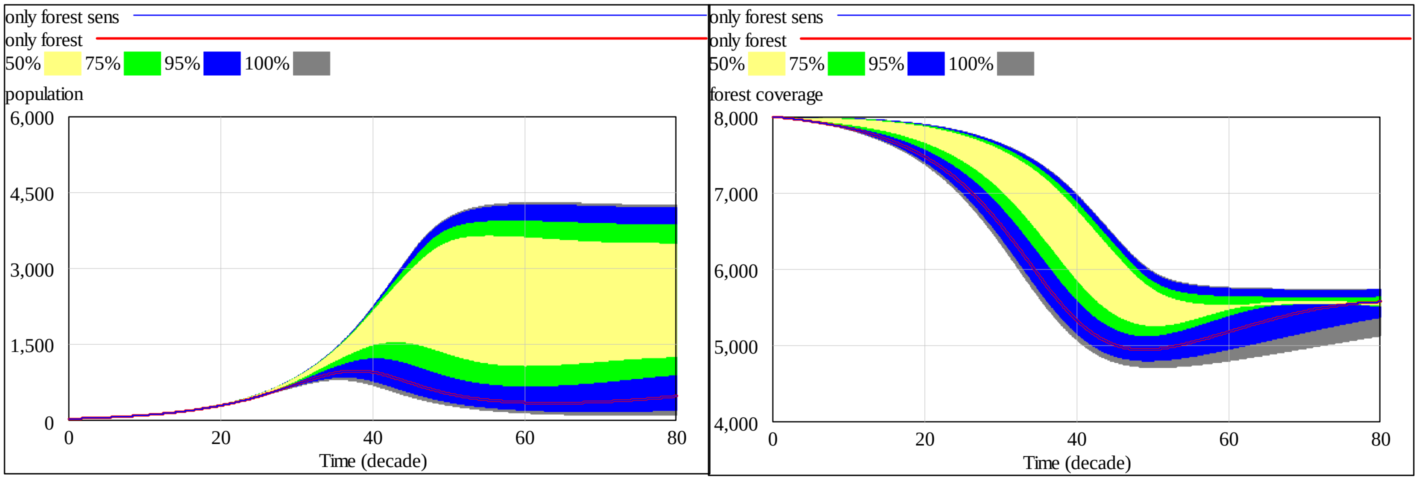


Figure 12:Sensitvity analysis,hunter-gatherer model regeneration fraction=RANDOM UNIFORM (0.01-0.5)

The growth rate of the forest turns out to be very important for a hunter-gatherer society. For societies with very fast growing trees even goal-seeking behavior is possible.

B. Easter Island – Agricultural Society

The parameters used in this part are the same as used in hunter-gatherer case except the fact that now the society can have farmers and use land. *Figure 13* shows the behavior from the base run:

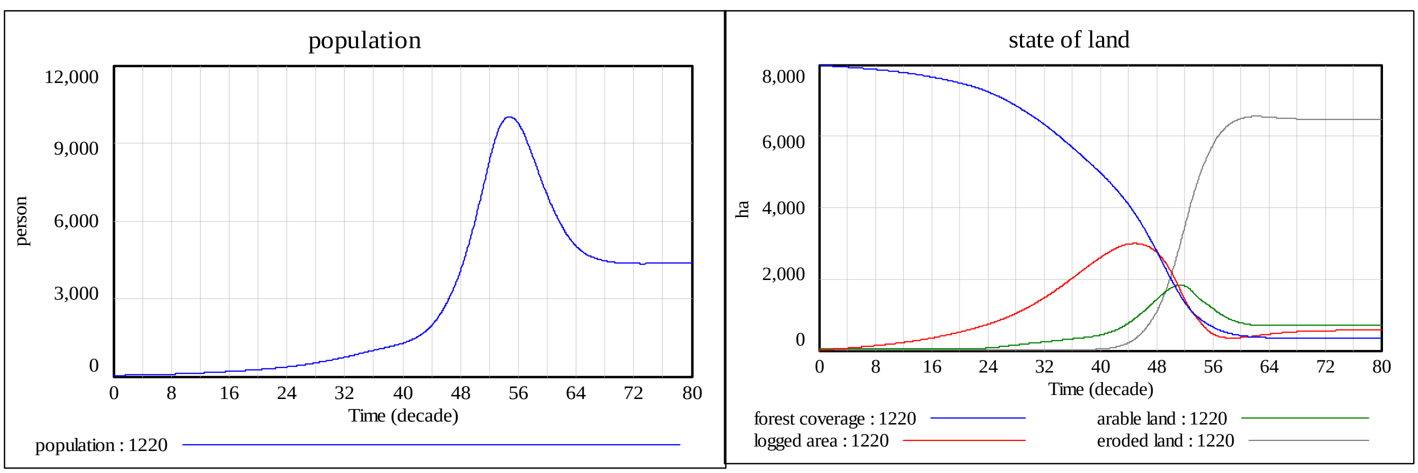


Figure 13:Base-run (named 1220) behavior of population and land stocks

The base run is similar to the reference mode discussed earlier. However, the differences are that the behavior happens about a century early, the peak value is lower and the behavior occurs more sharply. I think these can be bearable problems given the fact that the reference diagram is not based on concrete data but some intelligent guesses. To understand what is happening in the system, we need to look at other variables. *Figure 14* shows the behavior for self sufficiency of food, food normalcy, shelter availability, shelter normalcy and net birth fraction.

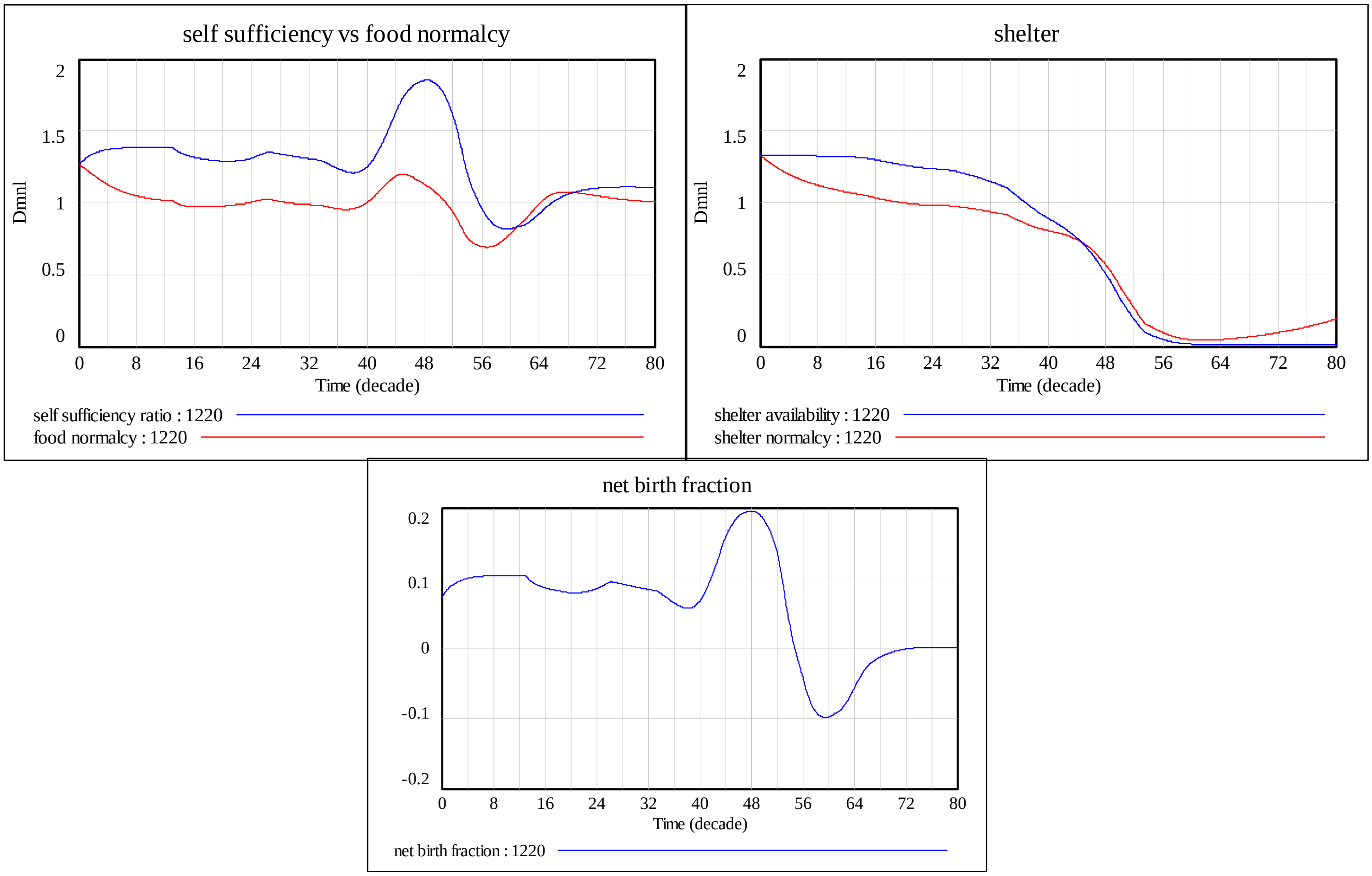
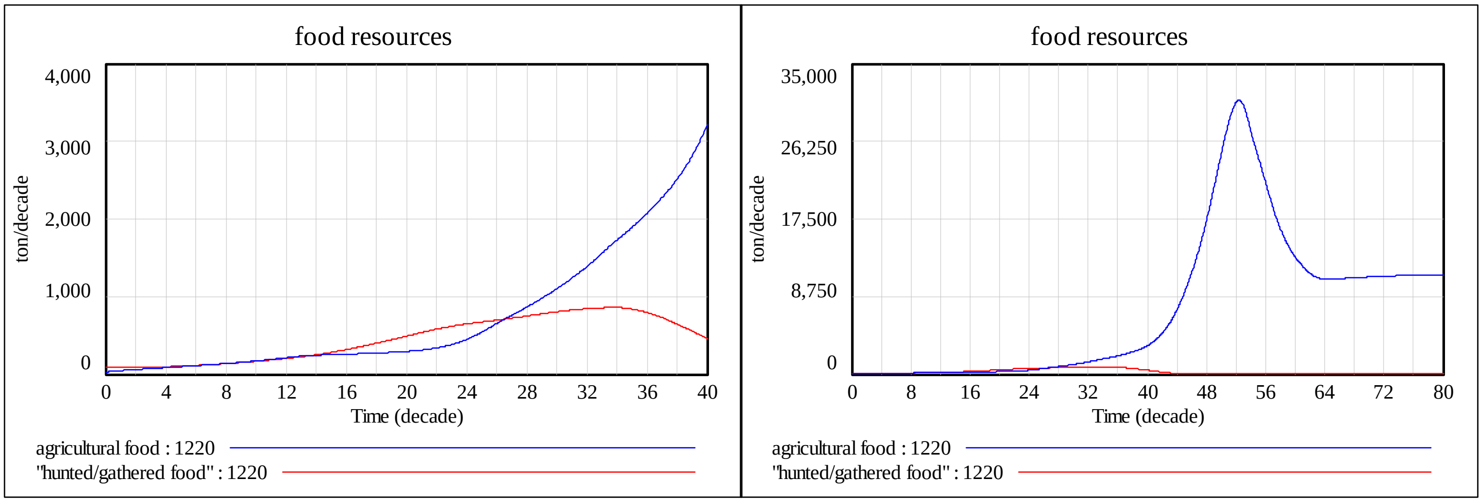


Figure 14:Base-run behavior of self sufficiency (food), food normalcy, shelter availability, shelter normalcy and net birth fraction

What drives the population up and down is that self sufficiency of food goes well over 1 and then goes below 1 very fast. This means that in a very short time interval a lot of food is produced and this encouraged people to have a lot of babies. However, after that came a crash in food sufficiency, so actually death rate took over the birth rate. Also, following the decline in the forest coverage shelter availability becomes almost non-existent. Both of these factors have driven net birth fraction up very fast and then down very fast. We see that the decline occurs very fast. The next step is to see what causes these fractions to show this behavior.

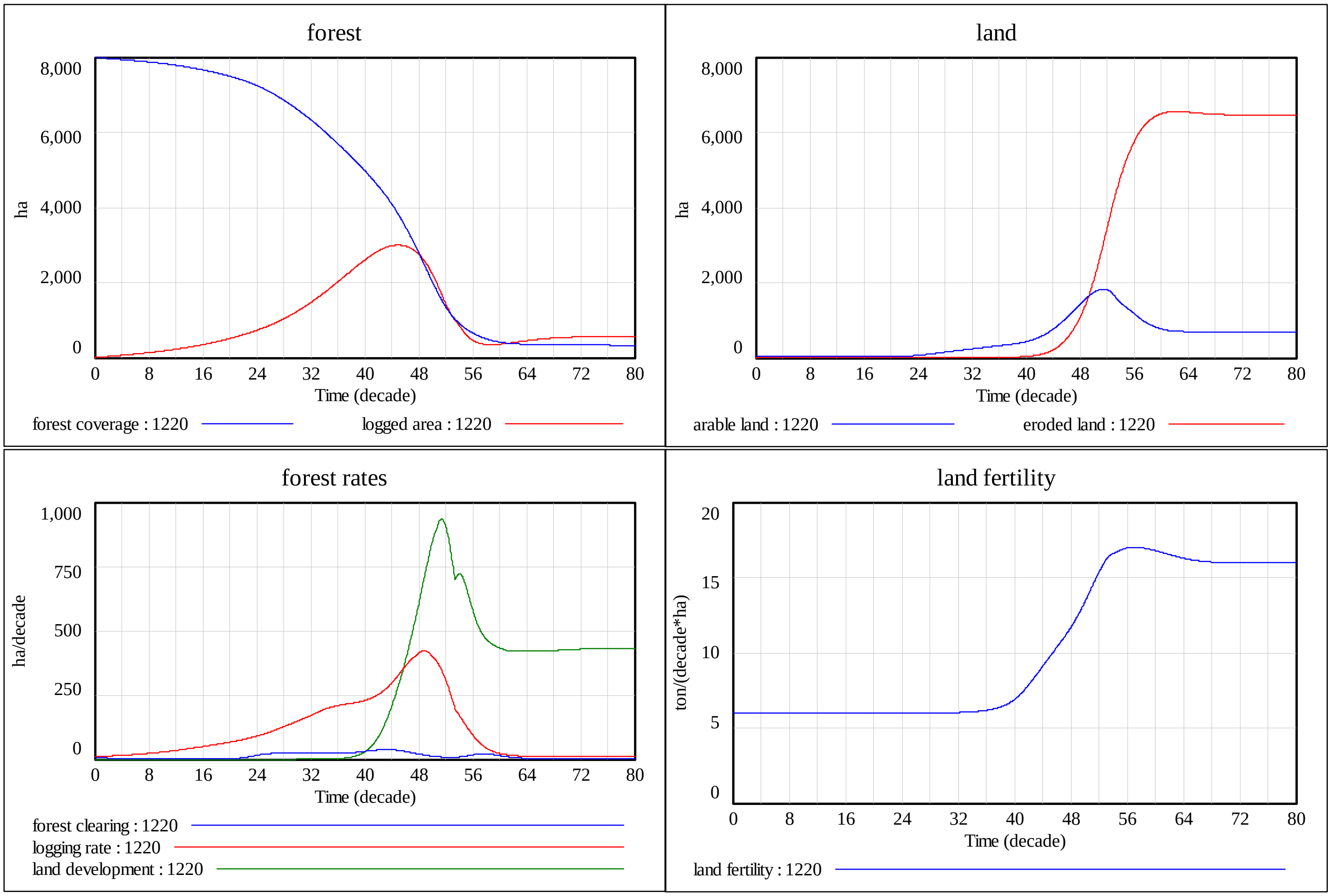


(a) *(b)*

Figure 15:Base-run behavior of food resources (a) is zoomed beteween t=0 and t=40

It can be seen from *Figure 15* that during the first two and a half centuries of the settlement, hunted/gathered food and agricultural food production were almost the same as each other. But as population grows and forest coverage declines, the food from the forest ceased to be sufficient. Therefore, society increases agricultural food production. The model behavior is very similar to the real case. First settlers consumed a lot of wild food such as big fish that can be caught by canoes made from wood; they ate palm nuts, etc. But about 300 hundred years after the settlement East Islanders started to be fed on agricultural products more and more with the inland plantations sites opened. Towards the end, East Islanders had to build enormous chicken houses to fulfill their diet (Diamond 2005).

Figure 16 shows the levels and the changes in different states of land. As seen, forest declined mostly as a result of logging rather than forest clearing. But after about 400 years (40 decades), land development sky rocketed. The reason is that at that time a lot of logged land has been generated which increased the productivity of land developers, the food normalcy was going below the subsistence level and forest coverage was declining rapidly. So, to be able to feed themselves Easter Islanders developed logged lands into arable lands.



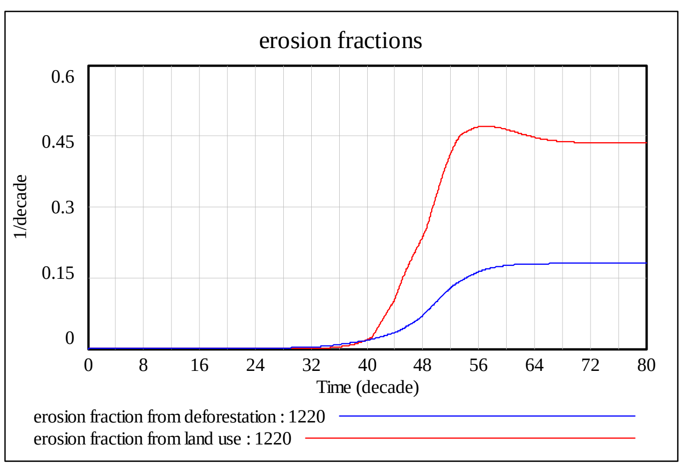


Figure 16:Base-run behavior of fores, logged ares, forest rates, arable, eroded land, land fertility and erosion fractions

We also see from *Figure 16* that at the same time land fertility has been increased by the land productivity improvers. As a result of the increased land fertility and decreased forest coverage, erosion has increased. So, arable land started to get eroded very fast, at a rate of 0.6 per decade, which means that the average life of a hectare of land is 16.7 years (1.67 decades).

Erosion is the main reason why the carrying capacity got so much diminished. This finding is in line with Diamond’s (2005) observations and claims.

As a next step let’s trace the behavior through the labor allocation (See *Figure 17*):

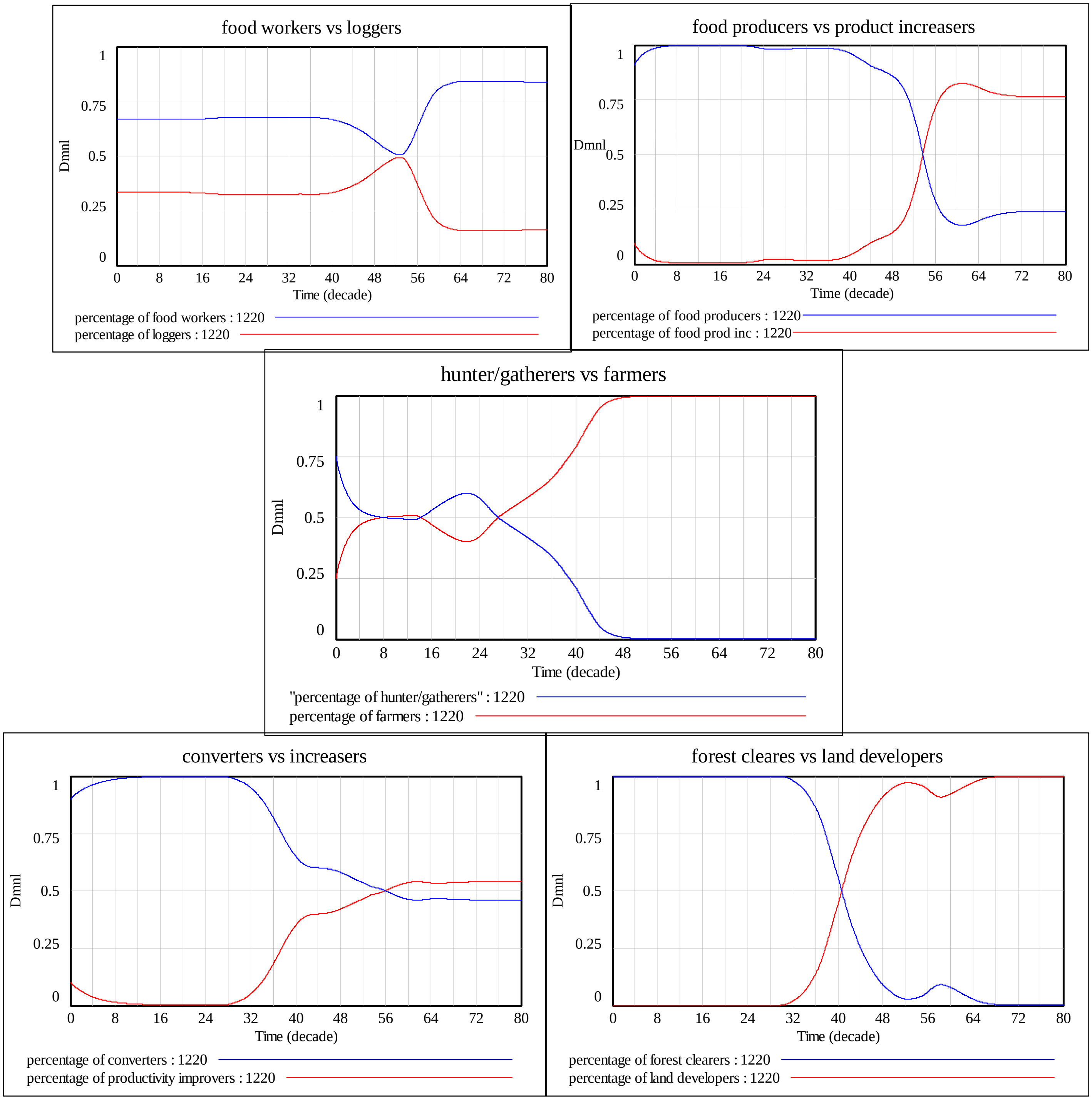


Figure 17:Behavior of labor

It can be seen that food workers and loggers stayed the same in proportion until forest coverage declined significantly. This reduced the productivity of each logger, so more loggers were assigned but after that logging became insignificant as per person logging went so low that they did not care to log any more and got used to not living with wood although it decreased their expected lifespan a bit.

Until the boundaries of production were hit by the farmers, the Easter Islanders were mainly producers and little effort to increase the capacity for agriculture was made. However, once the crises hit, they started to open up new lands very fast and increased the land fertility. This did not help them much in the end, as their land get eroded very fast as a reaction. Figure 15 shows that people became farmers in the end, giving up almost all wild food production.

The following output (See *Figure 18*) is from a test on the model where the erosion fraction normals for both erosion from land use and erosion from deforestation are both 0, i.e. there is no erosion possibility. Taken to this extreme we can understand if it is the main reason why the collapsing behavior occurs.

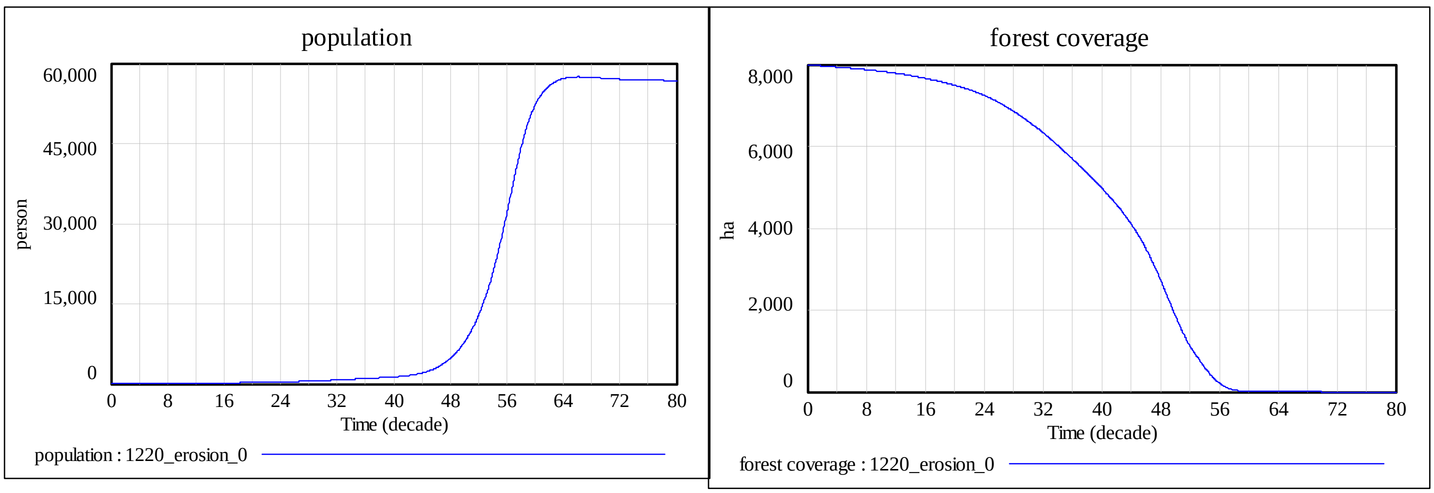


Figure 18:Behavior of population and forest coverage without erosion

We see that although the forest coverage went to zero, the population increased monotonically if we disregard the slight overshoot which can be caught by the attentive eye. Such a society would have substituted the forest goods with agricultural goods and luckily their land is very durable, so no matter how much they utilize it stays productive.

An interesting inquiry is to see if the behavior is repeated when the land use does not imply any erosion, i.e. when the erosion fraction normal from land use is 0. We see that the crash happens again but slower and with a higher population in the end (see *Figure 19*).

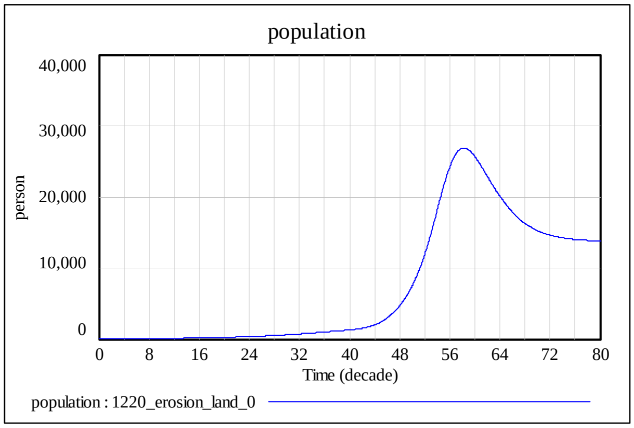


Figure 19: Behavior of population with zero erosion from land use..

Sensitivity Analyses

Land Conversion Productivities

Let us see if the behavior is sensitive to the productivity variables for converting land. It turns out that the dynamics of the population is not very sensitive to normal land development productivity= RANDOM_ UNIFORM(5,45); originally: 15; *Figure 20(a)*), somewhat sensitive to normal log prod= RANDOM_ UNIFORM(0.4,4); originally 1; *Figure 20(b)*) and not very sensitive to forest clearer prod normal RANDOM_ UNIFORM(2,15); originally: 5; *Figure 20(c)*) and forward convergent in this case. It seems that these productivity normals mostly affect the timing of the collapsing behavior.

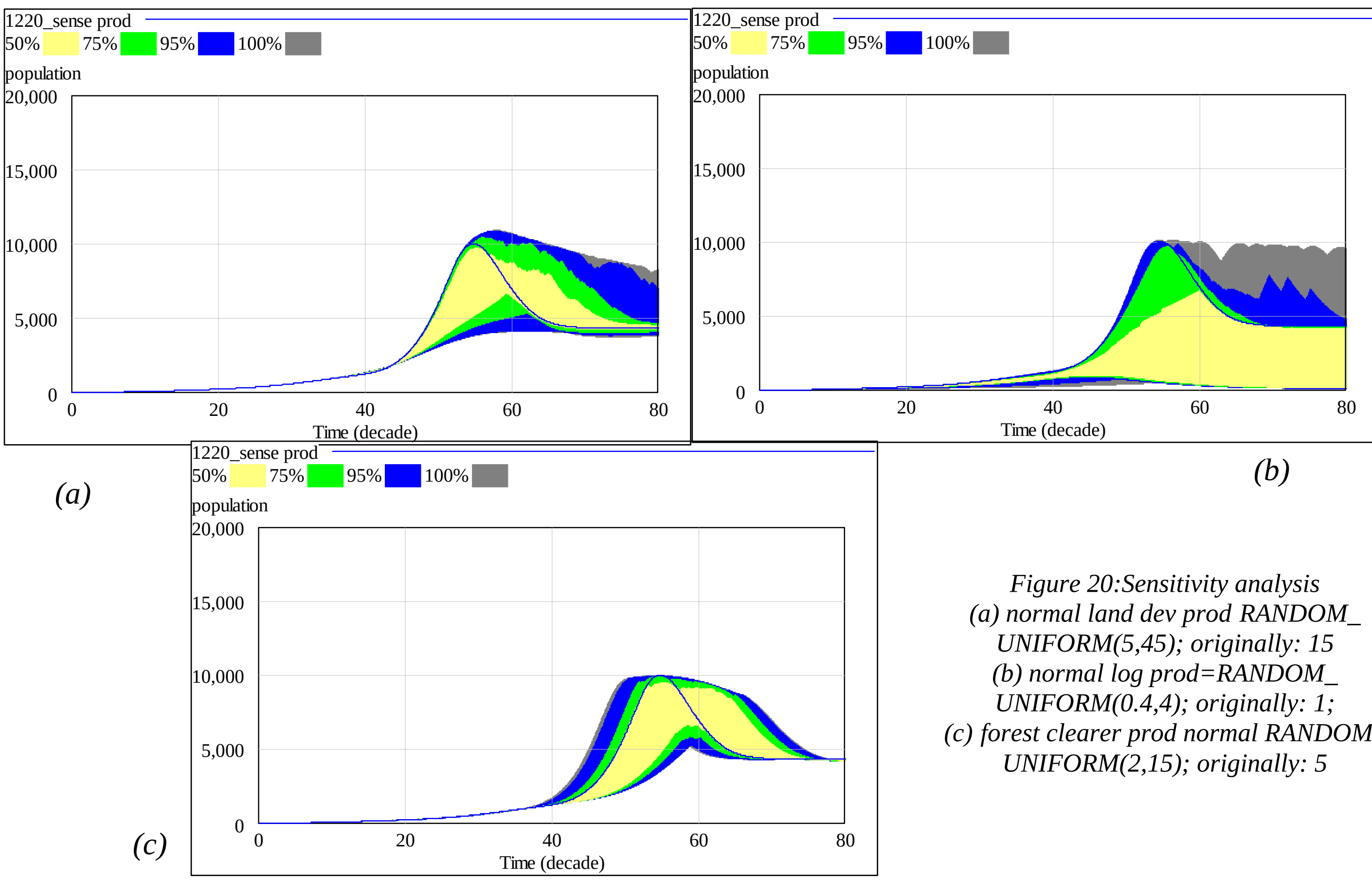


Figure 20:Sensitivity analysis
(a) normal land dev prod RANDOM_ UNIFORM(5,45); originally: 15
(b) normal log prod=RANDOM_ UNIFORM(0.4,4); originally: 1;
(c) forest clearer prod normal RANDOM_ UNIFORM(2,15); originally: 5

Forest Regeneration and Land Replenishment

As done with the hunter-gatherer society case, we need to see if the model is sensitive to the regeneration fraction. *Figure 21* is the output from forest regeneration fraction=RANDOM_ UNIFORM(0.01,0.5):

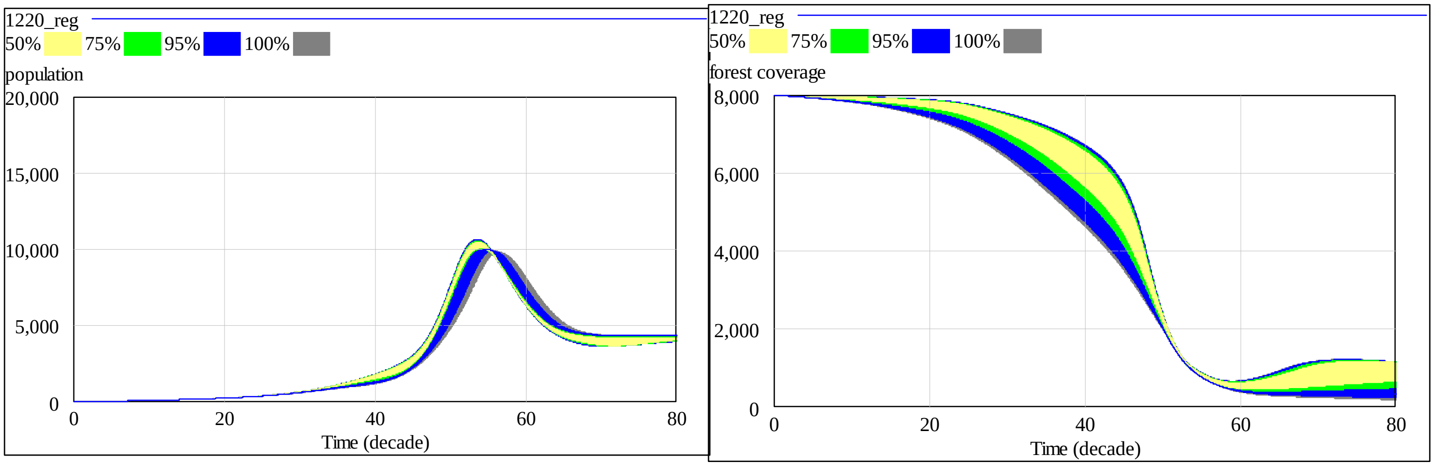


Figure 21:Sensitvity analysis,
forest regeneration fraction=RANDOM_ UNIFORM(0.01,0.5)

It can be seen that the model is very insensitive to the forest growth rate. The reason is that most of the land gets stuck as the land is eroded and forest cannot find a way to expand. So no matter how high the regeneration fraction is, once the soil is taken out of the logged area it is very hard for it to return back given that the land is fully utilized during a considerable amount of time, especially after the first few centuries. We can see that this is drastically different than the hunter-gatherer society case, whose every resource comes from the forest. Thus, an agricultural society in a limited space cannot rely on fast growing trees.

If only land replenishment time is changed (=RANDOM_UNIFORM=(5,45); originally:15), the output in *Figure 22* is obtained:

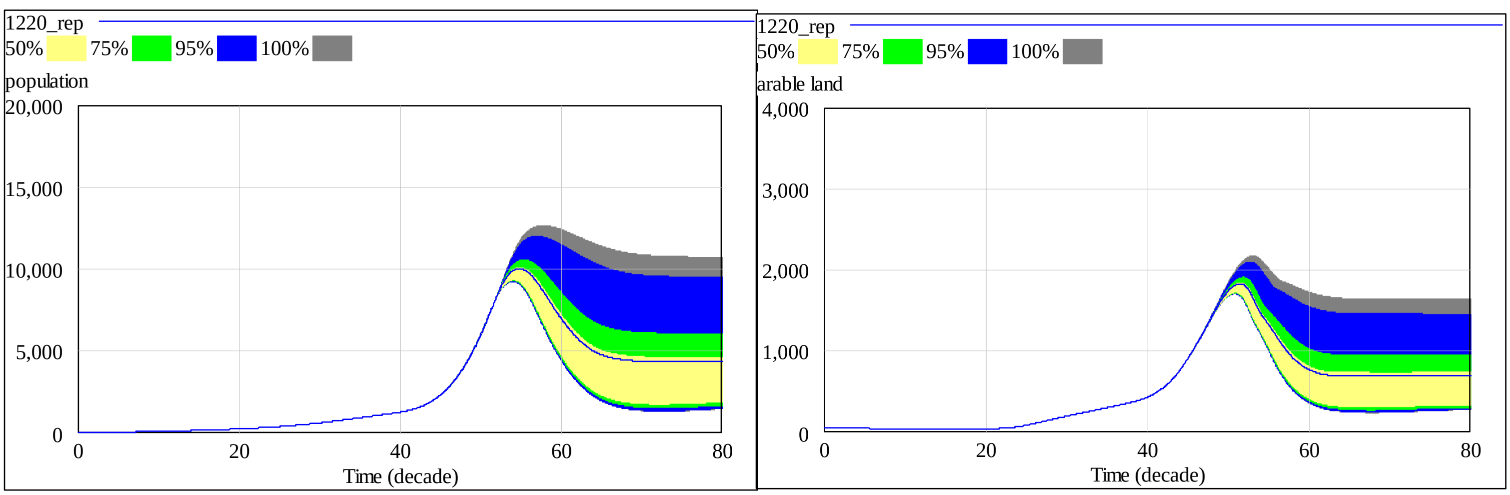


Figure 22:Sensitvity analysi
replenishment time is changed (=RANDOM_UNIFC

The amount of population left is somewhat sensitive to the replenishment rate but it is still not very likely to have a mild decline (see that for 75% of the time there will be a serious decline in population). The reason for the sensitivity is that in the end, the society ends up using more of their land at the same time, which means more carrying capacity in the end.

There is a broader implication of the discussion above for general modeling practices: differentiation between a forest and an agricultural sector is crucial while studying the dynamics of agricultural societies because the dynamics implied by both sectors and by their regeneration and replenishment rates differ considerably. However, the literature usually treated them as one as a second-order differential equation system is more elegant and easy to solve (Brander and Taylor, 1998; Anderies, 2000; Reveuny and Decker 2000). The problem is not an issue of validity unless the model purposes are set as really understanding what has been going on in the collapsing society rather than just creating awareness.

For example, Brander and Taylor (1998) discuss a lot about the slow growing palm of Easter Island with respect to other Polynesian Islands and they state that this makes the difference between a monotonically increasing society and a collapsing society. However, as this study shows, it is not really that much relevant once the forest does not have much place to grow.

Food Production

One of the variables which is hard to conceptualize in this model is cultivatable land per farmer. It is the amount of land that a farmer can cultivate producing the normal land fertility. The sensitivity analysis on the variable (RANDOM_UNIFORM=(0.5,4); originally: 2) shows that it is very effective on changing the timing of the collapse. However, it does not significantly change the maximum amount of the collapse or the character of the collapse in terms of its period (see *Figure 23*).

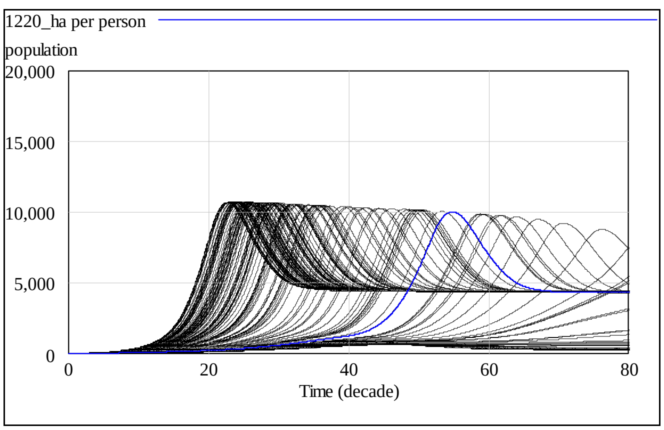


Figure 23:Sensitvity analysis, normal land fertility =RANDOM_UNIFORM=(0.5,4); originally:2

Another issue is the sensitivity to the hunter/gatherer productivity. In its current version, the number of hunter/gatherers stays very low for most of the model horizon. To test this, I changed two variables at the same time, productivity of food per hectare per decade =RANDOM_UNIFORM(0.5,6); originally:2 and normal productivity of hunter/gatherer =RANDOM_UNIFORM (1,10); originally:3. The model turned out to be very sensitive to these changes (see *Figure 24*). It seems that a better job should be done about the hunter/gatherer food formulation or the production function in general.

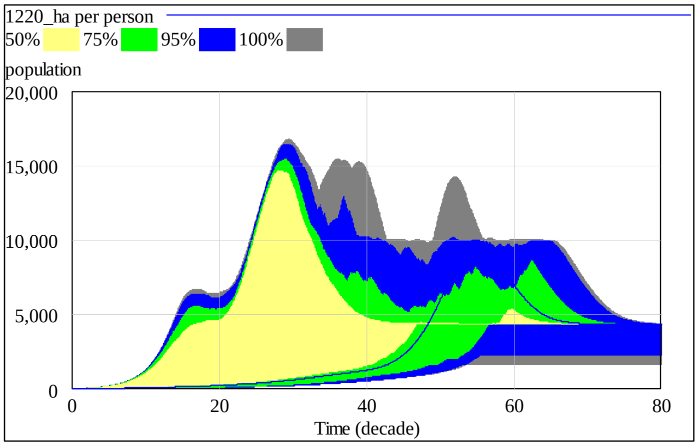


Figure 24:Sensitvity analysis,
productivity of food per hectare per decade =RANDOM_UNIFORM(0.5,6); originally:2
normal productivity of hunter/gatherer =RANDOM_UNIFORM (1,10); originally:3

Conclusions and Further Work

The story of Easter Island is one of collapse and this model tried to explain how this happened to be by assuming a culture which is more or less short-sighted and striving to be rational in resource extraction and food production allocation. Intuitively collapsing is something we would expect from a culture which does not learn.

The major conclusion from this portion of the study is the importance of distinguishing between the forest sector and the agricultural sector in such studies. The reason is that the dynamics are dramatically different from each other. One is just sensitive to a regeneration fraction parameter but if we disaggregate the resource sector, we find out that the aggregate regeneration fraction actually tells a weak story as we can do better in telling the story of societies and draw lessons from them if we can identify if forest regeneration or the soil regeneration make difference. This also causes harder but better and consistent stories which can be checked with archeological evidence.

As further work, the issue of conflict should be added into this model with the addition of building the statues. The story will be much better and complete that way and potentially more valid as the story might find a turn in that sector. Related to this consideration the fraction of workers should be made endogenous because the historical evidence shows that in the end the percentage of workers have actually increased with the chiefs being thrown down rather than sitting safely with the serfdom of the 40% of the whole population. The next step after improving the model with respect to the case of Easter Island, it should be tested using other islands which faced S-shaped growth like Tikopia mentioned by Diamond (2005) and Croix and Dottori (2008).

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