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Culture and Human Agro-ecosystem Dynamics: the Tsembaga of New Guinea

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In his classic work, *Pigs for the Ancestors*, Roy Rappaport proposed that the ritual cycle of the Tsembaga was a mechanism to regulate human population growth and prevent the degradation of the Tsembaga ecosystem. Rappaport provided detailed ethnographic and ecological information to support his claim, but many aspects of Rappaport's model were subsequently criticised. Several simulation models of the Tsembaga ecosystem were constructed to test Rappaport's hypothesis (Shantzis & Behrens, 1973; Foin & Davis, 1984) and evaluate possible alternatives (e.g. Foin & Davis, 1987). The basic conclusions were that it was possible to develop models supporting Rappaport's hypothesis but they were extremely sensitive to parameter choices, and other simpler population control mechanisms might be more likely (Buchbinder, 1977; Foin & Davis, 1987).

In this paper, a much simpler dynamical system model for a slash-and-burn agricultural system is developed and applied to the Tsembaga system. By analysing the structure of the model for different physical and socioeconomic conditions, sources of instability and possible stabilising mechanisms are identified. The model indicates that behavioral plasticity (ability to modify behavior over a wide range of behavioral options, quickly and easily) is a fundamental source of instability which is strong enough to nullify more direct stabilising influences such as malnutrition and disease. This suggests that the only possible mechanism to counter to this fundamentally destabilising force may be cultural, i.e. the ritual cycle. Finally, a condition is outlined for which the ritual cycle will produce (local) stability.

1. Introduction

The use of ecological concepts by anthropologists to understand the variation in social structure and behavioral diversity in human populations dates to the early part of this century. In contrast to the view that social structure was largely a product of unpredictable historical processes, in the 1950s Julian Steward proposed a research method that causally linked social structure and modes of subsistence (Moran, 1990). The difficulties associated with putting Steward's research method into practice and the development of the ecosystem concept in systems ecology (Odum, 1953) suggested a more biological approach where the ecosystem, rather than culture, was taken as the primary unit of analysis, (e.g. Geertz, 1963; Vayda & Rappaport, 1968). *Pigs for the Ancestors*, in which Rappaport (1968) proposed that cultural processes such as the ritual cycle of the Tsembaga play critical regulatory functions in their ecosystem is probably the best known work in applying the ecosystem concept in anthropology.

Of course, this work invited considerable criticism. The main points of criticism were that the work ignored historical factors and the role of the individual, relied on the controversial concept of group selection, and focused too much on the idea of equilibrium. It has been argued that studying the ecosystem as an integrated whole can not help explain *why* we see certain social structures or how they might have evolved and that concepts from evolutionary ecology stressing individual selection are more appropriate (Alden Smith, 1982). Here we are not focusing on how Tsembaga culture devel-

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oped, but rather the more general question of how behavioral plasticity (i.e. the very presence of humans) and associated cultural practices affect the structure and dynamics of agroecosystems. It is, however, possible to show how optimal individual decisions are critically dependent on the prevailing cultural environment (Anderies, 1996). If expected lifetime reproductive fitness is higher for individuals who participate in the cultural system into which they were born than for those who choose not to (if this were possible!), then a group phenomenon like the ritual cycle that prevents ecosystem degradation could be adaptive at the individual level.

In support of his hypothesis Rappaport provided detailed ethnographic and ecological information which invited several efforts at formal modelling. Several simulation models of the Tsembaga ecosystem were constructed with the aim of testing his hypothesis. Shantzis & Behrens (1973) developed a computer simulation based on Rappaport's data that suggested that the ritual cycle could produce a stable equilibrium for the Tsembaga ecosystem, but their model was very sensitive to parameter choices. Foin & Davis (1984) reexamined this model and variants of it using more realistic parameter values than Shantzis and Behrens' and concluded that the ritual cycle could not stabilize the Tsembaga model ecosystem. They suggest that the 200 years the Tsembaga have occupied their ecosystem is probably too short a time for such a finely tuned mechanism as the ritual cycle too have developed and some less finely tuned regulatory mechanism may be operating. In a later paper, Foin & Davis (1987) analyse the Tsembaga ecosystem in a broader context, asking whether it is in equilibrium or disequilibrium, but part of a greater regional equilibrium. They conclude that the Tsembaga ecosystem is "equilibrium seeking", but the mechanism is probably malnutrition and disease as proposed by Buchbinder (1977). Unfortunately, it is difficult to understand the structure and stability properties of computer simulation models.

In this paper a much simpler dynamic model is developed for a simple human agro-ecosystem with which we can more clearly see the interplay of stabilizing and destabilizing forces. The model is developed in three stages. First, a physical model for a simple human agro-ecosystem is developed and calibrated based on quantitative information provided by Rappaport (1968). Behavior (in terms of the effort devoted agriculture) is fixed, and the focus is on the importance of the food production function and associated feedbacks on the dynamics of the physical system. Next, the model is extended to allow for changing levels of work effort in agriculture based on the needs of the human and pig populations. Finally, more complex behavioral dynamics representing the ritual cycle of the Tsembaga are added.

Through the progression of the model development, several key points are made. First, model stability depends critically on the relative marginal productivities labor and soil. If labor is more marginally productive than soil (which is reasonable to believe in this system), the feedback indicating ecosystem degradation is weak which allows the system to become unstable as work effort (treated as a parameter) increases. Under these conditions, at lower work levels, the system exhibits a (locally) asymptotically stable fixed point. The stabilizing mechanism is intraspecific competition for food resources, i.e. malnutrition and disease as proposed by Buchbinder (1977). If the human population varies its work level in an attempt to meet its nutritional needs, the stabilizing mechanism of malnutrition and disease is destroyed. Behavioral plasticity tends to drive ecosystems to extremes where the only available mechanism to reestablish equilibrium may be cultural. Finally, if the deaths due to warfare are density dependent, the ritual cycle can stabilize the system which supports Rappaport's claim. Compared to the models of Shantzis and Behrens and Foin and Davis, the model presented herein is much less sensitive to parameter choices. Possible reasons for this difference are highlighted as the model is developed.

2. The Ecological and Cultural System of the Tsembaga

The Tsembaga occupy a rugged mountainous region in the Simbai and Jimi River Valleys along with several other Maring speaking groups with whom they engage in some material and personnel exchanges through marriages and ritual activity. These groups each occupy semi-fixed territories that intersperse in times of plenty and become more rigidly separated in times of hardship. Outside these interactions, the Tsembaga act as a unit in ritual performance, material relations with the environment, and in warfare.

The Tsembaga rely on a simple swidden (slash-and-burn) agricultural system as a means of subsistence. At the time of Rappaport's (1968) field work they occupied about 830 ha, 364 of which were cultivable. The Tsembaga also practice animal husbandry (the most prominent domesticated ani-

mal being pigs) but derive little energetic value from this activity. Pork probably serves as a concentrated source of protein for particular segments of the population as it is rarely eaten other than on ceremonial occasions, and several taboos surround its consumption that seem to direct it to women and children who need it most.

Much of the activity of the Tsembaga is related to the observance of rituals tied up with spirits of the low ground and the red spirits. The spirits of the low ground are associated with fertility and growth while the red spirits which occupy the high forest forbid the felling of trees. The ritual activity that is the focus here is the Kaiko, a year long pig festival. The Kaiko serves to end a 5–25 year long ritual cycle that is coupled with pig husbandry and warfare. It is this ritual cycle that Rappaport hypothesized acted as a self-regulatory mechanism for the Tsembaga population preventing the degradation of their ecosystem.

The three main ingredients of the ritual cycle, pig husbandry, the Kaiko itself, and the subsequent warfare, are intricately interwoven with the political relationships between the Tsembaga and the neighboring groups. The Tsembaga maintain perpetual hostilities with some groups and are allied with other groups without whose support they will not go to war. There are two important aspects of pig husbandry: raising pigs requires more energy than is derived from their consumption; pigs are the main source of conflict between neighboring groups because they invade gardens. From this perspective the keeping of pigs is completely nonsensical. However, the effort required to raise pigs is a strong information source about pressure on the ecosystem. The greater the pig population, the greater the chance an accidental invasion of others gardens will occur. Each time a garden is invaded, there is a chance that the person whose garden was invaded will kill the owner of the invading pig. Records are kept of such deaths which must be avenged during the next ritually sanctioned bout of warfare. From this perspective, pigs provide a meter of ecological and human population pressure and help "measure" the right amount of human population reduction to maintain ecosystem integrity. The Kaiko, when all but a few of the host groups pig herd are slaughtered, helps facilitate material transfers with other groups, allows the host group to assess the support of its allies, and resets the pig population.

The ritual cycle as the homeostatic mechanism proposed by Rappaport operates as follows: human and pig populations grow until the work required to raise pigs is too great. A Kaiko is called and most of the pig herd is slaughtered. The Tsembaga are then released from taboos prohibiting conflict with neighbors. Warfare begins with a series of minor "nothing fights" where casualties are unlikely then escalates to the "true fight" where axes are the weapons of choice and casualties are much more likely. Periods of active hostilities seldom end in decisive victories but rather when both sides have agreed on "enough killing" related to blood revenge from past injustices. The ritual cycle then begins anew with both the pig and human populations reduced to (hopefully) levels that will not cause ecological degradation. As the model is developed I will fill in the relevant details of each of the components summarized here.

3. The Model

3.1. DEFINITIONS

We are concerned with modeling the interaction of the human population and its culture with their land and thus need to define the following physical state variables:

$x_1(t)$: Tsembaga population density in persons per cultivable hectare. At the time of Rappaport's (1968) study the Tsembaga numbered 204, thus $x_1 = 0.56$;

$x_2(t)$: the biophysical capital (soil quality) in the Tsembaga ecosystem. Biophysical capital is related to the nutrient pool and soil structure of the 364 ha upon which the Tsembaga rely for their survival. It is difficult to assign meaningful units to capital, we view in terms of the services provided by the land cultivated by the Tsembaga. The variable x_2 should be thought of as an index of productivity;

and the following cultural state variables:

$c_1(t)$: Tsembaga per capita birthrate;

$c_2(t)$: fraction of population devoting 1 man year of energy (2000 hr at 350 kcal/hr) to horticulture each year. Thus the total energy devoted to horticulture at time t is given by $c_2(t) \cdot x_1(t) \cdot A_c$ man years of energy per year, where A_c is the total number of cultivable hectares available to the population.

We then specify the dynamics for each of the variables based on the interaction of human activities and the energy flows through the system. We define the function that governs human population growth as $f_1(x_1, x_2, c_1, c_2)$—the formal statement that population growth depends on the human population, land

productivity, per capita birthrate, and work effort directed to cultivating the land. Similarly, the biophysical regenerative process of forest recovery is defined as $f_2(x_1, x_2, c_1, c_2)$. The functions f_1 and f_2 represent the change in the human population and biophysical capital over time, leading to the two-dimensional dynamical system:

$$\frac{dx_1}{dt} = f_1(x_1, x_2, c_1, c_2) \tag{1a}$$

$$\frac{dx_2}{dt} = f_2(x_1, x_2, c_1, c_2) \tag{1b}$$

In the next two sections, we explicitly define the forms of f_1 and f_2 based on the ecology of the Tsembaga system. Major considerations are: the nutritional requirements of the Tsembaga population, soil properties and the food production process of the Tsembaga that couples them to the land.

3.2. TSEMBAGA SUBSISTENCE AND THE FORM OF f_1

The canonical way to represent f_1 is

$$f_1 = (b - d)x_1 \tag{2}$$

where b and d are the per capita birth and death rates, respectively. We are specifically interested in how these rates depend on food production and nutrition so we separate influences on birth and mortality into a constant component not associated with food intake and a component that does depend on food intake. First we define the food production of the population as $e(x_1, x_2, c_2)$, then f_1 can be written as:

$$f_1 = (b_n(c_1) - d_n(e(x_1, x_2, c_2)))x_1. \tag{3}$$

The term b_n is the "net birth rate" which is the natural (culturally dependent) birth rate less the natural death rate and **does not** depend on food intake. The term $d_n(e(x_1, x_2, c)$ is the "net death rate" which is the difference between the portions of fertility and mortality that **do** depend on food intake.

The form of d_n is inferred from the subsistence pattern of the Tsembaga. At low levels of production, below a minimum requirement of around 2500 kcal/day, the net per capita death rate increases quickly due to malnutrition. Buchbinder (1977) proposed that the mechanism linking malnutrition and mortality could be increased malaria infection due to reduced immunity. Above this minimum, the net death rate of the population can be decreased through the improved nutrition associated with better quality animal protein that improves characteristics such as sexual development, and immunity, etc. This decrease in net death rate is, however, small compared with the increase in net death rate associated with malnutrition.

The simplest way to represent $d_n(\cdot)$ mathematically is to assume that once the per capita food requirements are met, $d_n(\cdot)$ approaches 0 asymptotically. Below this minimum requirement, $d_n(\cdot)$ rises quickly. If we choose the units of $e(x_1, x_2, c_2)$ to be energy requirements per person per year then the quantity $e(x_1, x_2, c_2)/x_1$ represents the relative level of nutrition of the population. If this ratio is one, the nutritional needs of the population are just being met. If this ratio is larger than one, the population is producing more than it needs. It devotes the excess to pig husbandry and receives the benefits in terms of increased intake of concentrated protein and fat. The ratio being less than one has the obvious implications. A convenient function with the desired properties is the exponential, and we can represent $d_n(\cdot)$ as

$$d_n(e(\cdot)) = a \exp\left(-\alpha \frac{e(\cdot)}{x_1}\right) \tag{4}$$

where the parameter a characterizes the speed at which people die due to malnutrition and α indicates the response to nutrients. For example if $a = 3$ and there is no nutrient intake, 40% of the population would be dead within 2 months, and 78% would perish by 6 months. In the model, I have chosen α and a in the interval [1, 10]. There are many reasonable choices but the behavior of the model is qualitatively unchanged by any reasonable combination of these parameters. We can now define $f_1(x_1, x_2, c_2)$ completely as

$$f_1(x_1, x_2, c_1, c_2) = \left(b_n(c_1) - a \exp\left(-\alpha \frac{e(x_1, x_2, c_1, c_2)}{x_1}\right)\right)x_1 \tag{5}$$

and turn our attention to the definition of f_2.

3.3. THE ECOLOGY OF SLASH-AND-BURN AGRICULTURE

The Tsembaga agricultural system amounts to a piece of land being cleared, cultivated for 1 year and then left fallow for 15–25 years. The gardens are cut in the wetter season in May and early June, allowed to dry, then burned in the dryer season between June and September, and planted immediately thereafter. Because the Tsembaga live on a fixed amount of land, the fallow period and amount

of land in production at any one time are directly related. For the Tsembaga, the 15–25 year fallow period correlates to about 19 ha or a little over 5% of the available land being cultivated at any one time. During the cultivation phase, nutrients contained in the biomass of the forest are released into the soil through burning, a portion of which are subsequently removed through cultivation. In addition to direct nutrient removal, gardening has other negative effects on soil quality, especially on soil structure. Juo & Manu (1996) have catalogued some of these indirect effects:

—the removal of ground cover exacerbates erosion;
—increased frequency of clearing and cultivation causes the gradual destruction of the soil macropore system due to increased foot traffic and tilling;
—burning and cultivation lead to the gradual destruction of the root mat, the decomposition of humidified organic matter, and the reduction of the contribution of organic and microbial processes to nutrient cycling.

Frequency and intensity of cultivation probably both effect recovery times (Szott *et al*., 1994) and the negative effects of agriculture on soil productivity probably increases nonlinearly with food production. I assume, probably conservatively, that these effects increase linearly with food production.

During the subsequent fallow phase, the nutrient cycling process is reestablished through forest succession. The rate of the cycling process and the associated rate at which nutrients are recycled and fixed in the soil depends on tree growth which, of course, depends on soil nutrients. Thus, the rate of change of soil nutrients depends on the level of nutrients in the soil. Finally, the nutrient cycling process is governed by the characteristics of the community of decomposing and mineralizing organisms in the soil which set an upper limit on the amount of nutrients in the soil. The simplest way to capture this behavior is by the well known logistic function. This is obviously an oversimplification for a very complex process. However, if compared to a detailed, much more complex model for this process (Huggett, 1993), the qualitative behavior is captured reasonably well by the logistic. Combining the effects of biophysical regeneration and degradation due to agriculture we have

$$f_2(x_1, x_2, c_2) = n_r x_2(1 - x_2/x_2^{max}) - \beta e(x_1, x_2, c_2) \quad (6)$$

where n_r is the maximum regeneration rate, x_2^{max} is the maximum soil nutrient level for the ecosystem, and β is the appropriate conversion factor relating food production to nutrient removal.

There is some difficulty associated with the determination of n_r for the forests the Tsembaga occupy. It is possible, however, to get an idea of the order of magnitude n_r from other studies. The time of successional recovery from slash and burn to stable litter falls ranges from 7 years in the plains of the U.S. (Scott, 1976) to 14–20 years in the tropics (Ewel, 1986). We can scale n_r for a characteristic recovery time of 15–25 years if the forest is left undisturbed. By studying the recovery times of the model specified by eqn (6) for different values of n_r and different initial conditions, $x_2(0)$, we can bracket reasonable values of n_r to be between 0.05 and 0.2.

With f_1 and f_2 now completely defined, we can rewrite the dynamical system representation of the Tsembaga ecosystem defined by eqns (1a) and (1b) as

$$\frac{dx_1}{dt} = \left(b_n(c_1) - a \exp\left(-\alpha \frac{e(x_1, x_2, c_1, c_2)}{x_1}\right)\right)x_1 \quad (7a)$$

$$\frac{dx_2}{dt} = x_2 n_r(1 - x_2/x_2^{max}) - \beta e(x_1, x_2, c_2). \quad (7b)$$

Given the problems with associating units to biophysical capital, it is convenient to rescale the model by x_2^{max} by letting $x_2 = \tilde{x}_2 \cdot x_2^{max}$, with $\tilde{x}_2 \in [0, 1]$. Now, $\tilde{x}_2$ represents the mean productivity index per hectare of the land the population is occupying, one being maximum productivity, zero being barren. We also drop the explicit dependence of b_n on c_1 by assuming b_n is a linear function of c_1 and treating b_n as a parameter. The rescaled equations are (dropping the tilde notation):

$$\frac{dx_1}{dt} = \left(b_n - a \exp\left(-\alpha \frac{e(x_1, x_2, c_1, c_2)}{x_1}\right)\right)x_1 \quad (8a)$$

$$\frac{dx_2}{dt} = x_2 n_r(1 - x_2) - \beta e(x_1, x_2, c_2). \quad (8b)$$

Our final task is the specification of $e(\cdot)$.

3.4. THE FOOD PRODUCTION FUNCTION

Although several simple causal relationships are understood, there is no fundamental scientific understanding of how nutrients, soil processes and crop output are related. Examples of work on this problem include France & Thornley's (1984) development of plant growth models and Keulen & Heemst's (1982) empirical work on crop response to the supply of macronutrients. Economic approaches that focus on energy inputs and resource degra-

dation can be found in work by Cleveland (1995a,b) and Giampietro *et al*. (1992). Econometric work on determining the form of production functions has been carried out by many authors, see for example (Ackello-Ogutu *et al*., 1985; Paris & Knapp, 1989).

Several functional forms have been suggested for modeling crop output including the Cobb–Douglas, trans-log, Leontif, inverse polynomial, polynomial, and the von Liebig. The von Liebig function is based on von Liebig's law which states that crop output is a function of the most limiting resource. The functional form is

$$y = A_{sw} \min_{i \in I} [f_i(x_i)] \tag{9}$$

where y is output, A_{sw} is the yield plateau set by the soil and weather, x_i is the total availability of the i-th nutrient, and each f_i is a concave function from $\mathscr{R}$ to [0, 1]. Lanzer & Paris (1981) proposed to use this functional form in place of the commonly used polynomial forms and in a later paper, Ackello-Ogutu *et al*. (1985) tested the von Liebig crop response against polynomial specifications and were able to reject the hypothesis that crop response is polynomial. Further, they could not reject that crop response was of the minimum or von Liebig type.

The problem with the von Liebig function for our purposes is that it is not smooth. This will cause difficulties when analysing the dynamical system. Instead, I employ a commonly used production function in economics, the Cobb–Douglas given by

$$y = k \prod_{i=1}^{n} x_i^{a_i} \tag{10}$$

where x_i is the i-th input and a_i are constants. The problem with this function is that it allows infinite substitutability. That is, if the inputs were land and water, this function says that productivity can be maintained in the face of a drought by bringing more land under cultivation. This is clearly absurd. If on the other hand, the inputs of interest are not physical quantities, for example energy input, the situation is different.

If the general form of the von Liebig function given by eqn (9) is used to model output where the input variable is energy, the physical inputs f_i (energy in) may be nonlinear. This is definitely the case for the Tsembaga with regard to the amount of land brought into cultivation for a given amount of labor. Here, the Cobb–Douglas is not such a bad approximation to the von Liebig. The two inputs to agriculture accounted for in my model are human energy and biophysical capital. Other inputs such as rainfall and solar energy input are assumed to be fairly constant, which based on the indications of the Tsembaga, is accurate. They indicate that the weather never fluctuates significantly enough to influence crop output, at least not in their lifetimes. Under these assumptions, the food energy production function is of the form:

$$e(x_1, x_2, c_2) = k(w(x_1, c_2))^{a_1} x_2^{a_2} \tag{11}$$

where $w(x_1, c_2)$ is the amount of energy the population directs towards agriculture, a_1 and a_2 are the marginal productivity of energy and biophysical capital, respectively, and k is a proportionality constant. Fortunately Rappaport (1968) made detailed measurements of the energy input per unit area of land cultivated along with the associated output. Using this information we can calibrate the food energy production function, i.e. for a given choice of a_1 and a_2, Rappaport's data can be used to compute an estimate of k as follows.

Rappaport indicates that when the human population was 204 and the pig population was 169 animals weighing between 120 and 150 lb, the amount of land cultivated was about 18 ha or 6% of the total cultivable land, leaving 94% fallow. The trophic requirements of pigs are similar to those of humans, and their population can thus be converted into equivalent Tsembaga numbers. The average Tsembaga weighs 94 lb so their 169 pigs would have the same trophic demands as 240 Tsembaga. Thus, the 18 hectares supported approximately 444 Tsembaga equivalents.

Based on his energetic analysis, one person year (2000 hr at 350 kcal hr^{-1}) of energy input is sufficient to clear, burn, cultivate, and harvest 1 ha of land. Using energy units in human annual energy requirements, 18 man years of energy input produced 444 units of total energy output or 1.22 energy units per hectare. Now, making a guess at the stage of recovery of the secondary forest when brought into cultivation, we can estimate k. Supposing soil quality is 80% that of a mature forest, we have

$$1.22 = k(18)^{a_1} 0.8^{a_2} \Rightarrow k = \frac{1.22}{(18)^{a_1} 0.8^{a_2}}. \tag{12}$$

Then, given the definition of c_2, the work devoted to agriculture is $w(x_1, c_2) = x_1 c_2 A_c$. For the situation described above, $c_2 = 0.09$, and $A_c = 364$.

Assuming that the villagers do not waste labor, a certain work effort is roughly correlated to the amount of land being cultivated. If the relationship were linear, increased effort would increase land under cultivation proportionately. If an additional

amount of land of equal quality is brought under cultivation, one would expect that output would increase proportionately. This situation would be modeled by choosing $a_1 = 1$. Given the terrain of the Tsembaga, however, increased work input will not increase the amount of land cultivated proportionately. Each marginal unit of land brought into cultivation requires further travel distances which may require substantial elevation gains, and the passage of natural barriers such as ridges and rivers. This suggests that $a_1 < 1$ but not substantially. Estimating a reasonable value for a_2 is more difficult and will be discussed later.

4. Dynamic Behavior of the Model

Equations (8a) and (8b) represent a family of models parameterized by c_2, a_1, and a_2. The main objective of studying this model is to divide this parameter space into regions where the model has the same qualitative behavior, e.g. regions where the model exhibits a stable equilibrium, exhibits cyclical behavior, or is unstable. Computing these boundaries is a difficult task in general. If the system is of low dimension, standard methods of dynamical systems analysis can be applied reasonably easily (Kuznetsov, 1995). For large dimensional systems, such analysis becomes impractical. The main tool I employ is a numerical technique known as pseudo arclength continuation (Doedel, 1981) available in the software package Auto. The analysis amounts to starting at a known fixed point of the system and tracking its behavior in very small steps. By locating points where the stability of the fixed point changes, we can detect local bifurcations and use these to divide the parameter space as mentioned above.

Applying this technique to our model system allows us to assess its sensitivity to the structure of the food production function and the work level of the population. Over a wide range of physically meaningful values for b_n, a, α, n_r and β, the model exhibits a (locally) asymptotically stable equilibrium population density of around 0.6 when $c_2 = 0.09$ which agrees with the demographic data previously discussed. The corresponding equilibrium biophysical capital value is around 0.75; quite reasonable given that cultivated land is rotated so at any one time at least 10% of the land has just been cultivated and other land is in various stages of recovery.

The model's qualitative behavior is sensitive to c_2, a_1, and a_2. If we fix $a_1 = 0.7$ and $a_2 = 0.3$ representing the case where bringing more land under cultivation is more marginally productive than increasing biophysical capital (soil quality), the model exhibits a Hopf bifurcation when c_2 is varied as shown in the bifurcation diagram in Fig. 1. Points on the solid line represent stable equilibria while those on the dotted line represent unstable equilibria. The large solid circles represent stable limit cycles. For c_2 less than approximately 0.1354 the system will exhibit a stable equilibrium. For c_2 greater than 0.1354, the equilibrium becomes unstable, and a stable limit cycle with a period of about 300 years appears in which population builds and reaches its maximum after about 250 years then declines over the next 20–30 years. When the population density is extremely low, the land recovers over the next 20–30 years and the process begins again. The key point is that if the population works at a level $c_2 = 0.09$ as it was during Rappaport's field work, the ecosystem is very stable.

More interesting is the model's dependence on the relative marginal productivities of soil and labor. If we make the common and sensible assumption that the food production process exhibits constant returns to scale, we must have that $a_1 + a_2 = 1$. This reduces the dimension of the parameter space by one. It turns out that there is a relationship between the marginal productivity of energy input vs. biophysical capital as is made clear by comparing Fig. 2 with Fig. 1.

When $a_1 = 0.7$ a bifurcation occurs near $c_2 = 0.1354$ as previously noted but when $a_1 = 0.4$, no bifurcation occurs for any value of c_2 as indicated by Fig. 2.

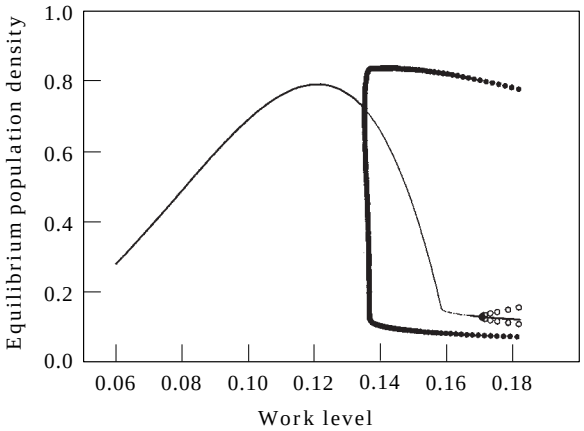

FIG. 1. Bifurcation diagram for swidden agriculture with $a_1 = 0.7$ and $a_1 = 0.3$. The heavy solid line represents stable equilibria points while the thin line represents unstable equilibrium points. The dark circles represent the maximum and minimum values taken on by x_1 on the stable limit cycle, i.e. as the system goes through one cycle x_1 varies from 0.1 to 0.8 people/cultivable hectare.

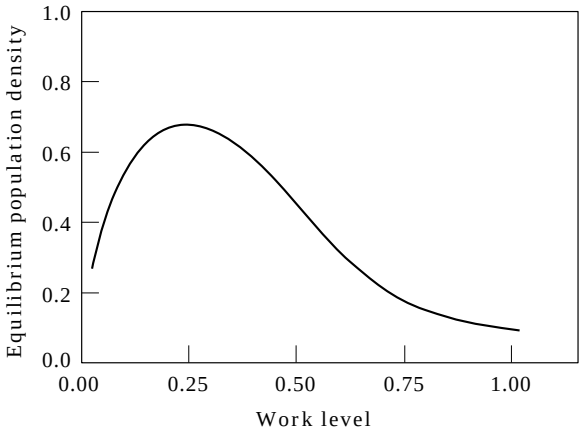

FIG. 2. Bifurcation diagram for swidden agriculture with $a_1 = 0.4$ and $a_2 = 0.6$. As in Fig. 1 the solid line represents stable fixed points.

In order to understand this behavior, we create a two parameter bifurcation diagram, Fig. 3, that shows all the combinations of c_2 and a_1 for which a Hopf bifurcation occurs. The curve generated by these points separates c_2–a_1 parameter space into regions with qualitatively different behaviors shown in Fig. 4. Curves for two different cases are shown, one where the population is more and less susceptible to death due to malnutrition as indicated on the diagram. In each case there is a threshold value of a_1 below which no bifurcation occurs, i.e. the system remains stable for any level of work. This phenomenon has an interesting ecological interpretation.

In any ecological model, the relative strengths and timing of feedbacks between state variables governs model stability. In our case, the agriculturalists receive feedback from the land in terms of productivity per unit effort and the land receives

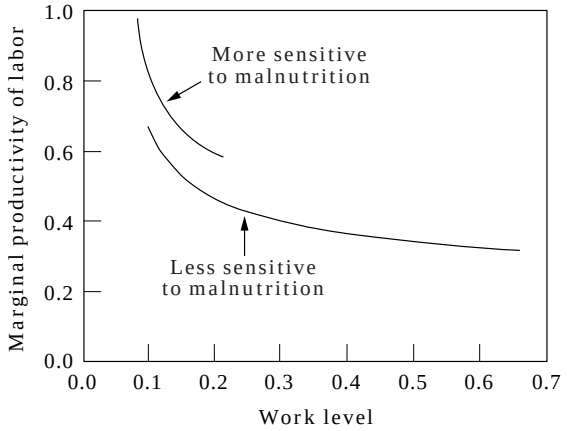

FIG. 3. Two parameter bifurcation diagram for the swidden agriculture model. The curves represent parameter combinations at which a Hopf bifurcation occurs.

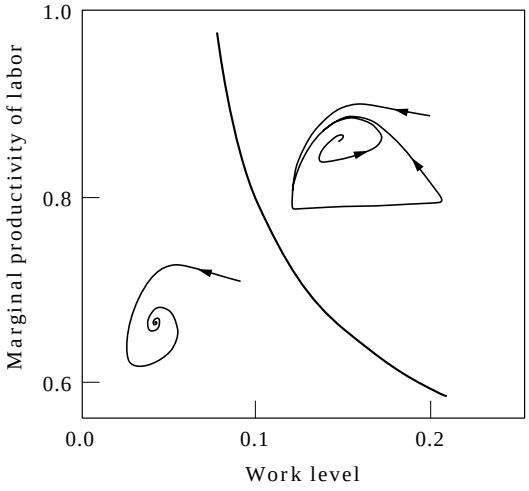

FIG. 4. Change in dynamics as the bifurcation boundary is crossed. The system goes to a stable equilibrium for parameter values to the left and below the curve while for those above and to the right, the system exhibits stable, cyclic behavior.

feedback from the agriculturalists in the form of population density.

Given that $e(x_1, x_2, c_2) = k(c_2 x_1)^{a_1} x_2^{a_2}$, the marginal productivity of the i-th input is defined as

$$\frac{\partial e(x_1, x_2, c_2)}{\partial x_i} = \frac{a_1 e(x, x_2, c_2)}{x_i}. \tag{13}$$

The parameters a_1 and a_2 determine the increase in productivity associated with increasing work effort and biophysical capital, respectively. If the marginal productivity of labor is higher than the marginal productivity of soil quality, it will pay to bring more lower quality land into production (shorter fallow periods) as opposed to preserving soil quality. The declining soil quality feedback is weakened by the stronger feedback of increased yields due to increased cultivation effort. Under these circumstances, the ecological system exhibits a bifurcation from a stable to an unstable system if the work level becomes too high.

If on the other hand, the marginal productivity of labor is lower and that of biophysical capital correspondingly higher, the possibility of bifurcating from a stable to an unstable system is reduced. The feedback from decreased biophysical capital is now stronger and exerts more pressure on the population. This pressure keeps the population in check before natural capital is degraded to the point below which the population can not be supported. From the agriculturalists' point of view, the gains from cultivating more land are more than offset by the productivity losses associated with reduced soil quality resulting from the shorter

fallowing periods, a strong feedback to not work the land too hard.

Notice that the curve for the case where the population is less sensitive to malnutrition and disease extends to lower values of a_1 for which a bifurcation occurs. Malnutrition and disease is the mechanism through which reduced agricultural productivity affects the population. If this mechanism is weakened, the stabilizing influence of reduced soil quality is also weakened. This has the effect of making the model unstable for wider range of values of a_2 The critical point to take away from this analysis is that as marginal productivity of labor is increased and the relationship of malnutrition and disease to mortality in the population is weakened, the **potential** for ecosystem instability increases. Whether or not that potential is realized depends on how behaviorally plastic the population is, the issue to which we now turn our attention.

5. Behavioral Plasticity

In general, in models of animal population dynamics, behavior, although state dependent, is relatively inflexible. Dynamics and stability characteristics are determined by physical aspects of the ecosystem coupled with the fixed behaviors of organisms that occupy it. Mechanisms that might cause a change in the qualitative behavior of such a system might be changes in the external environment or evolutionary dynamics.

In an ecological model involving humans, the situation is quite different. The system can move in and out of regimes of stability and instability very quickly with changing behavior. Indeed, the amount of land that the Tsembaga put into cultivation (the value of c_2) is not constant—it depends on the human and pig population. To investigate, we treat c_2 not as an exogenously set parameter, but rather, as an endogenously determined quantity by allowing the population to adjust c_2 to attempt to meet nutritional requirements. The work level is governed by the difference between actual food production and desired food production and the availability of additional labor. A simple expression for the dynamics of c_2 is:

$$\frac{dc_2}{dt} = \lambda_{c_2}\left(d_f - \frac{e(x_1, x_2, c_2)}{x_1}\right)(c_2^{max} - c_2) \qquad (14)$$

where d_f is the food demand, c_2^{max} is the upper limit on the fraction of the population working full time cultivating the land, and λ_{c_2} is the speed of response of the population to changes in demand.

The food demand is culturally set. I define food demand to be 1 if the minimum food requirements of the population are being met on average, about 3000 calories per day. Significant deviations away from 1 are possible, as human populations exist on a daily caloric intake ranging from around 2000 up to 6000 calories. The parameter c_2^{max} could be culturally set or set by physical limitations. The parameter λ_{c_2} is a measure of the behavioral plasticity of the population, setting the time scale on which behavioral change can occur. As λ_{c_2} increases, the population can change its behavior on shorter time scales. If we append eqns (8a) and (8b) with eqn (14) we have a three-dimensional dynamical system that describes the human agroecosystem. This system exhibits a steady state if either food demand is met ($e(x_1, x_2, c_2)/x_1 = 1$), or the population is working at the maximum permissible level ($c_2 = c_2^{max}$).

By treating c_2^{max} as a bifurcation parameter, we can explore the behavior of the system defined by eqns (8a), (8b), and (14) The results are shown in Fig. 5. If $c_2^{max} < 0.1354$ the model exhibits a stable equilibrium. The stable equilibrium vanishes when $c_2^{max} > 0.1354$ and a stable limit cycle develops.

If the population is somehow limited in the maximum effort it devotes to agriculture, the nutrition and disease population control mechanism proposed by Buchbinder (1977) would effectively stabilize the system. From the description of their computer simulation model, it seems that Foin & Davis (1987) set an upper limit on "cultivation intensity" which would explain their conclusion supporting Buchbinder's hypothesis.

If, on the other hand, the maximum effort the Tsembaga could devote to agriculture if necessary is above the critical level, (which is reasonable to believe since, for example, this would only require that 15% of the population be willing to work in agriculture if necessary) the mechanism proposed by Buchbinder would not be sufficient to stabilize the system. Thus, if there is any hope of the ecological system being stable, some other mechanism, perhaps cultural, must come into play.

If we let $c_2^{max} = 0.25$, meaning one-fourth of the population could devote a person year of energy to agriculture if necessary, the population could work hard enough to meet food demand and then c_2 is dynamically set by the relation

$$1 = \frac{e(x_1, x_2, c_2)}{x_1}. \qquad (15)$$

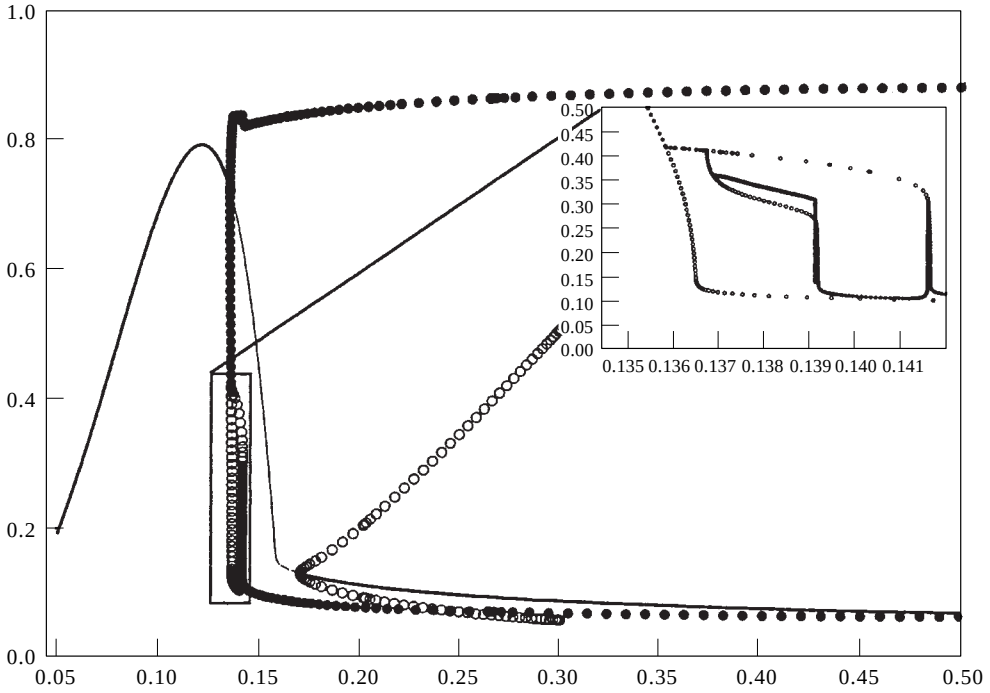

FIG. 5. Bifurcation diagram with w_{max} as the bifurcation parameter in the swidden agriculture model. The upper inset is an exploded view of the boxed region in the main bifurcation diagram showing the increase in complexity of the dynamics when culture is added to the system. These dynamics occur over an extremely narrow parameter range, thus having a low probability of being observed in the physical system.

Then from eqn (8a) and (8b), for equilibrium we must have

$$b_n - a\exp(-\alpha\cdot 1)=0 \tag{16a}$$

$$x_2 n_r(1-x_2) - \beta x_1 = 0. \tag{16b}$$

If the parameters b_n, a, and α are such that eqn (16a) is satisfied, the nonlinear system defined by eqns (15) and (16b) defines a one-dimensional stable manifold in $\mathscr{R}^3$. The equilibrium population, soil quality, and work level depend on initial conditions. Of interest to us is how the net birthrate must be exactly balanced by the net death rate associated with the nutritional level achieved when food demand is met. If the population could, through some cultural mechanism such as infanticide or some other type of birth control, match these rates, the system would be (neutrally) stable. Here, we see how extreme behavioral plasticity can destabilize a system by nullifying the feedback control of resource limitation and transferring the responsibility of ecosystem regulation from environmental to cultural mechanisms.

It is probable that the net growth rate of the population is positive when food demand is met which violates the stability condition given by eqn (16a). In this case the ecosystem exhibits cyclic behavior. It is very interesting to compare the limit cycle behavior of the cases with and without behavioral plasticity. Figure 6 shows the limit cycles that develop in the system where the work level is treated as a parameter (inner cycle) set constant at $c_2 = 0.14$ and those that develop when the work level is dynamically set with $c_2^{max} = 0.25$ (outer cycle). Figure 7 shows the work level and food

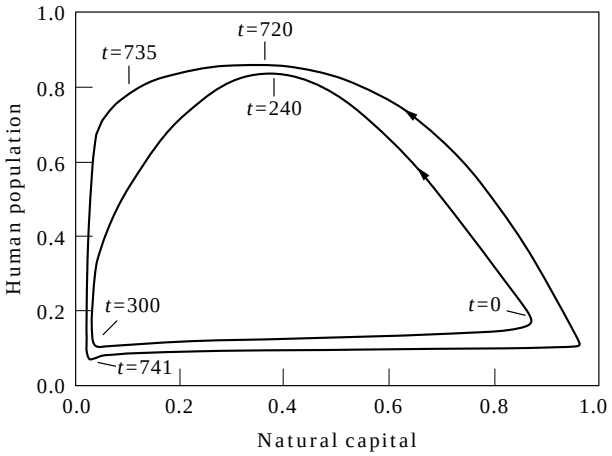

FIG. 6. Limit cycles that develop as the system becomes unstable. The inner cycle is for the case where the work level is constant at 0.14. The outer cycle represents the case where the work level is set by demand.

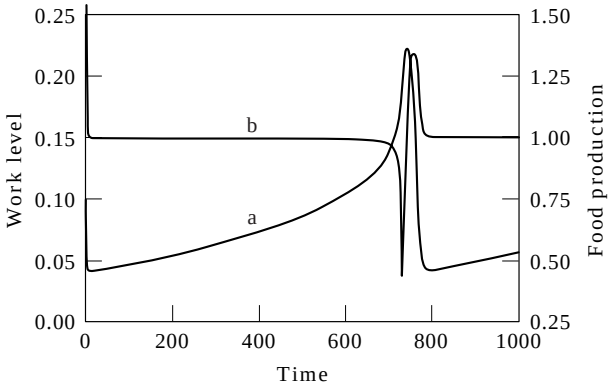

FIG. 7. Work level (curve a) and food production (curve b), over time.

production over time. Several interesting points are worth making about these figures.

First, the period of the outer cycle where the work level is dynamically set is about twice that of the case were the work level is constant. The reason for this can be seen in Fig. 7. Notice that the initial work level is very low, around 0.05. This is because if the population is low and biophysical capital is high at $t = 0$ little effort is required to meet food demands. The population does not over exploit its environment just because it can, and just meets food demands. With the case where the work level is constant at 0.14, the population exploits the environment at a constant rate. When biophysical capital is high, the population can produce an abundance of food which increases the growth rate of the population. Thus, the population that just meets food demand grows much more slowly than the case where the work level is constant. The difference is indicated in Fig. 6 by the difference in time required for the population to reach a maximum: 240 vs. 720 years for the constant and dynamic work level cases, respectively.

Next, notice that in the constant work level case, after the population reaches a maximum, it begins to decline immediately. This decline to the lowest population level takes about 60 years. In the dynamic work level case, by increasing work level dramatically as shown in Fig. 7 around $t = 720$, the population is able to delay the precipitous decline in population for about another 15 years. In doing so, however, the population puts itself into a more precarious position of very high population density in a very degraded environment. The precipitous decline now takes 6 years instead of 60 years!

Since the Tsembaga do adjust their work level, the model suggests that unless some mechanism intervenes, their ecosystem is doomed to crash. This could be avoided by maintaining the knife edge set of parameters required for stability in eqn (16a) by controlling birth and death rates within the population, or possibly by the ritual cycle. It seems that the former is not the case; the Tsembaga actively seek to be as "fertile" as possible as evidenced by their rituals to improve fertility. In the next section, we add the dynamics of the ritual cycle and determine the conditions under which it could maintain a balance in, and prevent the degradation of, the Tsembaga ecosystem.

6. Modelling the Ritual Cycle

The ritual cycle dynamics are added in two parts. First we address pig husbandry to find that even without the ritual cycle, pig husbandry alone can help stabilize the system. Next we add the ritual cycle to show that under certain assumptions the ritual cycle can stabilize the system, and that stability is not as sensitive to parameter choices as it is to how the number of people who ought to be killed during warfare is related to pig invasions.

6.1. THE PARASITISM OF PIGS

The bulk of the responsibility of keeping pigs falls on Tsembaga women. They do most of the work in planting, harvesting and carrying the crops used to feed the pigs. In this sense, the pigs can be viewed as parasitizing Tsembaga women. They benefit from energy derived from the ecosystem but do not contribute to obtaining that energy. It turns out that this relationship, in and of itself, is enough to *help* stabilize the ecosystem. The mechanism is related to the fact that working too hard is a major factor in destabilizing the ecosystem. If the human population is the sole benefactor of its agricultural effort, it grows in number, produces a larger labor pool, and the per-capita work level remains constant. If, on the other hand, the population keeps pigs, as the pig population grows relative to the human population, The per-capita work level *increases*. In this way, the pigs act as an ecosystem monitoring device.

This is clearly illustrated by the model. In all the previous investigations, it was assumed that the Tsembaga devoted a constant 55% of their harvest (based on demographic information at a point in time) to pigs maintaining a constant pig to person ratio (no ritual cycle). By treating this ratio as a parameter, r_p, we can generate a figure similar to Fig. 4. where the parameters of interest are the percentage of food being consumed by humans and c_2^{max}. Figure 8 is the result.

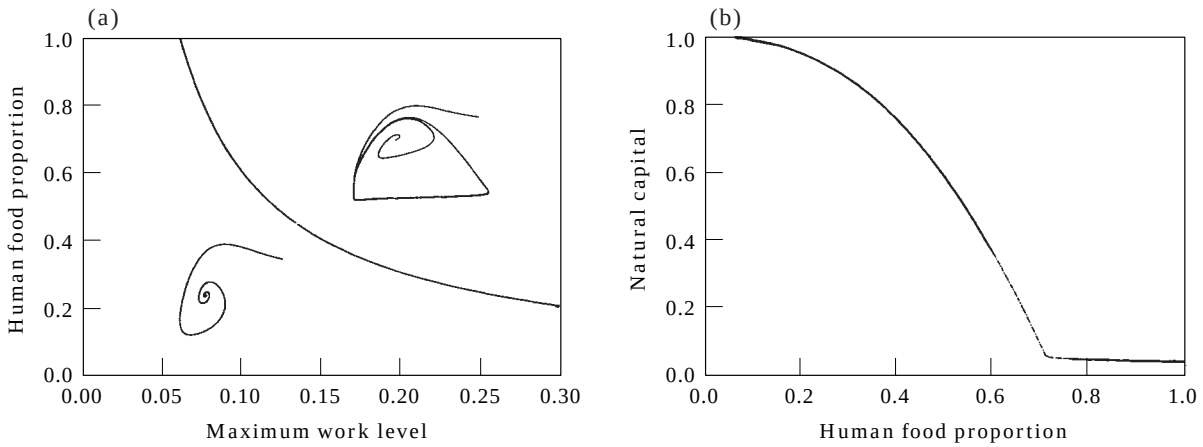

FIG. 8. The influence of pigs on system dynamics: (a) shows the bifurcation boundary in $c_2^{max} - r_p$ parameter space; (b) shows the equilibrium natural capital level as a function of the human food production ratio—r_p.

The curve in graph (a) separates regions in parameter space of stability and instability. Notice that the more food the humans eat themselves, i.e. $r_p \to 1$, the lower the level of c_2^{max} at which the system becomes unstable. Recall that with $r_p = 0.45$, the system goes unstable when $c_2^{max} = 0.1354$. This represents only a 50% increase in work effort which is plausible. Now consider the case where $r_p = 0.3$, the system remains stable until c_2^{max} reaches approximately 0.22. This represents a more than doubling of work effort which may be intolerable to the population. Thus, just by being there, the pigs help stabilize the system. Note that this stability comes at the expense of human nutrition. In this model, food is first fed to the pigs and the remainder is fed to the human population. This is not what happens; the Tsembaga eat the best food first and give the rest to their pigs. This difference requires the more elaborate ritual cycle mechanism to stabilize the system.

6.2. THE RITUAL CYCLE

The ritual cycle consists of periods of ritually sanctioned truces separated by warfare. The rituals that mark the transitions between the phases are the Kaiko that marks the end of the truce period and the planting of a plant called rumbim (*Cordyline fruticosa*) that marks the beginning of the next truce. Figure 9 is a representation of the cycle.

The length of the arcs on the circle is loosely representative of the times between events. The Kaiko itself lasts 1 year. Warfare lasts for a matter of months. The time between planting the rumbim that signifies truce and the Kaiko (typically about 12 years) depends on the demographics of the pigs. In this period enough pigs must be grown to satisfy ritual requirements, but the staging of the Kaiko also depends on when women get tired of being parasitized by pigs. The question mark between the uprooting of the rumbim and the beginning of warfare indicates uncertainty about the timing of the onset of warfare, although Rappaport indicated that fighting had usually resumed within 3 months of the uprooting of the rumbim.

After a truce, the populations return to tending gardens and pigs. As the pig population increases, work load on the women also increases. Rappaport computed that there were an average of 2.4 pigs of the 120 to 150 lb size to each mature female at the outset of the 1962 Kaiko. This translates into a pig to person ratio (in terms of biomass) of about 1.2. The range of the number of pigs kept was 0–6. Rappaport observed only one woman keeping six, and four keeping five and postulates that these

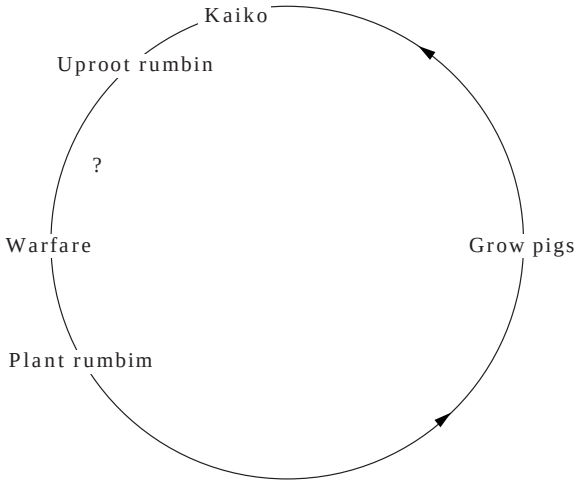

FIG. 9. The ritual cycle of the Tsembaga.

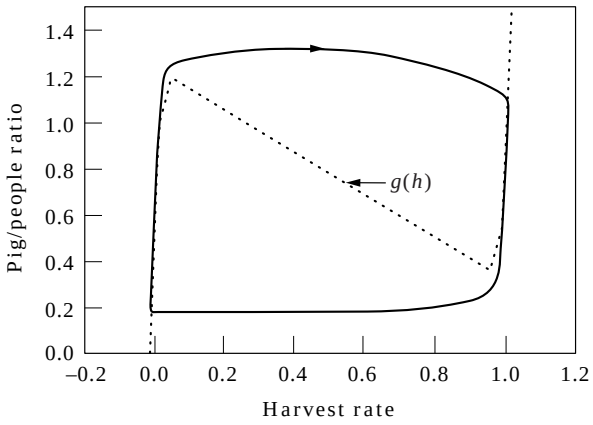

FIG. 10. Form of $g(x)$ in eqn (17a) and the associated limit cycle.

figures may represent the maximum physically possible. When females are burdened with this many pigs, their complaints to their husbands become more frequent. The husbands then call for the Kaiko to be staged during which the pig herd is drastically reduced via ritual sacrifice.

To model this we add variables for the pig population (x_3) and the "harvest" (h) level of pigs. When x_3 is less than the level tolerable by the Tsembaga women, h is very low. When x_3 reaches a critical level of about 2–3 pigs per woman, the Kaiko "breaks out" and h increases very rapidly. The dynamics of this type of system can be modeled by a dynamical system of the form:

$$\frac{dh}{dt} = \tau(x_3/x_1 - g(h)) \tag{17a}$$

$$\frac{dx_3}{dt} = (r - h)x_3 \tag{17b}$$

where r is the intrinsic growth rate of the pig population and the function $g(h)$ has the form in Fig. 10, and τ, which is relatively large is the relaxation time. The trajectory in the phase plane generated by the dynamics in eqns (17a) and (17b) is superimposed on $g(h)$.

When the quantity x_3/x_1 is between 0.2 and 1.2, eqn (17a) forces h to track the function $g(x)$ very closely. Once outside these limits, the difference between x_3/x_1 and $g(h)$ grows causing h to change very quickly, as shown in Fig. 11.

The graph on the left shows the pig population dynamics. The population grows exponentially until it becomes unbearable to support. At this point, the Kaiko "breaks out" and the pig harvest level increases very rapidly, remains elevated for approximately 1 year during the pig festival until the pig population is reduced significantly.

After the staging of the Kaiko, the ritually sanctioned truce between hostile groups is ended by the uprooting of the rumbim plant. Hostilities are then allowed to, but do not necessarily, resume. If hostilities can be avoided through two ritual cycles, lasting peace between the two hostile groups can be established. Rappaport notes, however, that hostilities are generally resumed by 3 months after the Kaiko and can last up to 6 months.

During actively hostile periods, actual combat is frequently halted for the performance of rituals associated with casualties and for pigs and gardens to be tended. Warfare comes to a halt with another ritual truce when both sides feel that enough killing has taken place or combatants simply tire of fighting. Since the fighting forces are composed of principal combatants and their allies, as time goes on, the support of allies becomes more difficult to maintain increasing pressure to bring hostilities to an end. To model this we use the fact that after several casualties have occurred, the people to pig ratio begins to decrease. As this happens, the per-person work level begins to increase and daily living activities become more pressing. The pig to

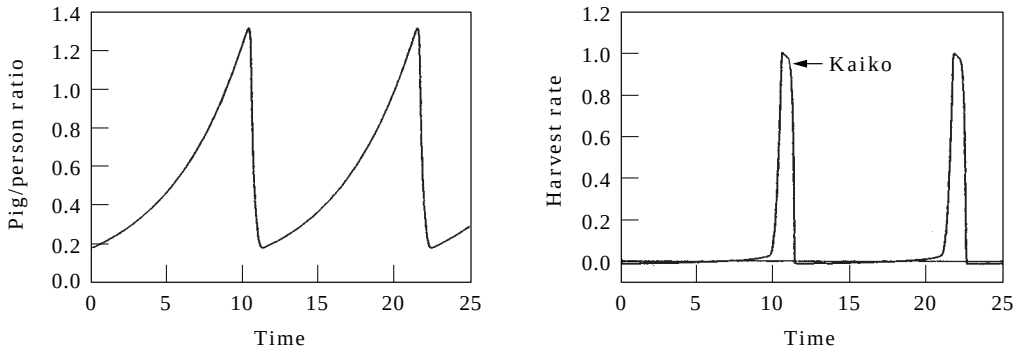

FIG. 11. The dynamics of the ritual cycle. These represent the time plots of the limit cycle shown in Fig. 10. Between Kaikos, the harvest rate is very low. When the pig to person ratio exceeds the tolerable level, the harvest rate increases dramatically representing the pig slaughter associated with the Kaiko as shown in the graph on the right.

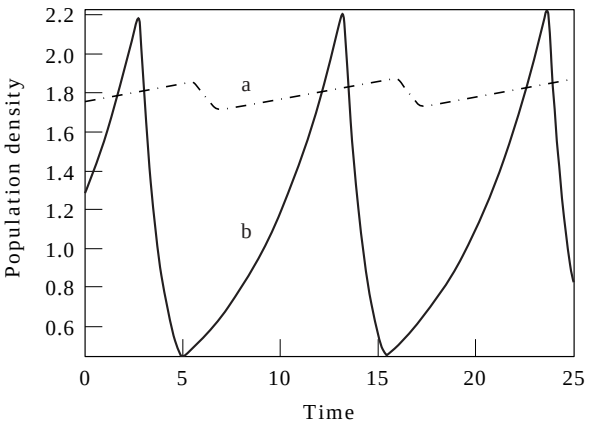

FIG. 12. An example of the human (a), and pig (b), population trajectories under cultural outbreak dynamics. After the Kaiko when the pig population drops drastically (curve b) warfare resumes and the human population drops (curve a). As people are killed, the human pig ratio drops until a cut-off is reached and a truce is called.

person ratio acts as a proxy for this increased work effort and the warfare outbreak dynamics can be expressed by:

$$\frac{dw}{dt} = \tau(x_1/x_3 - \gamma g(w) + \delta) \tag{18}$$

where w is the per-capita death rate due to war and γ and δ merely scale and shift the ratio of people to pigs where the outbreak of war and ritual truce occur. The human and pig population dynamics under this scenario are shown in Fig. 12.

The pig population increases until the Kaiko breaks out when the pig population is drastically reduced. Soon after, war breaks out and the human population is reduced until the pig to people ratio dictates that the rumbim be planted and a truce put in place. With this, the cycle begins anew. We now examine the dynamics of the full system.

6.3. THE BEHAVIOR OF THE FULL SYSTEM

The most critical aspect of the full model is the assumptions about the effect of warfare on the population. Unfortunately, data on warfare related mortality are not rich—estimates range from 2 to 8% of the population (Foin & Davis, 1984). This is not an important issue with regard to stability, however. The key point is the assumption that the number of deaths due to warfare is a constant fraction of the population. If we make this assumption then the human population dynamics would be given by

$$\frac{dx_1}{dt} = (b_n - a\exp\left(-\alpha\frac{e(x_1, x_2, c_1, c_2)}{x_1}\right) - w)x_1. \tag{19}$$

If the system is to evolve to a stable limit cycle, the parameters that govern the dynamics of w must be chosen such that the average value over one cycle of the quantity

$$(b_n - a\exp\left(-\alpha\frac{e(x_1, x_2, c_1, c_2)}{x_1}\right) - w) \tag{20}$$

vanishes. Since the cultural dynamics act to drive $e(x_1, x_2, c_1, c_2)$ toward 1, the growth rate of the human population is nearly constant and only very weakly dependent on the *physical state* of the system over most of a cycle. The average war mortality over a cycle must be balanced against essentially a constant growth rate, and there is no mechanism by which the model can "seek" an equilibrium population level. In this case the ability of the Kaiko to stabilize the system is very sensitive to parameter choices. This may help explain why the model due to Shantzis & Behrens (1973) was neutrally stable and, of course, why when Foin & Davis (1984) used different parameters [making the counterpart of expression (20) in their model positive in mean over one cycle] found that the Kaiko would not stabilize the system. Here, there is no mechanism by which the model can "seek" an equilibrium population level.

If, on the other hand, we assume that mortality due to warfare increases nonlinearly with the population size, the Kaiko can stabilize the system. Rappaport actually indicated that this was the case. As there are more pigs, people, and gardens there are more ways for pigs to invade gardens and cause conflict, increasing the number of required blood revenge deaths during an active period of warfare. The number of ways a pig might invade an enemies garden rises much faster than linearly with increases in pig and garden numbers. If we assume that number of war mortalities behaves roughly as the square of the population size, the human population dynamics are given by

$$\frac{dx_1}{dt} = (b_n - a\exp\left(-\alpha\frac{e(x_1, x_2, c_1, c_2)}{x_1}\right) - wx_1)x_1. \tag{21}$$

We then define the full ecological system by the physical component defined by eqns (21), (7b) and (17b) and the cultural component defined by eqns (17a), (14), and (18).

The dynamics of the ritual variables are confined to stable limit cycles and the work level follows

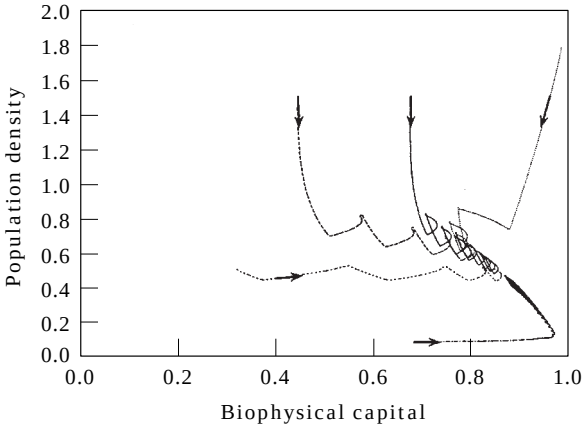

FIG. 13. Sample trajectories for the full model. Any time that the human population is large compared to biophysical capital, the pig to people ratio will be high and warfare will break out. This drives the population to a more stable (or sustainable) region in the state space whence the system collapses onto the very low amplitude limit cycle shown in Fig. 14.

food demand forcing the overall system behavior to be cyclic. With the human population dynamics defined by (21), the ritual warfare acts to drive the system to equilibrium keeping the human population in check. Figure 13 illustrates the behavior of several trajectories beginning from different reasonable initial conditions. They all collapse onto a very small amplitude stable limit cycle. Projections of this cycle onto the $x_1 - x_3$ and $x_2 - x_1$ planes are shown in Fig. 14.

The ritual cycle effectively keeps the human population density in the interval (0.41, 0.49) and the natural capital in the interval (0.86, 0.89). Compare these fluctuations to the case without the ritual cycle (see Fig. 6). The model predicts that if the Tsembaga attempt to meet food demand, it is possible that the ritual cycle could play a critical role in stabilizing the ecosystem.

7. Conclusions

The dynamical system model for the Tsembaga ecosystem based on the ethnographic work of Rappaport (1968) developed in this paper suggests that behavioral plasticity, feedback from the land, and the relationship between people and pigs are the main factors affecting ecosystem stability. Behavioral plasticity is strongly destabilizing because it allows people to attempt to overcome nutritional deficiencies that would otherwise help stabilize the system. Critical to the effect behavioral plasticity has on the model is the relative productivity of labor. If the increased nutritional intake generated by increased effort more than offsets the soil productivity losses due to the associated shorter fallow periods, the model stability structure is sensitive to changes in effort directed to agriculture. Increased marginal productivity of the soil (sensitivity of soil productivity to increased effort) has a stabilizing influence, reducing the importance of behavioral plasticity in determining the stability of the system.

If the marginal productivity of labor (in the short run) is higher than that of soil (probably reasonable) then the destabilizing effect of behavioral plasticity can be so strong as to nullify the stabilizing effect of malnutrition and disease proposed by Buchbinder (1977) opening up the possibility of temporally violent oscillations in population numbers. By extending the model, it was shown that pig husbandry, in and of itself, helped stabilize the system. Finally, pig husbandry combined with the ritual cycle can act as a homeostatic mechanism to stabilize ecosystem as proposed by Rappaport *if war mortality is density dependent*. This runs contrary to earlier results (Foin & Davis, 1984, 1987; Shantzis & Behrens, 1973) that emphasized sensitivity to parameters. The model presented

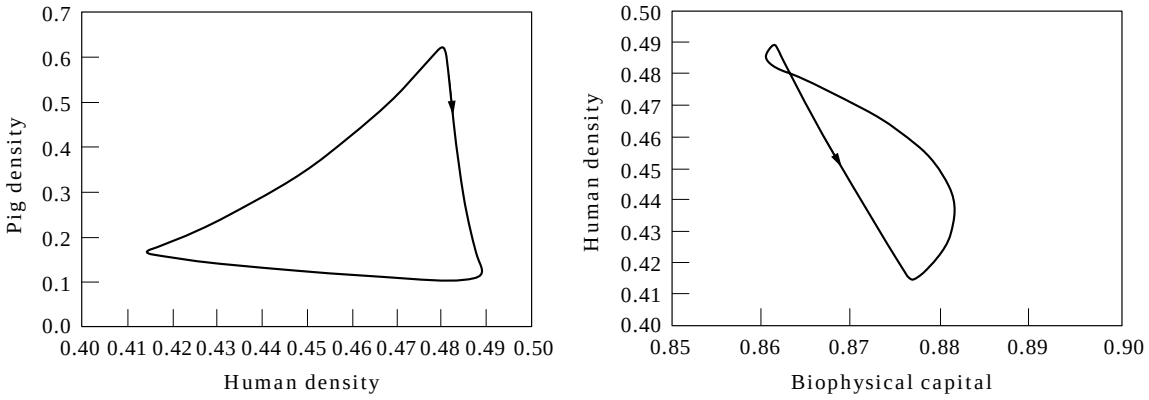

FIG. 14. Limit cycle for the full model projected into the $x_1 - x_3$ and $x_2 - x_1$ planes respectively.

here is fairly robust to changes in parameters and suggests that the key factors are the structure of the food production function and density dependence of war related mortality.

Many of the original criticisms of Rappaport's work centered on the problem of explaining how the Tsembaga cultural system might have come about, and the appropriateness of the ecosystem concept as he applied it. Of course, no model can explain the evolution of behavior, at best it can only shed light on how certain behavior could be adaptive. The focus of this paper was to study the effects humans and their cultural practices can have on an ecosystem. We found that culture can be both destabilizing (how hard a population decides to work) and stabilizing (the ritual cycle). The model presented here supports the claim that a cultural mechanism such as the Tsembaga ritual cycle can operate to prevent ecosystem degradation. If an individual can do better by participating in the existing cultural "environment" rather than going against it, any cultural construct that prevents ecosystem destruction could have adaptive value for the individual. In this sense the ritual cycle of the Tsembaga could have adaptive value as Rappaport originally proposed. The model also highlights the destructiveness of a society that directs ever increasing quantities of energy to agriculture in the face of continually degrading soil quality, and the importance of the role "sustainable culture" might play in both past and present sustainable human agro-ecosystems.

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