Understanding Evolutionary Societal Decision-making for Sustainable Social Systems Engineering Purposes

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Abstract. To engineer sustainable social systems for Earth's future, we need to understand how they change over time based on human decision-making. The problem of the rise and fall (or overshoot and collapse) of cultures has been studied in the social sciences for centuries, so it is a useful pattern for this purpose. To understand this behavior pattern from an operational, social systems engineering perspective, this paper reviews two of the main simulation modeling approaches to this problem and finds them to be limited (from an operational perspective) by a basis in non-human population dynamics that leads to a problematic dependence on initial conditions. We build upon this previous work, adapting it to include decision-making and show how these decision-making processes change the behavior over time. To demonstrate our process, we start with a recent model of Easter Island's collapse and add operational structures that allow human decision-making to enter the modeling structure. We show how the addition of operational decision-making structures provides a better fit to the anthropological data and how these structures were used to generate policy on the island of Tikopia. Finally, we argue that these decision-making structures are, themselves, engineered objects that can be improved through better understanding of their evolutionary nature.

Section 1: Introduction

One of the most important grand challenges of our time is the problem of overshoot and collapse. Human beings are overshooting their resource base in many areas (fisheries, forestry, etc.) and are further overshooting the sustainable level of atmospheric CO_2 with every passing year (see for example Meadows 2004). This paper deals with the problem of overshoot and collapse of human cultures from an operational perspective. "[T]hinking in terms of operations in social systems means to think in terms of actual decision-making processes continuously carried out by free actors. From this perspective, the performance of a social system is recognized as the result of human action" (Olaya 2015). Traditionally the problem of overshoot and collapse of human cultures has been modeled from either an economic or ecological perspective that does not include human decision-making in its conceptualization of system structure, and this makes the traditional understanding less useful for social system engineering purposes, which requires better understanding of the inherent uncertainties in the design and maintenance of social systems, including the efficiency of their decision-making processes (Bulleit 2018).

We respect the purposes behind these traditional modeling choices and understand that their theoretical purposes add enormous value to the knowledge base (see below for discussion). We seek to build upon this work. We hypothesize that the dynamics of societal overshoot and collapse are caused by many factors previously studied. We add the hypothesis: all collapse stories involve decision-making processes that can be engineered for increased efficiency. We agree with Martin Schaffernicht that policy solutions arise at the nexus of evolution and engineering. We're interested in how those decision making processes naturally evolve and use this understanding to generate better designed processes (Schaffernicht 2018).

Hence, in this paper, we build upon the work done in traditional approaches to modeling collapse. We discuss the limitations of these traditional approaches for modeling dynamic, operational human systems. We also share a model that adds the decision-making processes necessary for understanding how collapse dynamics function operationally. Our model is based on a traditional ecological-economic model of the overshoot and collapse of culture on Easter Island (Roman et al. 2017). We built our operational model upon this traditional Easter Island basis for two reasons. First, we hope to show how this traditional approach can be made operational and, thus, include human decision-making. Second, Easter Island is a Polynesian island, and so it is part of a larger set of islands that share an array of ecological-economic parameters. These shared parameters will allow us to test how decisions made a difference in many similar cases, since many of the other islands in that set have managed to avoid collapse. To test this multiple case approach, our model is based on the Easter Island model; however, we have changed some of the parameters so that they represent a different island, Tikopia, where the evolution of human decision rules led to a sustainable outcome.

Section 2: Problem Identification

The problem of overshoot and collapse is both a classic systems archetype (see for example Sterman 2000, pp.123-127; Senge 1994, p. 125), and a classic problem in the social sciences as it relates to the collapse of human societies (see for examples Tainter 1988; Diamond 2004). Most importantly, overshoot and collapse is the driving structure behind our current socio-ecological grand challenge of climate change, which is one of its symptoms (Heinberg 2017). Within the last fifty years, since the publication of *The Limits to Growth* (Meadows, et. al. 2004), the problem has entered the public policy sphere with questions of how the limits of resources (for example oil) and limits of other less tangible resources (for example, the natural sinks that absorb carbon dioxide and pollutants) might lead to societal collapse in the future. Now as never before, there is a need for policy solutions for these kinds of problems, and this paper is a step in that direction. Our goal is to explore some of the modeling tradition that has sought to understand these collapse dynamics and to begin to tease out policy solutions from these explanatory models by adding operational structure.

The problem of cultural collapse has a "structural cause" and a "structural effect" reference mode, and both of these reference modes have desired and feared outcomes for engineering purposes (for example in terms of the United Nations Sustainable Development Goals). The structural cause of the problem is population growth. As populations grow, they tend to desire more growth because growth itself generates benefits for cultures in terms of their ability to self-organize and to assure more growth (Turner 2003; Chase-Dunn 2016). The structural effect of this process is that as populations grow they extract food and non-food resources. This extraction reduces the stock of each resource and causes damage to the resource renewal rate, so the resource itself eventually becomes depleted or exhausted (Chase-Dunn 2016, Meadows 2004, Diamond 2004). For engineering purposes, this leaves cultures with a problem to solve, and societal collapse stories most often have some variation of this core archetype at their heart (Diamond 2004; Acemoglu 2012). We will point out the solutions of the Tikopia islanders to this set of problems in a later section.

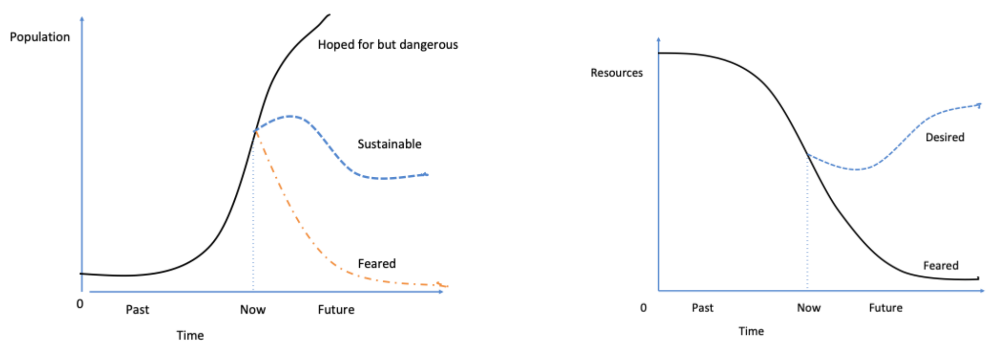

Figure 1. Reference mode drawings of structural cause and effect variables.

Jared Diamond (2004) and Joseph Tainter (1988), together, provide over thirty historical case studies of cultural collapse developed along these lines. They just touch the surface of this problem that may well be the biggest challenge we face today, as our current world-wide resources (water, topsoil, oil, etc.) and environmental sinks become over-exploited (see Meadows 2004).

Section 3: Hypothesis

The problem of cultural collapse appears not to be the deterministic result of population growth and resource extraction that can be implied by traditional ecological and economic models of this problem, since they can be highly dependent on initial conditions (see Roman et al. 2017 for review of the modeling literature). Instead, we accept the hypothesis that it is an operational problem of strategic decision-making in the service of goals assessed relative to risk that leads to socio-environmental system change through engineered processes (Diamond 2004; Acemoglu and Robinson 2012). Cultures do not deterministically rise and fall based solely on initial conditions. Instead, they make decisions based on adaptive assessments of socio-environmental conditions, and these decisions create the evolving conditions of their cultural success or failure (Chase-Dunn 2016; Acemoglu 2012). This kind of decision-making is a traditional problem in business dynamics (as modeled for example in Warren, 2008; Sterman, 2000) and social systems engineering (Garcia-Diás et. al. 2018). Given the importance of determinism in the ongoing debates about societal collapse and resilience (see for example, O'Sullivan 2008), it seems important to develop a means by which to foreground decision-making in our modeling processes. In this paper, we present a conceptual simulation model that builds upon the traditional modeling approach by adding a set of additional variables that allow for decision making to occur relative to a perceived risk. This model is used to develop a generic framework that we can then extend to a cross-cultural, comparative case study in future work.

Given the short scope of this paper, we limit our discussion to two reference models. These provide evidence of the two, somewhat divergent, modeling schools of thought on this issue (Motesharrei et. al. 2014; Roman et al. et. al. 2017). This step is necessary to understand the traditional approach to this very complex problem and also to determine whether or not a social systems engineering decision-making perspective might be useful. Although each traditional school of thought comes to the problem from different positions, they are not concerned with decision-making processes, since they are working on different elements of the collapse problem. This makes it difficult to use their models to develop a holistic understanding of their system design (Schwaninger and Klocker 2018). Also, their basis in predator-prey modeling traditions (as discussed below) leads to a deterministically problematic dependence on initial conditions that is quite useful when modeling non-human animals, but that becomes problematic when looking at operational decision-making systems. Given the importance of determinism in discussions of historical models of collapse (see, for example, O'Sullivan 2008), we go into this issue in some depth.

Section 3: Background on traditional modeling approaches

Roman et al., in their extensive review of the literature on these traditional models categorize the first school of thought as "economic type models" that represent people as utility maximizing, rational agents (2017). The classic example of this type is a paper by Brander and Taylor (1998) that uses this economic thinking along with a predator-prey structure to model the dynamics of the relationship between population and resources on Easter Island. Roman et al. defines this school of modeling as follows:

> "By appealing to neo-classical utility maximisation arguments, along with a set of functional forms widely used in ecology (e.g., logistic growth) Brander and Taylor (1998) arrive at a set of predator-prey type equations used to describe the evolution of the human population and renewable resources on Easter Island. Following this work a stream of papers appeared that adopted the methodology of Brander and Taylor (1998), expanded on it or applied it to other cases. We can broadly categorise these models as 'economic type models', meaning that they represent people as utility maximising, rational agents" (Roman et al. 2017, p.

265).

The mathematical model in Motesharrei et. al. (2014) provides an example of this approach. This model has four stocks (Commoners and Elites, Nature and Wealth). You can see the behavior generated by the interactions between these stocks over time through the graph in Figure 2. The commoners prey on nature and generate wealth, some of which they consume. The elites then prey on the commoners, in a traditional trophic relationship, by feeding off the wealth the commoners alone generate. This is the Motesharrei formulation for an equitable society. Everyone consumes nature, and surplus wealth is gained that allows the society to ignore the damage done to the environment until it is too late. Nature is depleted, and wealth allows the humans to continue to live for a while after nature has been almost entirely destroyed. Collapse of culture occurs, and, hundreds of years later, nature comes back to life with no humans left to worry about. Note the predator-prey basis for this model, which we will discuss in a later section.

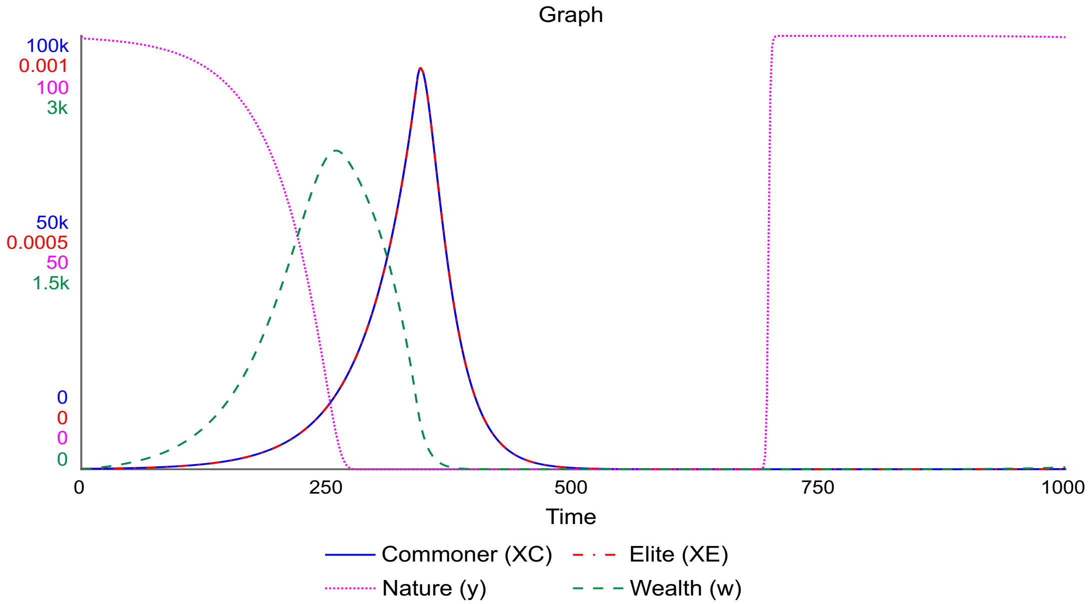

Figure 2. Graph of collapse dynamics according to Motesharrei.

The second class of collapse models is “ecologically inspired models.” Roman et al. define it as follows:

> “There is a second class of models that aim to capture societal development that we label ‘ecologically inspired models’. In this case the choice of dynamical system is made heuristically to capture the observed real-world dynamics of the society, while respecting modelling principles of population biology (Turchin, 2003), but rationality of individuals is not enforced. An early model following this approach was developed by Anderies (1998) to capture the social dynamics of the Tsembaga of New Guinea. The wider diversity of assumptions that underlie the ecological style of modelling means that the endeavour tends to lack the

> conceptual unity of economic models. The theoretical appeal of the more unified economic framework is understandable, with modelling efforts that were initially ecological in style (Anderies, 1998; Janssen et al., 2003), soon joining the economic camp (Anderies, 2000; Janssen and Scheffer, 2004)" (Roman et al. et al. 2017, p. 265).

The underlying difference between the two traditions is in their theoretical modeling framework. As Roman et al. phrases it:

> "The economic type models use a narrower set of assumptions, typically including utility maximisation as a driver of human behaviour along with a decision on the global institutional policy. The ecologically flavoured models are less restrictive in their theoretical underpinnings, more attentive to characteristic features of the society and try to account for emergent social phenomena that can contrast with or even contradict economic rationality, e.g. sunk-cost effects (Janssen et al., 2003) or war rituals (Anderies, 1998)" (Roman et al. 2017, p. 265).

Figure 3 contains a stock and flow formulation of the Roman et al. model, which represents the second school of thought (for mathematical documentation, see Roman et al. 2017).

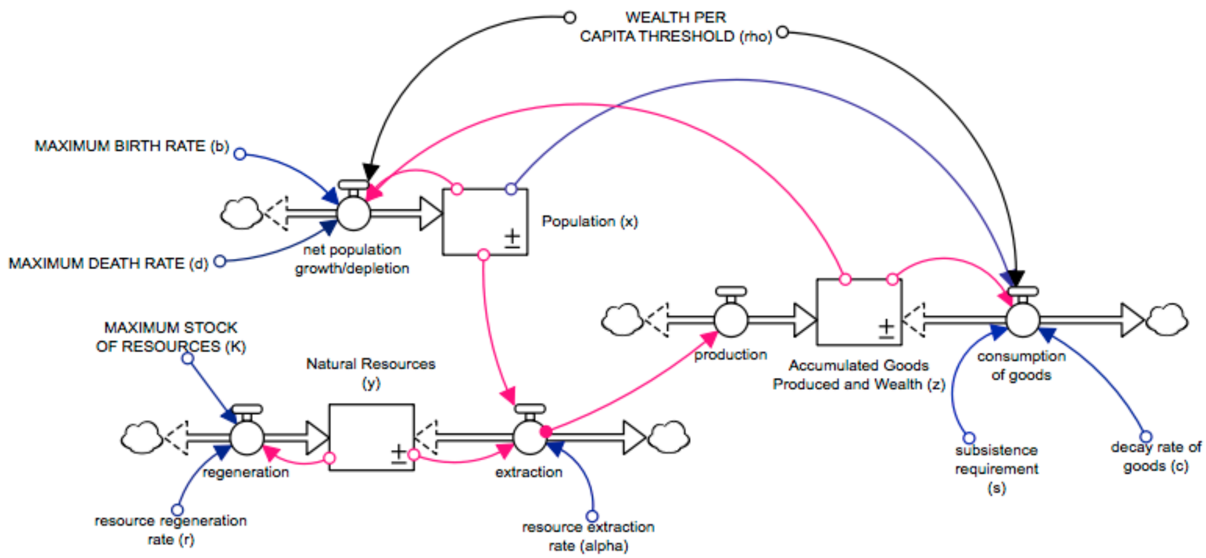

Figure 3. Stock and Flow diagram from Stella rendition of Roman et al. et al. 2017

As in the Motesharrei model, population feeds off of natural resources to generate wealth. This wealth then brings death rate down as wealth increases, thus making the society's road to growth simpler. Carrying capacity does enter the story through the formulation for regeneration (discussed below), and the overall outcome is as seen in Figure 4.

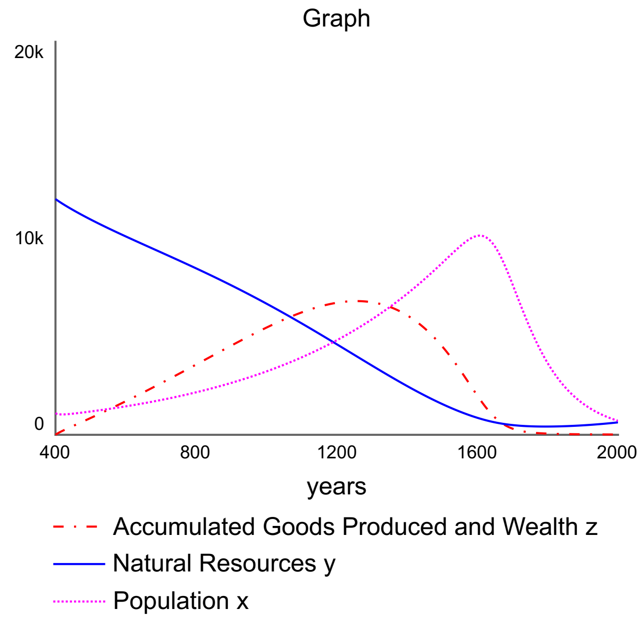

Figure 4. Outcomes of base run of Roman et al. et al. 2017.

All models abstract information from the world to create structures useful to solve particular problems. Neither of the modeling traditions we've discussed embeds decision-making processes in their system structure because those were not the structures of interest to the modelers. Thus they provide excellent representations of historical information with no capacity to see the unfolding decision rules that governed the behavioral dynamics. In other words, there is no dynamic agency in the modeling structure (Olaya 2015). Consequently, these models can potentially be read as stories of deterministic processes instead of documentation of the complexity of consciously self-organizing human-ecological relationships. Second, these two modeling traditions do not embed sociological evolution in their system structure. The evolution of societal structures is central to understanding of collapse processes and cultural development in general (Turner 2003; Chase-Dunn 2016, Schaffernicht 2018), and this makes the predator-prey basis of both modeling traditions problematic for engineered human systems, since social evolution is not part of that dynamic pattern. Thus, we see an opportunity to build upon these legacy models and develop modeling structures that embed human agency. However, before we get to that new work, we will explore in some detail the problem of the underlying predator-metaphor that we solve in our conceptual model.

Section 4: Analysis

Section 4A: Predator prey models and carrying capacity. Predator prey modeling is based on the concept of carrying capacity and the way a population of predators relates to a population of prey in a limited environment, producing a typical pattern of oscillatory behavior. For example, see Figure 5.

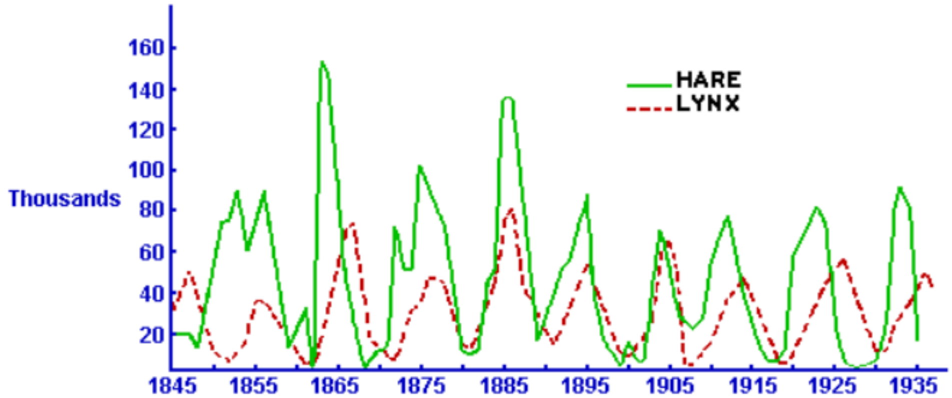

Figure 5. Traditional Predator Prey Oscillations. Adapted from Odum, Fundamentals of Ecology, Saunders, 1953)
https://services.math.duke.edu/education/webfeats/Word2HTML/Predator.html

Here we see the pattern of a lynx population and a hare population oscillating through predatory cycles. Note that both populations go through these oscillatory patterns, potentially forever, within clearly defined ecological limits.

This pattern is unlike human ecological interactions for two main reasons. First, when human societies overshoot a prey population, instead of producing oscillations, they often produce an extinction event (Braje et al. 2013). In the predator-prey model shown in Figure 5, oscillations occur at regular intervals as predators consume prey, and this consumption reduces the number of prey that reproduce. As the prey numbers fall, the predators have less to eat, so their numbers fall as well, and this reduction in predation allows the prey population to rise again. As the prey population rises again, the predator population rebounds and the next oscillation cycle commences. One could include a third stock to represent the plant matter the prey feed upon, and there would be another oscillation in the model. This could continue, all environmental circumstances being equal, forever. This oscillatory structure is the heart of predator-prey dynamics. In systems that include humans as predator, the situation is radically different because humans are unique predators in that they have a much wider resource consumption capacity than a typical predator. They consume many varieties of food (allowing them to easily shift between varieties of prey), and they use resources for many things other than food. Because of this unique resource consumption capacity, predator-prey models are inappropriate for understanding human-ecosystem interactions. For example, when humans migrated into Polynesia, they encountered mega-fauna, and they hunted most of them to extinction, shifting to smaller prey as the mega-fauna died out (see Kirch 2017). No oscillations occurred in this human predator prey story because the humans were able to eat their prey to the death of the species without an increase in the human death rate due to lack of prey. The human ability to shift resource needs to another species when the prey went locally extinct allowed the human population to continue rise while the prey population went to zero.

Second, the essential concept of carrying capacity is different for human cultures than it is for typical animal relationships to an ecological niche (Kirch 2017). In predator prey dynamics, carrying capacity is a limit defined as the number of organisms that an ecosystem can sustainably support (https://biologydictionary.net/carrying-capacity/). For example, the amount of forage in a location determines the number of potential hares in the "lynx and hare model" shown in Figure 5. The oscillations occur because the lynx consistently eat hare, and this consumption pushes their population upward, forcing it to hit a carrying capacity limit defined as the number of hare necessary to maintain the current population of lynx. Once this limit is passed, the lynx numbers fall, the hare numbers rebound, and the system oscillates around these limits.

In a human/ecosystem structure, carrying capacity is, instead, a shifting social systems engineering goal that involves human decision-making processes, such as those described in Schaffernicht (2018) or as described in Raymond Firth's many books on Tikopia (see for example 2004). Because of this, when a human society overshoots carrying capacity, it doesn't do so primarily because the limit has been passed, as would be the case in a typical predator/prey model. Instead, it fails in this case because the shifting carrying capacity goal has been mismanaged (for a full discussion of this management process, see Kirch 1994). We explore this concept in detail later. In brief, humans have evolved to move through ecosystem limits by deciding to engineer cultural technologies that allow populations to endure hardship and change ecological limits (Turner 2003). For example, when a Polynesian group settled a new island, many animal extinctions occurred, starting with megafauna. Unlike a predator facing the loss of its unique prey, a human population can make decisions that allow it to change its hunting capacity, so it can endure a much wider array of crises in a local area before simply migrating to the next, eventually to every niche on the planet. Human populations also have the capacity to change the state of their environmental limits by making changes to the environment itself (see for example Kirch 1989 and 1994).

Section 4B: Population growth and evolutionary self-organization of institutions.
For better or worse, human societies always consciously self-organize (Turner 2003; Chase-Dunn 2016), and a model that runs without the possibility for change of this type, through operational innovation, deflates the structures of human agency that are an underlying principle of societal dynamics over time (Olaya 2015).

The easiest way to explore these potential insights is through a tour of the system structure of the Roman et al. et al. model we've been discussing (2017). We'll start by thinking about institutional evolution and its importance in the story of Easter Island. It is important to note that the Roman et al. model sets parameter values for Easter Island that duplicate the historical behavior over time quite well. Their model was created with a very different purpose from duplication of sociological structures or historical exploration of human strategic management decisions, but it serves as an excellent reference model upon which to build operational structures.

In Figures 3 and 4 we see a simplification of Roman et al.'s model via a stock flow diagram and base run. A population extracts resources. Extraction of resources leads to the production of wealth. The production of wealth then generates an effect on deaths that allows the population to grow at a maximum rate as wealth increases and to drop to a minimum rate as wealth declines. The natural resources stock recovers at a logistical rate (r) to a maximum capacity (K). The behavior generated from this model, as seen in Figure 4 accurately reflects the unfortunate story of Easter Island.

The most important point to keep in mind in viewing this graph is that as population rises it does so against a fixed stock of available land. Hence, as the population rises, so does population density, and this increasing density creates an increasing pressure for transformation in social institutions (Kirch 1989 and 2017; Turner 2003). In brief, the more people per kilometer squared, the more competition and the more efficient the processes of extraction can become. These are vital pressures that can generate extremely complex cultural adaptation in the short term. And, the increasing social complexity increases a society's capacity to manage (and mismanage) the environment (Kirch 1989 and 2017). Without inclusion these kinds of structures, it is possible to see this process as a non-operational means of wealth extraction, as though the wealth is extracted by non-thinking animals, and this leads to a deterministic result, much like the story of the lynx and hare..

If we run the Roman et al. model for a longer period (Figure 6), we get the following results:

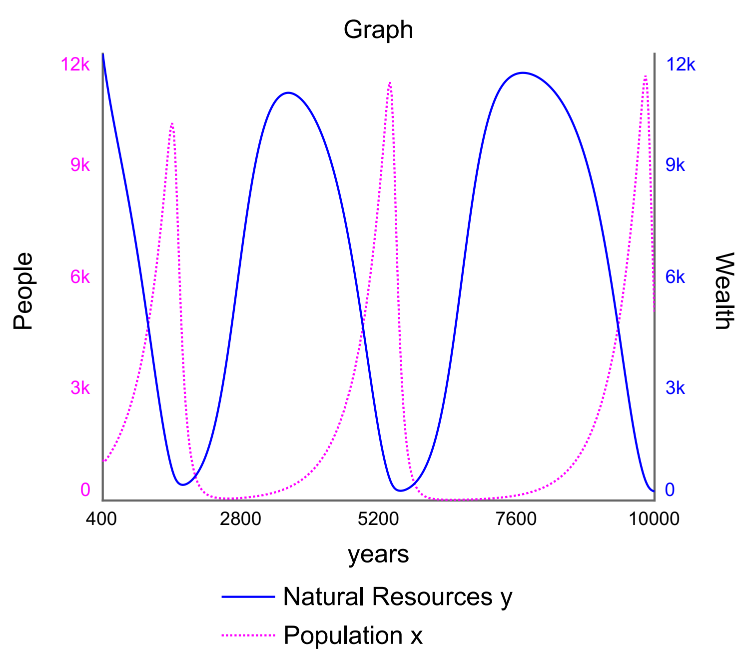

Figure 6. Roman et al. et al set to a longer time scale

These predictable, predator-prey oscillations (see Figure 5) do not typically exist in a human-ecosystem relationship. For example, the population of Easter Island collapsed, and when the population began to grow again, the curve was radically different in the second cycle than in the first (Kirch 2017). After a society's collapse, new social institutions develop from a new set of initial conditions radically different from traditional predation oscillations because of the human capacity for self-organization (Turner 2003). Each post-collapse population would be so different from the others as to develop an entirely different shape for each waveform; and, essentially, the pattern would vary from cycle to cycle and potentially cease to exist based on as yet to be determined decision rules because the initial conditions from wave to wave within the oscillation would never be fixed enough to create the structure we see here. The reality on Easter Island is that the original collapse led to a loss of cultural complexity that never returned. There was nothing like the oscillatory behavior we see in Figure 6, since initial conditions (due to human decision making) changed the nature of the growth cycle (Kirch 2017).

Further, while it seems that carrying capacity should be generalizable throughout these experiments, it turns out not to be so, again because of human decision rules and variable social systems engineering. It is understood in the literature that human populations in Polynesia generally follow an *r* to K transition in which an initial high intrinsic growth rate (symbolized by *r*) gradually declines as a population approaches carrying capacity (symbolized by K) (Kirch 2017). However, the carrying capacity itself can be adjusted by technology or reconceptualization of social system design. For example, Tikopians replaced pig husbandry on the island of Tikopia with a less biota destructive means of food production, the planting of extensive orchards (Kirch 1989). As Kirch puts it,

> "In highlighting an *r* to K population cycle as a big process of Oceanic history, I nevertheless emphatically reject a simple demographic determinism, or a unicausal explanation for the transformation of Oceanic Societies. Population growth can never be a *sufficient* prime mover to explain cultural change; what it offers is a *necessary* condition without which other kinds of social, technological, ideological, or political changes are unlikely to occur" (Kirch 2017, p. 276).

Rather than having their populations deterministically rise and fall as a result of starvation in the face of carrying capacity, as one sees in predator-prey systems, human systems (as exemplified by our Polynesian cases) have self-organized and developed emergent, operational management structures that either helped them or hindered them in their quest for survival (Kirch 1989). Some developed powerful hierarchies, some developed simpler structures, but most developed methods of population self-governance. By their own decisions they kept the necessary balance between populations of humans and the natural resources upon which they depended (Kirch 1989, p. 118), thus putting the human population itself into an accumulating stock that was successfully quantified for strategic management by the cultures themselves.

Section 5: Methodology

To build on the traditional schools of collapse modeling, we have developed a conceptual, operational model based on Roman et al. (2017) that includes some of the variables needed for human decision-making processes in the model structure. We have chosen to model the Tikopia decision-making processes rather than those of Easter Island because the ethnographic literature gives us a much clearer picture of decision-making in that system (Kirch 1984, 1997, 2017). Using the Easter Island base-model allows us to start developing a comparative case study approach to these problems. Polynesian islands have useful similarities for this purpose (Oliver 1989).

Figure 7 reproduces the structure of our model. This model has been calibrated to fit many of the parameters of the island of Tikopia (discussed individually below). Other parameters will be added during the next steps.

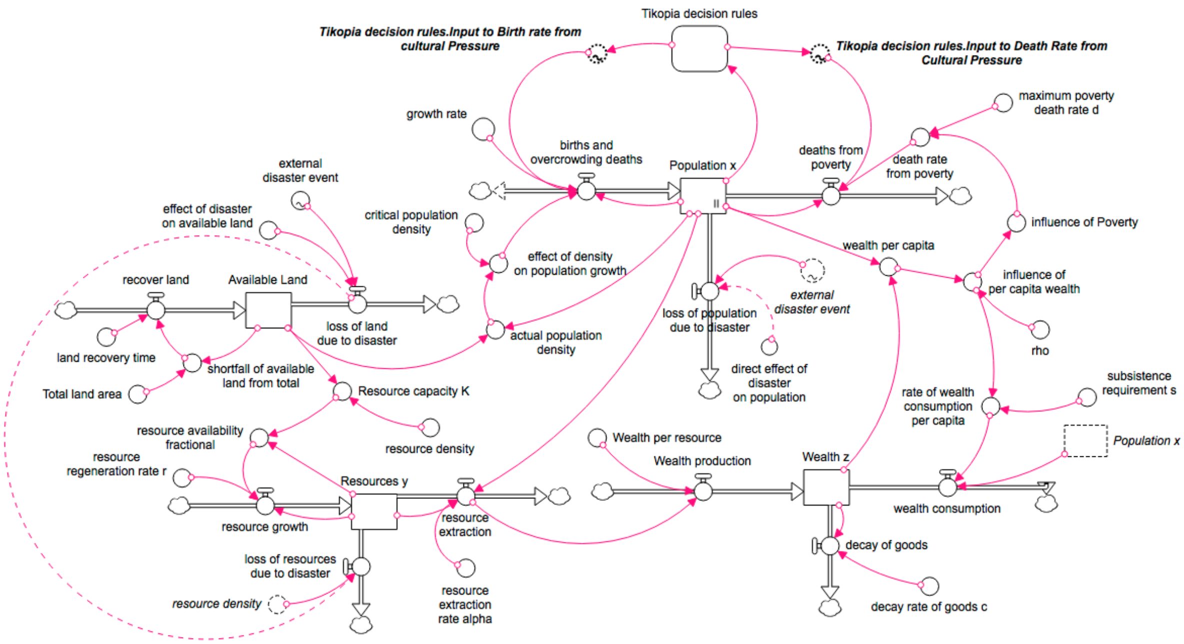

Figure 7. Conceptual model of Tikopia decision-making processes

Ultimately the key variable that puts the human/environment story outside the predator-prey and ecological modeling continuum is a stock of perceived information that allows human agency to enter the model via decision rules that lead to the creation of social systems engineered artifacts. We have modeled the underlying conditions necessary for that perceptual process to occur (as discussed below). We hope to build a more detailed model of the historical perceptual development itself through work with Polynesia experts in our next steps.

Schaffernicht explains this perceptual process in detail, so we will quote him at length:

> "As humans, we interact with others. Interaction constitutes an enactive system in the sense of Varela (1995, p. 30): 'perception consists of perceptually guided action'. *Perceiving* is an internal activity of the individual, modulated by sensorial stimuli, and that which is perceived drives *decisions*, which drive *actions* on the environment, which then lead to new *perceptions*. Since our environment is made up by other, similar individuals, each actor is interconnected with others in a

> ‘creative circle’ (Varela, 1984), where one’s *actions* trigger the other’s *perceptions*…Our minds also contain individual *policies*, and these are driven by *belief* systems, which we can recognize…However, no person lives alone…Therefore there need to be *collective* policies—more or less internalized by the individuals—to bring orderly patterns into the interactions between individuals” (Schaffernicht 2018, pp. 70-71).

The above perception-to-policy process leads to the creation of social systems artifacts. Addition of these fundamental elements of social change to collapse models would allow the collapse modeling tradition to include operational thinking as discussed in Olaya (2015), and, thus, it would make that whole tradition useful for better understanding the wide variety of means by which humans have faced these challenges throughout history.

The first of new structures necessary for operational purposes is at the top of our stock and flow diagram and contains a stock called Available Land (Figure 8).

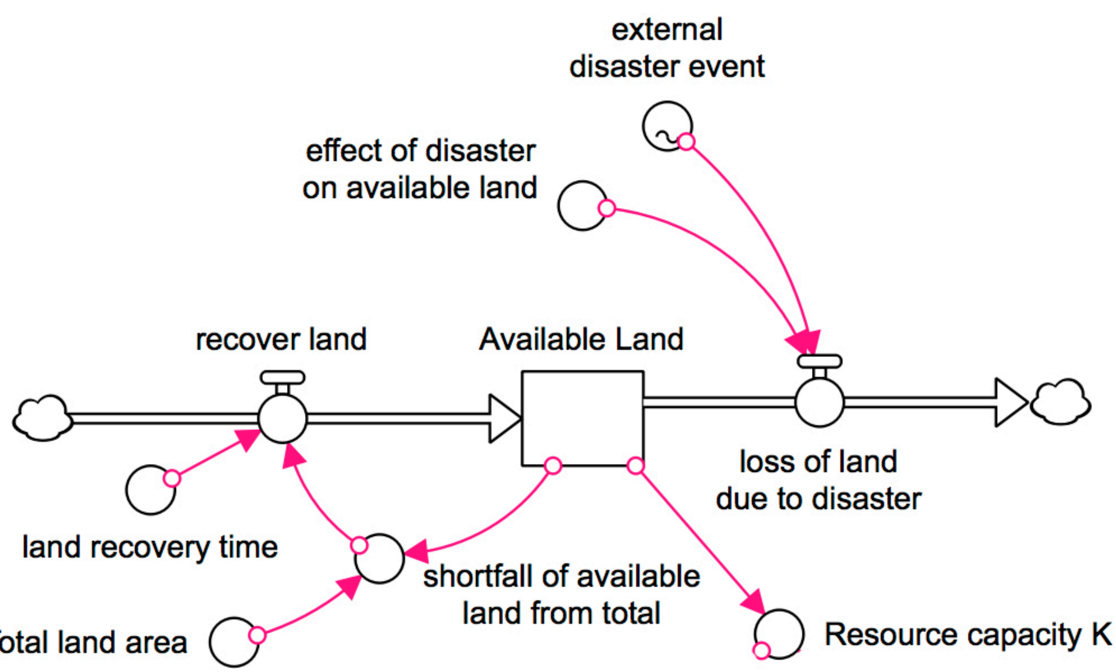

Figure 8. Stock and flow structure of land available for orchards on Tikopia

It is clear from the literature that the people of Tikopia came to perceive this variable and used this information in the evolution of decision rules (Kirch 1984, p117). We have modeled this as a stock defined by a shortfall from a Total land area (5 square kilometers) that yields land productive for orchards.

Tikopians compared this quantity of available land to a population density variable that we have modeled as shown in Figure 9.

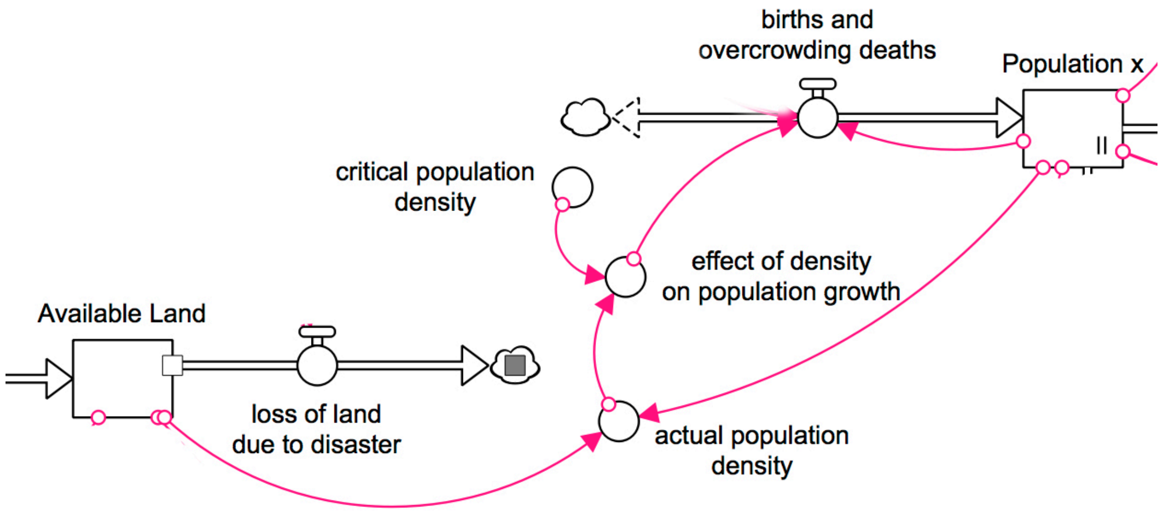

Figure 9. Population density conceptual structure

By making this comparisons between the land available for cultivation and the population density, Tikopians constructed decision rules such that "…not only is there a tendency for families to be regulated in size according to the quantity of their orchards and other ground, but there is a conception of a total population for which food has to be provided" (Firth 1939, 39). This set of concepts is embedded in Tikopian lore under the concept *fakatau ki te kai*, "measure according to the food" (Firth 1939, 43).

Our hypothesis is that these concepts arise out of an information flow into this system through the effect of disaster (for example in the form of hurricanes) on available land, modeled as shown at the top of Figure 8. Figure 10 shows the likely structure of the effect of disaster as perceived with repetition over time.

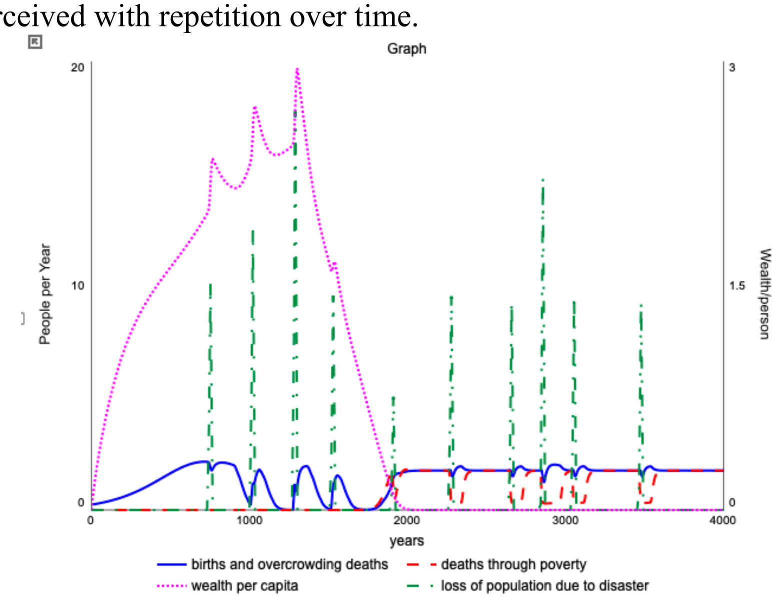

Figure 10. Generic effects of disaster as probably perceived by Tikopians

With each hurricane, the population would suffer a culturally perceived spike in deaths and a loss of wealth through loss of productive land. Births would slowly increase, but, until the land became fully workable again, deaths from poverty would climb. Only as wealth began to grow again would the population begin to recover. Hurricanes are a frequent occurrence on Tikopia, so the above structure of devastation was a recurrent factor whose effects were embedded in the learning structures and evolution of institutional patterns of landscape and population control through the concept of *onge* (disaster induced famine) (Kirch 1984, p 119).

We have modeled the effect of disaster in three structures. First, as in figure 8, there is a loss of capacity as accumulated in the stock of available land. Second, there is an additional outflow from Resources. Third, there is an additional outflow from population (see figures 11 and 12).

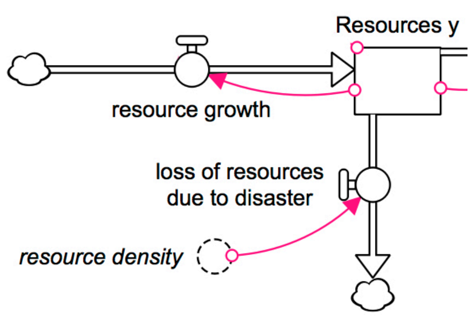

Figure 11. Effect of disaster on Resources.

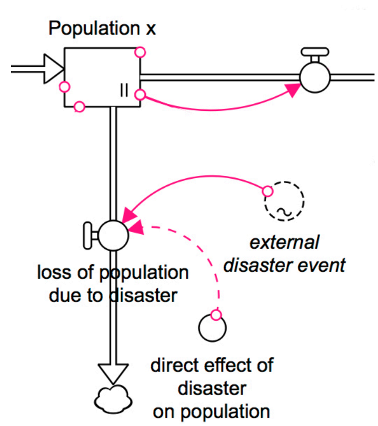

Figure 12. Effect of disaster on Population.

We have yet to model the perceptual processes and the way those processes generated learning outcomes that led to strategic transformation in the culture of Tikopia; however, we do know that such transformation occurred. Tikopians created a complex set of ritualized injunctions to keep population in check.

From their long experience over time, the Tikopians learned that their island could support approximately 250 people per square kilometer or 1150. In modeling terms, this can be called their Desired Population (as shown in Figure 13) that we can understand as a goal relative to an actual population (labelled Population x in Figure 13). In order to maintain that number, they then evolved a religious structure that embedded a series of taboos and other mechanisms to limit the growth of the population, through celibacy and coitus interruptus. If these means did not suffice, similar religious imperatives drove decision rules that increased the death rate, through abortion, infanticide, suicide through sea-voyages and, finally, war. We have modeled these population control mechanisms as graphical functions in Figure 13 that influence the birth and death rates in the model (see Figure 14 for this structure). Both effects have a strength adjustment that allows one to experiment with severity of policy, as the Tikopians would have done (Kirch, 1984). You can see this in Figure 13 as the two variables called "strength of decision rule", one of which affects birth rate and one of which affects death rate.

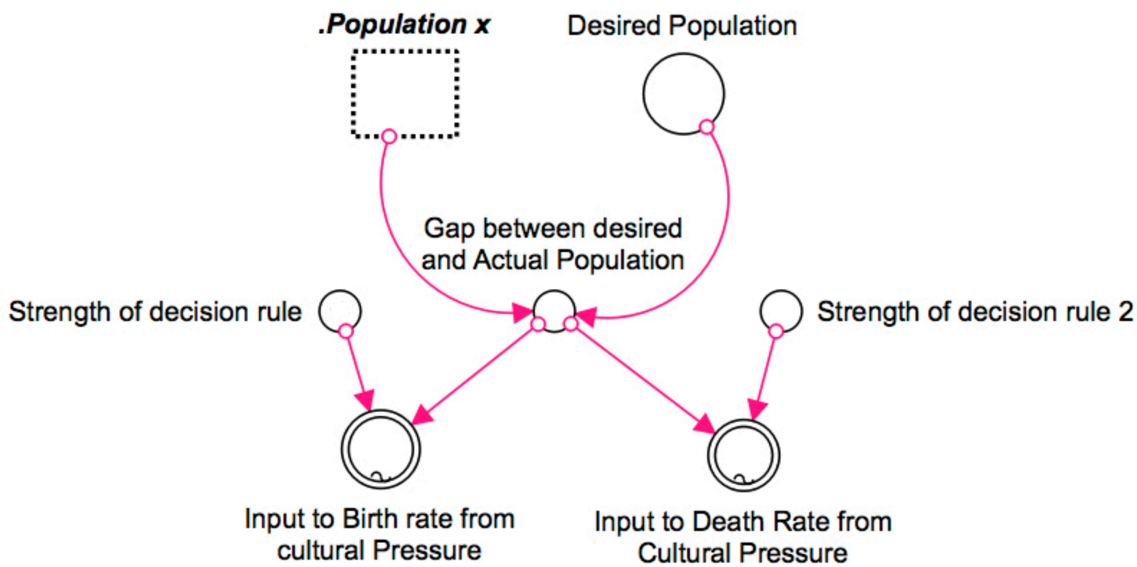

Figure 13. Gap between desired and actual population with graphical inputs to model

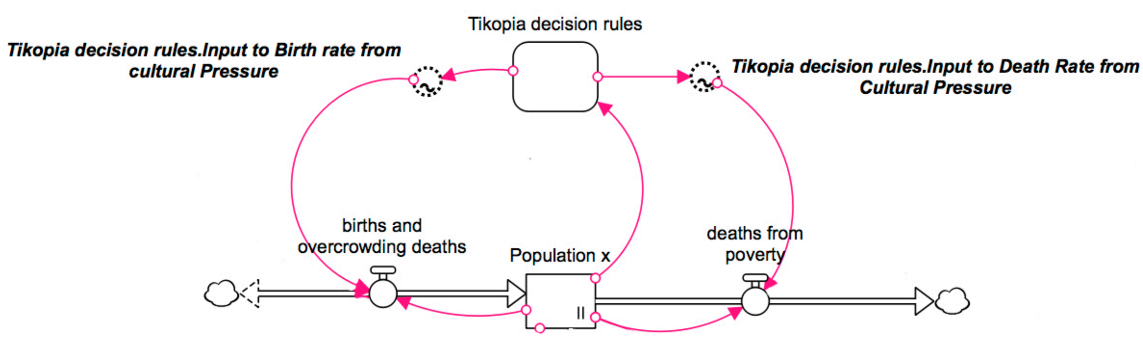

Figure 14. Decision rule inputs to birth and death

These elements of the model are still at a conceptual stage, since we need to work with Tikopia experts in the next stage of our work to better quantify them. However, the two variables accurately represent the conceptual process by which the Tikopians managed their long-term population numbers. Because there is a tendency for island populations to meet a demographic transition naturally as they approach carrying capacity, there is some question as to how intensely these decision rules needed to be applied. This yet to be determined strength of gain in the balancing loop is represented in the model by the two variables for strength of decision rule. These and other variables can be adjusted with dials and sliders in the model's interface to vary the policy applications and change the results over time (Figure 15 and see Figure 16 for results from a different policy choice). Many different policy options can already be investigated with the current model, and we hope to further develop it into a multi-culture case study that goes into the wide variety of policy choices made in Polynesia under the varying conditions on each island.

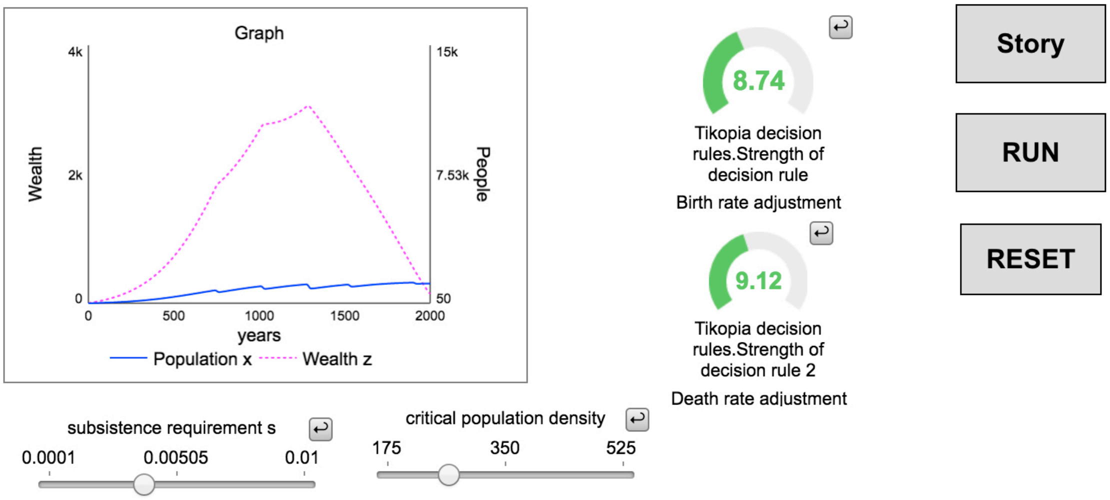

Figure 15. Model interface

Section 6: Next Steps

Having demonstrated, we hope, the usefulness of operational modeling for discussion of overshoot and collapse dynamics for policy design, we hope to develop the model further to illustrate more of the decision-making and sociological structures necessary for a full multi-case comparison study. Polynesian islands are perfect for this purpose because of the demographic similarities in their populations and the relative isolation of each case in geographic terms (for more on this approach, see Oliver, 1989). Using the Tikopia structure we have built above, we intend to model the perceptual process more explicitly, and then to show how those perceptions encouraged sociological change that generated more complex ecological-economic structures of at least two types. First, there was a strategic transformation of the overall land capacity. The Tikopians understood that it was helpful for capacity purposes to replace pigs with orchards, and this strategy created greater capacity of the land to generate increased food per square kilometer. Second, Tikopians used innovation to develop new food storage technology that allowed them to store fermented starches for years at a time. Future iterations of the model will create a daily use outflow from wealth so that this storage decision can be made explicit. There is also a need to address the problem of hierarchy development in social structures. The process of societal evolution has many emergent structures in it that result in state changes in the system structure (Turner 2003; Chase-Dunn 2016; Acemoglu 2012). We hope to include these structures in further developments of the model with the assistance of experts in Polynesian systems.

Section 7: Conclusion

In closing, we refer to comparison graphs of the outcomes of the Tikopia and Easter Island stories (Figure 14). The reason these outcomes differ is not the sum of deterministic happenings over time as might be implied by non-operational models of collapse. Instead, the outcomes are the sum of operational decisions made by human agents based on information perceived and managed through a social systems engineering process. Our hypothesis is that efficiency of information processing relative to effective risk assessment and policy implementation probably makes all the difference.

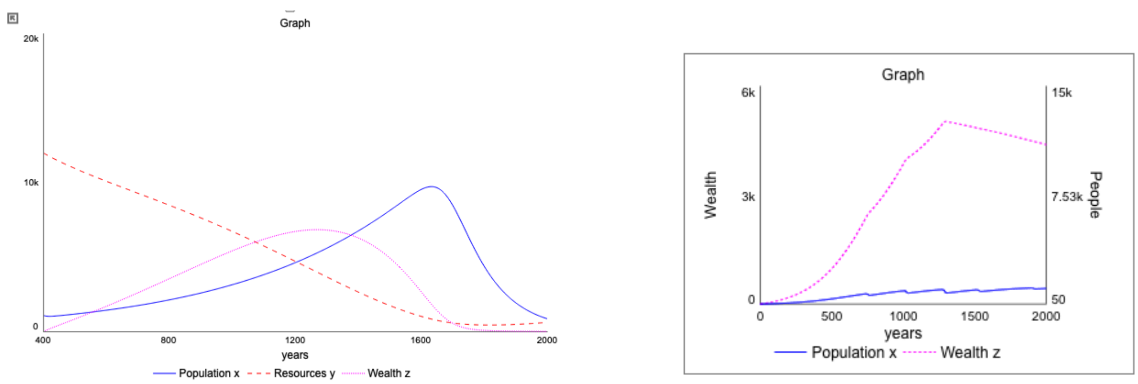

Figure 16. Comparison of Roman et al. (2017) Easter Island collapse with one of many possible sustainable outcomes for Tikopia

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