Version 2,
January, 2012

Anthropology Exercises:

Pigs for the Ancestors

These exercises provide an opportunity to use system dynamics to study the cycles in human and pig populations described in *Pigs for the Ancestors: Ritual in the Ecology of a New Guinea People.* The book is shown in photo 1. Roy Rappaport, the author, is shown along side of the Tsembaga clansmen in photo 2. The exercises begin with background on the Tsembaga clan, their pig population, their slash & burn gardening and the pivotal roles of pig festivals and human warfare.[1]

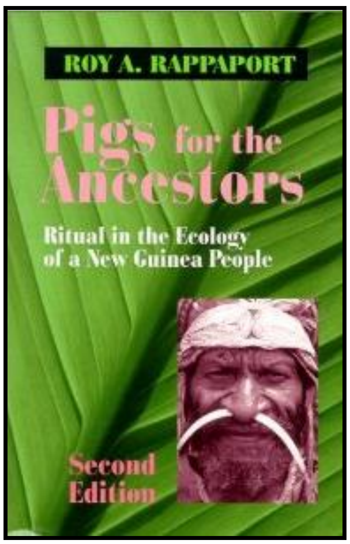

Photo 1. Pigs for the Ancestors

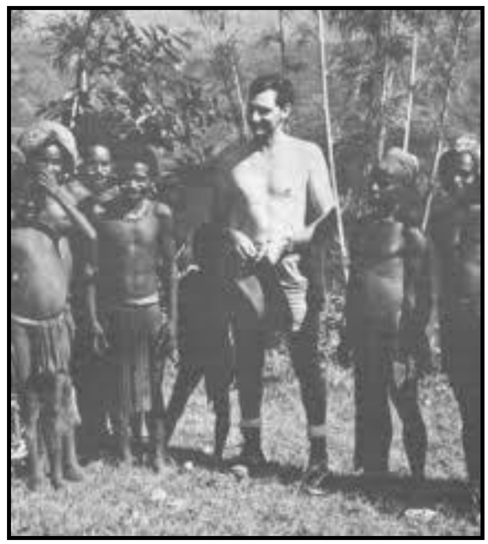

Photo 2. Roy Rappaport & the Tsembaga.

The exercises call for a series of models to explain the cyclical pattern of the human and pig populations. Each model will build from the previous model, allowing you to develop a model of the sustainability of the Tsembaga system. Their key physical resource is the fertility of land in the tropical forest. The Tsembaga land allows for slash and burn gardening that can provide adequate yields for a limited population. However, if the population were to grow too large, the Tsembaga face difficult choices about the use of their land to feed the growing population.

[1] The modeling exercises are based on a system dynamics model of the Tsembaga by Shantzis and Behrens (1973). They describe the model's feedback structure one-loop-at-a-time with the help of causal loop diagrams. The entire model is then presented in the form of a DYNAMO diagram and equations. The model is extensively tested to show behavior under a wide range of conditions. They used their model to study the sustainability of the Tsembaga population with and without warfare. They concluded that warfare was an integral part of the overall system. They believed that the system had evolved into a homeostatic mode of behavior that controls the population at levels that could be sustained indefinitely. Their simulations without warfare showed an unsustainable situation, and they questioned the wisdom of those who would intervene to disallow warfare. These exercises take a different approach. You will start with small models that can be tested and verified before you move on to larger models. Your model will represent very similar dynamics and yield similar conclusions. And your model will provide a more explicit portrayal of the patterns of land use.

Background

Pigs for the Ancestors is Roy Rappaport's classic anthropological study of the Tsembaga tribesmen in the New Guinea highlands. The Tsembaga are a sub clan of the Marring-speaking peoples. Rappaport was interested in the Maring because of their relative isolation and interesting culture. The Maring practice slash-and-burn agriculture in which only a portion of their total acreage is cultivated at any given time. The area is cleared of forest and burned over. The burning clears away the underbrush for planting and produces a nutrient ash residue which adds to soil fertility. The Maring cultivate root crops which provide their main sustenance. The crops in one area are harvested for a year or two, depleting the nutrients in the area. When yields decline, they move to a new area and repeat the process of clearing, burning and cultivation. The previously cultivated land quickly becomes covered by tropical rain forest. It will be suitable for clearing and cultivation in around fifteen years.

The Tsembaga Subclan

This exercise introduces you to the Tsembaga, a Maring subclan living in the heart of a virgin forest.[2] The clan numbered around 200 people when Rappaport arrived. The Tsembaga herd pigs, and their domestic herd could range in size from 50 to 200 pigs depending on when the pigs were counted. The pigs were highly valued. Indeed, the owner of many pigs is accorded both respect and material reward. The pigs are normally not killed except to meet religious or family obligations. The pig herd grows at around 14%/year during most years. This rapid rate of growth means that the pig population would double every 5 years. If there were 50 pigs today, there would be 400 pigs in 15 years. The pigs can be troublesome since they interfere with the Tsembaga gardens and the neighboring clan's gardens. The women are responsible for caring for the pigs. Imagine the challenge for 100 women caring for 400 pigs: each woman has to deal with 4 pigs. The job is too much to bear, and the tensions mount as the pigs create problems in the both the Tsembaga gardens and in the neighboring clan's gardens.

When the pigs become too difficult, a festival is initiated; a major fraction of the pig population is slaughtered; and the Tsembaga celebrate with a feast. People from neighboring tribes are invited, and great ceremony is made of the presentation of pigs to ritual friends and relatives. The precursor of the festival is the uprooting of the rumbim, a special garden of tubers planted ten to fifteen years earlier at the close of the previous warfare. War is prohibited while the rumbim are in the ground. Once they are uprooted, the taboo is lifted, and the tribe is free to engage in conflicts. War with neighboring clans breaks out almost immediately after the festival is declared. Conflict usually continues for a year. The main objective of warfare is to redress past grievances, and conflict continues as each side attempts to "get even." Inevitably, warfare does not produce the desired results, and the warring parties negotiate a temporary truce. The Tsembaga may experience 12% fatalities by the time the truce is declared. The truce allows them to return to routine life. Internal restrictions against warfare are reinstated, and they apply until the next pig festival. The episodes of warfare between the Tsembaga and neighboring populations occur in intervals of around 12-15 years.

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[2] The Tsembaga village is in the Madang Province of Papua New Guinea (PNG). The PNG occupies the eastern half of the island of New Guinea. (The western half is administered by Indonesia.) The 1973 work by Shantzis and Behrens addressed the impacts of prohibiting warfare. This was an issue for Australian administrators at that time. The PNG gained its independence in 1975.

Exercises: Build, Simulate and Verify

This background provides a sufficient introduction for you to launch into the modeling exercises.

<u>Exercise 1. Cycles in the Pig Population</u>

Build the model shown in Figure 1. The stock keeps track of the pig population by accumulating the effect of *net pig births* and *pig deaths in festivals*. Assume that the:

initial pig population = 40, human population = 160
net pig birth rate = 0.14/year, pig kill fraction = 0.85, and
pig_deaths_in_festivals = festival_declared?*pig_kill_fraction*pig_population

Assume that a festival is declared whenever the ratio of pigs to humans exceeds 1.0. (This corresponds to a tolerable load of 3 pigs per female if one-third of the population are females.[3]) We can use a binary variable *pig festival declared?* (where 1 means yes, 0 means no):

festival_declared? = IF(pigs_per_human>1) THEN 1 ELSE 0

Simulate the model with DT = 1 year. Turn in a time graph to verify that you get the results in Figure 2.

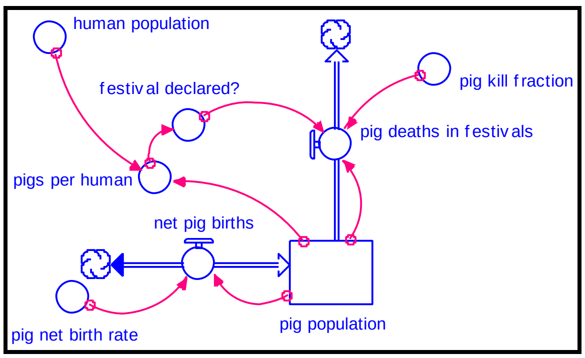

Figure 1. Model to explain cycles in the pig population.

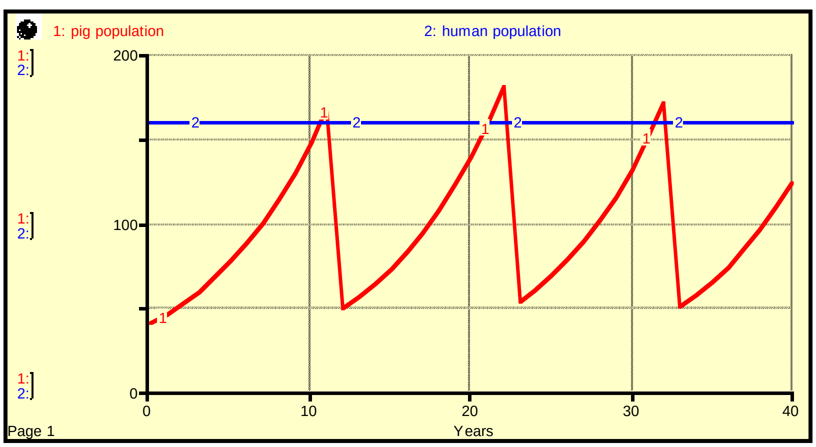

Figure 2. Simulated cycle in the pig population (with DT = 1 year).

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[3] Shantzis and Behrens (1973) took note of Rappaport's finding that 32% of the Tsembaga population was female.

Figure 2 shows the pig population growing from 40 to 160 during the first ten years of the simulation. With 160 pigs (and 160 humans), the burden is too great, and a festivals is declared. The pig population falls by 85% during the festival. It then grows at 14%/year. This rate of growth ensures that the pigs will be too numerous around 12 years later. A second festival is declared, and the pig population is again reduced by 85%. The interval between the festivals is approximately the same as the interval observed by Rappaport.

Exercise 2. Testing the Pig Model with Different Values of DT

We normally check the numerical accuracy of a simulation by cutting DT in half and repeating the simulation. Give this a try for the model in Fig 1; you may be surprised by what you see. With DT = 0.5 years, the pattern of oscillations will bear no resemblance to Fig 2. Try setting DT = 0.25 years and simulate the model. Once again, you will see an entirely new pattern which bears no resemblance to Fig 2. These tests reveal that the model in Figure 1 only works properly if DT = 1 year.

If we wish to simulate with smaller values of DT, we need to introduce the *time step*, as shown in Figure 3. The new equation for the pig deaths from festival would be:

*pig_deaths_in_festivals = festival__declared?*pig_kill_fraction*pig_population/time_step*

Notice that this equation uses the previous value divided by the *time step*. We will simulate the model with the time step at 1/8th of a year. When we divide by 1/8th, the flow would be 8 times higher than in the previous model. This may sound too high, but the flow is exactly what we need since it must accomplish the pig deaths in 1/8th of a year (rather than in 1 year).

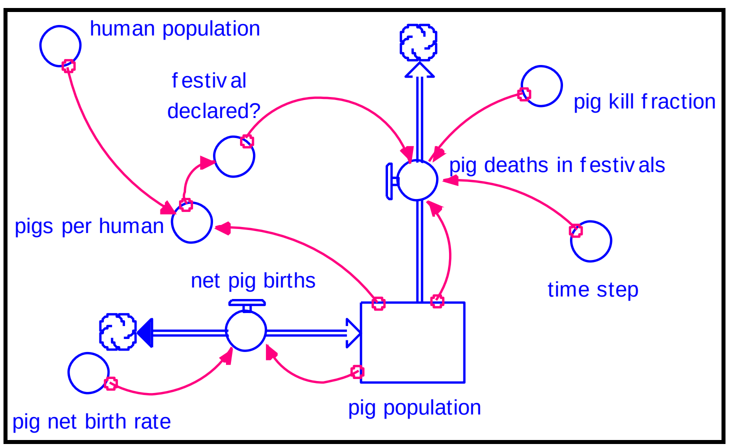

Figure 3. Changing the pig deaths in festivals.

Build the model in Fig 3 with the *time step* and DT = 0.125 years. You should see the results in Fig 4. Compared to the previous model, we see a more rapid decline in the pig population since the pig deaths are concentrated in 1/8th of a year. The new time graph shows that the festivals are declared exactly when the pig population reaches the same value as the human population. The new simulation shows a 13-year interval between festivals, a result consistent with intervals reported by Rappaport.

Figure 4. New simulation of the pig cycle with a smaller DT.

Exercise 3. Add Human Population Growth to the Model

Expand the previous model as shown in Fig 5. It introduces a new stock to keep track of the human population. The net human births represents the net effect of births minus deaths from normal life. The other flow keeps track of the human deaths from warfare. To keep the model simple, we assume that the deaths occur at the same time as the pig festival. [4] This assumption allows us to write the equation for human deaths in war similar to the pig deaths in the festival. That is:

human_deaths_in_war =
*pig_festival_declared?*human_kill_fraction*human_population/time_step*

As before, a festival is declared whenever the number of pigs exceeds the number of humans. The pig festivals in the new model will trigger the loss of 85% of the pigs and 12% of the humans.

Simulate the model for 40 years, and verify that you get the results in Figure 6. The rapidly growing pig population triggers the first festival around the 11th year. We see a 12% decline in the human population as well as the 85% decline in the pig population. Figure 6 shows three festivals with around 13 years between the festivals. The simulation shows that the two populations are held in check by the combination of pig festivals and warfare.

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[4] War breaks out almost immediately after a pig festival and takes place sporadically over a year. The exact timing of the human deaths in warfare will not be crucial in this set of exercises, so we simplify the model by assuming that the deaths occur immediately after the pig festival.

Readers interested in a more detailed simulation of the humans engaged in warfare may turn to the article by Kampmann (1991). He provides a critical review of the Shantzis and Behrens' model along with some alternative formulations to achieve similar results.

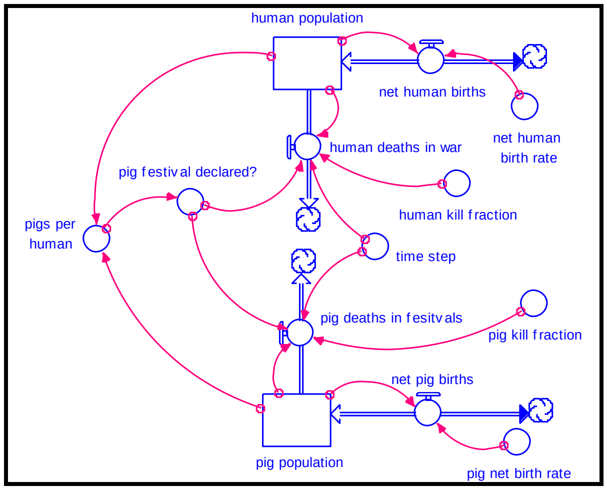

Figure 5. Add the human population to the model and simulate with the following parameters: net human birth rate = 0.01/year; human kill fraction = .12, pig kill fraction = 0.85, pig net birth rate = 0.14/year, initial values = 160 humans and 40 pigs, and the time step and DT = 0.125 years

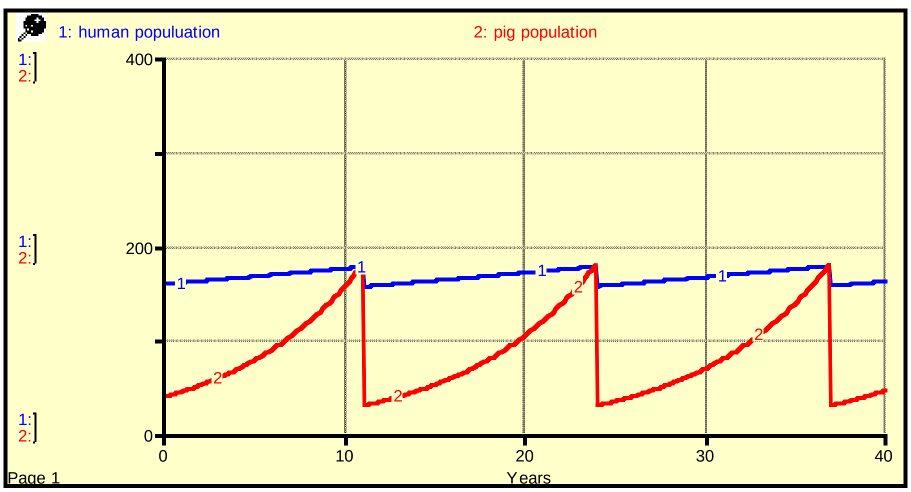

Figure 6. Repeating cycles in human and pig populations.

Figure 6 gives the impression that the populations would be held in check by the Tsembaga rituals. To verify that the population are, indeed, held in check, simulate the model for 160 years. Does the human or the pig population ever exceed 200?

Exercise 4. Population Growth if Warfare is Prohibited

Simulate the model in Figure 5 with the human kill fraction set to zero. With this assumption, pig festivals would still be declared, but warfare with the neighbors is prohibited.[5] Simulate the model for 160 years and verify the results in Figure 7. By the end of the simulation, there are 800 people. A few years later, there would be 800 pigs.

[5] Elimination of warfare might be achieved if the Australian government convinced the Maring to discontinue the practice of ritualistic warfare. One purpose of the Shantzis and Behrens (1973) chapter was to show the long-term consequences of eliminating this built-in population control mechanism.

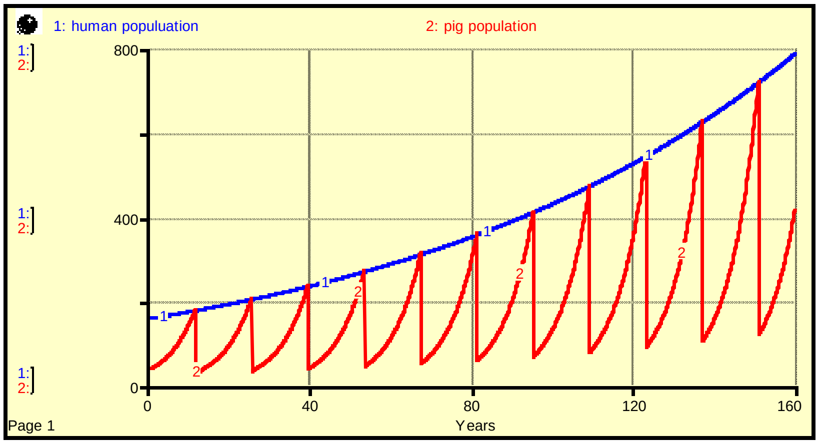

Figure 7. Growth in human and pig populations if warfare is prohibited.

Exercise 5. Add Cultivation Requirements to the Model

Build the model shown in Figure 8 and simulate it for 120 years with DT and the time step = 0.125 years. Set the human kill fraction = 0 (i.e., warfare is prohibited) and verify the results in Fig 8.

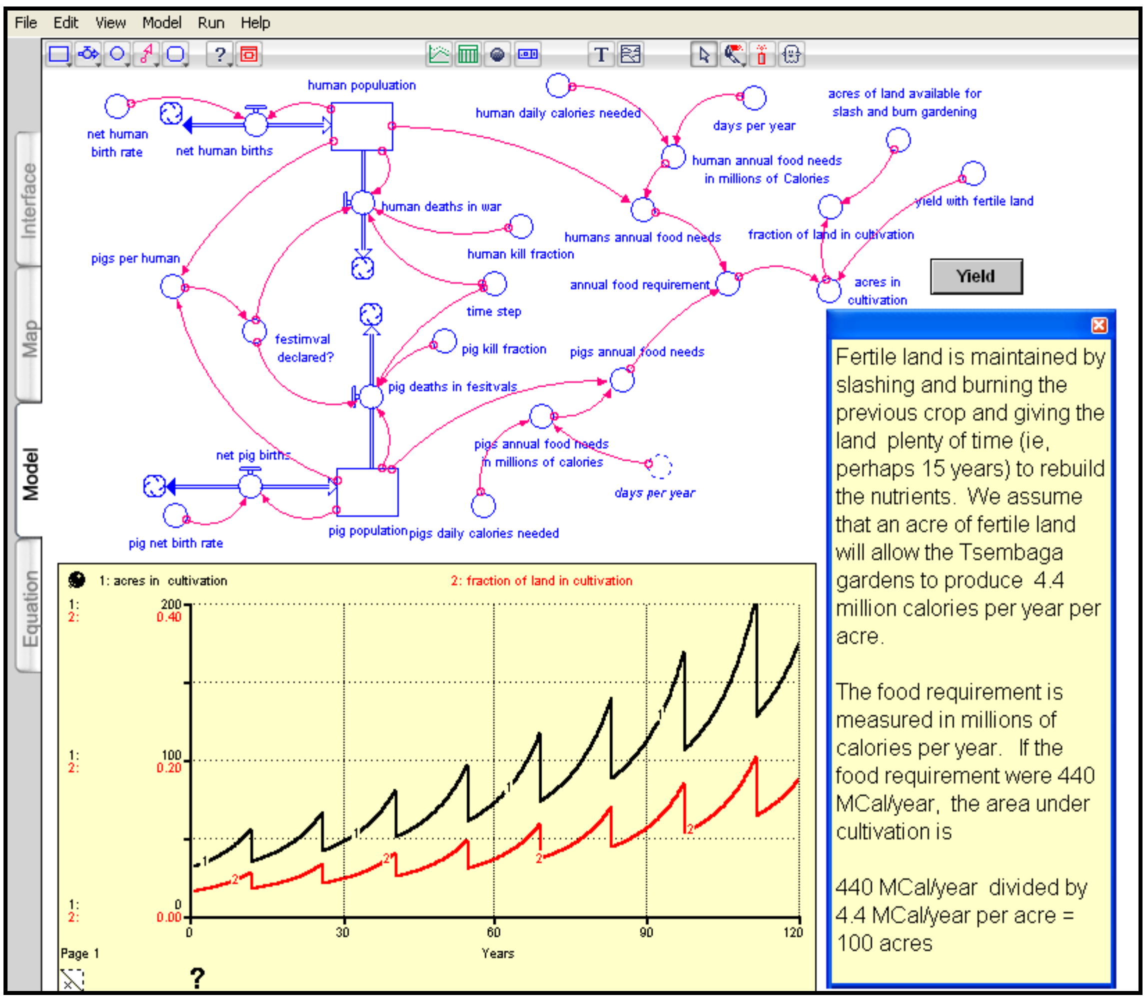

Figure 8. Model with food requirements in a simulation with warfare prohibited.

The new model includes variables to keep track of the annual food requirements and the acres in cultivation. The food requirement for the average human is 2,000 calories per day; the average pig needs 1,600 calories per day. Annual food needs are obtained by multiplying by 365 days/year and dividing by 1e6 (one million) to get the requirements in millions of calories per year (MCal/year). The average human needs 0.73 MCal/year; the average pig needs 0.58 MCal/year. When the land is cultivated with a sufficiently long fallow period, the yield is 4.4 MCal/year per acre. As explained in the yield button, we divide the annual food requirement by the yield to obtain the acres under cultivation.

The black curve shows the acres under cultivation. We assume a total area of 1,000 acres.[6] The red curve shows the fraction of this land under cultivation. The simulation begins with 32 acres under cultivation. This is only 3.2% of the total area, so there is plenty of land. Cultivated acres increases over time due to the growth in the number of pigs and the number of humans. The declines in cultivated acres coincide with the 85% reduction in pig population when festivals are declared. The model counts pig food needs as part of the total. When the total need drops, the acres under cultivation drops as well. The abrupt declines in cultivated land would probably not occur in the actual system.[7] So we should focus our attention on the general, upward trend in land cultivation. The black curve in Fig 8 shows cultivated acres exceeding 100 acres by the 66th year and exceeding 200 acres by the 112th year.

The 200 acres is 20% of 1,000 acres assumed to be available in this simulation. The 20% result is a problem for the Tsembaga because it only allows a 5-year fallow period before the land would be put back into cultivation. This period is far too short for the yield to recover properly. If we want a fuller understanding of the implications of prohibiting warfare, we need to expand the model to simulate the land use practices and their possible impact on yield.

<u>Exercise 6. Simulating a Land Use Policy to Ensure Full Yield</u>

Build the model in Fig 9 using the parameter values shown in Tables 1 & 2. Simulate the model for 150 years with DT (and time step = 0.125 yr) . Verify that you obtain the results in Figs 10 and 11.

initial value of the stocks:	160 humans, 40 pigs
net human birth rate	0.01/year
human kill fraction	0 (warfare is prohibited)
pig kill fraction	0.85
pig net birth rate	0.14/year

Table 1. Population parameters for the model in Figure 9.

[6] The area that could be gardened with slash and burn is difficult to estimate given the hilly terrain and the potential for erosion if the Tsembaga stray into the hilly area. Shantzis and Behrens (1973) estimate the arable land at around 1,300 to 1,400 acres. We use 1,000 acres (a nice, round number) in this exercise so that the fraction under cultivation is easy to understand.

[7] We would expect the Tsembaga to anticipate these abrupt declines and deal with them through advance planning or with food storage. If these measures were simulated in the model, the acres of cultivated land would probably follow a smoothed version of the black curve shown in Figure 8.

The simulation begins with 40 pigs and 160 humans. Each human needs 2,000 calories/day, which is the same as 0.73 MCal/year. The annual food needed for the 160 people would be 117 MCal/yr. Each pig needs 1600 calories/day, which is the same as 0.58 MCal/yr. The annual food needed for the 40 pigs would be 23 MCal/yr, and the total food requirement is 117 + 23 or 140 MCal/yr. We assume that the land use is carefully controlled to maintain the yield at 4.4 MCal/yr per acre. The simulation begins with 32 acres under cultivation (see Table 2), so food production would be 32 acres times 4.4 MCal/yr per acre = 140 MCal/yr. The land cultivation time is 1 year, so the acres returned to the fallow state is 32 acres divided by 1 year = 32 acres/year.

initial value of fallow land:	1318 acres
initial value of land in cultivation:	32 acres
fallow interval to rebuild the yield	15 years
land cultivation time	1 year
yield with fertile land	4.4 MCal/year per acre
human daily calories needed	2000 calories/day per person
pig daily calories needed	1600 calories/day per pig
days per year	365 days/year

Table 2. Food needs and land use parameters for the model in Figure 9.

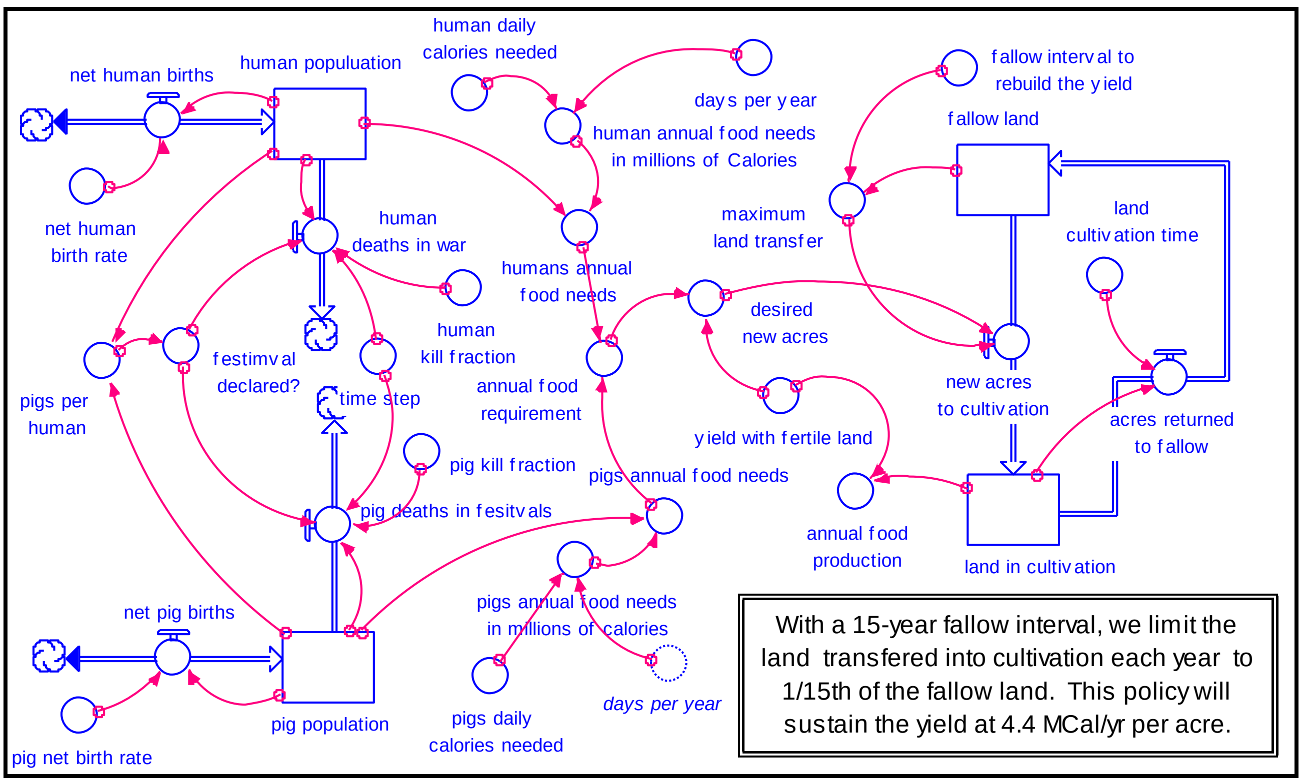

Figure 9. Land cultivation is expanded to meet the annual food requirement, as long as there is a sufficiently long fallow period to sustain the yield per acre.

The key variable in the new model is the maximum land transfer that would be allowed so that the new acres put into cultivation will deliver the standard yield. We assume a 15-year fallow interval is required for the land to rebuild its fertility after the 1-year period of cultivation. The simulation begins with 1318 acres in fallow state.[8] This means the maximum transfer at the start would be 1318 acres divided by 15 years = 88 acres/year. The Tsembaga only desire to put 32 new acres into cultivation at the start, so the maximum of 88 acres/year does not limit what they plan to do at the outset.[9]

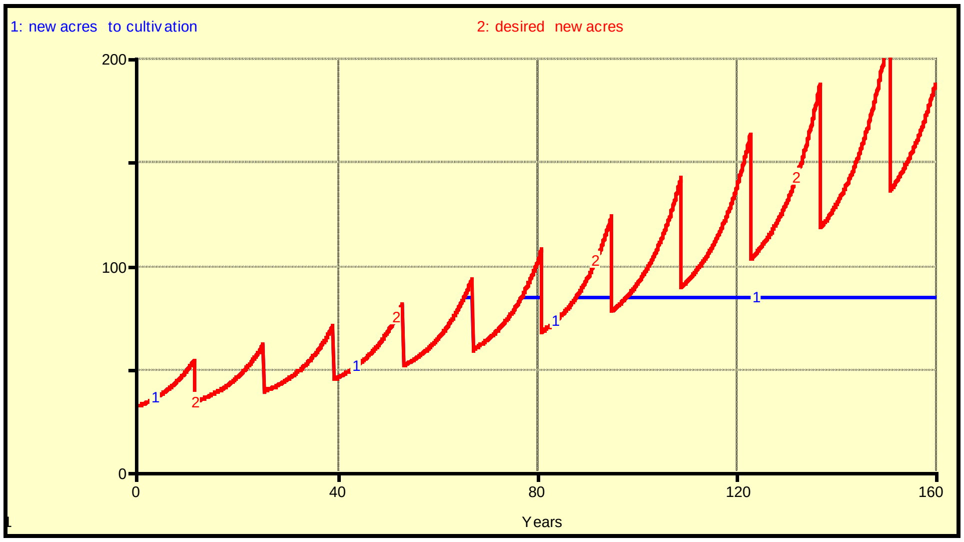

Figure 10. Desired new acres and actual new acres to cultivation in a simulation without warfare.

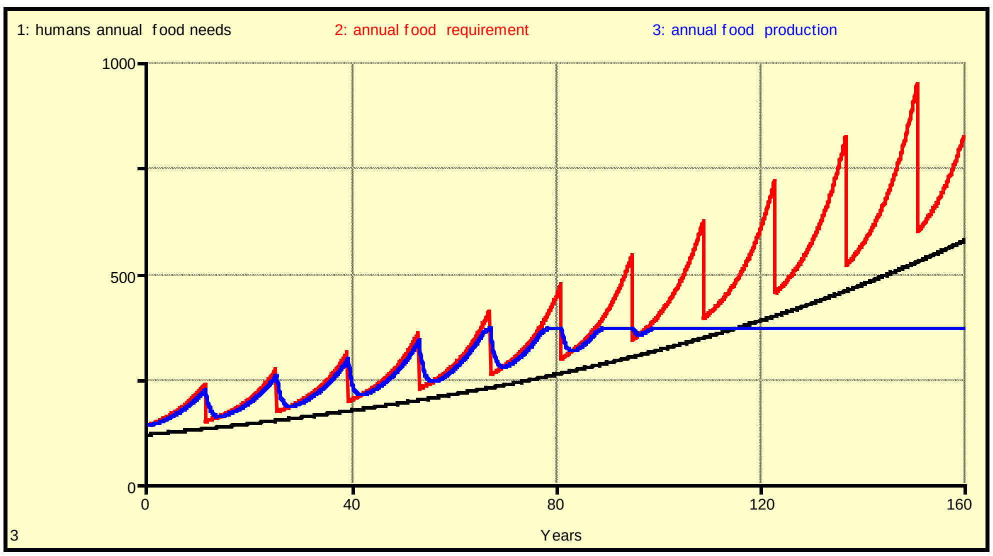

Figure 11. Food needs and food production in a simulation without warfare.

But problems appear in the 77th year of the simulation. The Tsembaga restrict the land under cultivation, as shown by the blue line in Figure 10. If yield is to be protected, only around 84 acres can be put into cultivation each year. Figure10 shows desired new acres (in red) climbing far beyond the new acres that can be put into cultivation.

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[8] Shantzis and Behrens (1973) estimated the total, arable land at 1,350 acres.

[9] Use Stella's MIN function to make sure that the new acres to cultivation is the smaller of the two values. That is:

new acres to cultivation = MIN(maximum land transfer, desired new acres).

The impact on food production is shown in Figure 11. The black curve shows the humans' need for food; it grows exponentially at 1%/year, so it will double every 70 years. The total food needed is shown in red in Figure 11; it grows rapidly when the pig population is growing at 14%/year. It drops dramatically every 13 years when 85% of the pigs are slaughtered in a festival.

The adequacy of food production is evident from a comparison of the blue and red curves in Figure 11. Food production is in blue; it keeps pace with the red curve until the 77th year. The Tsembaga would then face a food shortage, and they would have to decide how the shortage would be allocated between the humans and the pigs. The food shortage becomes more and more severe in the next few decades. By the 95th year, there is little food remaining after meeting human needs. At this point, one might envision the Tsembaga abandoning the pig herd to preserve the food for human consumption. This drastic step would eliminate their way of life, but it would allow human needs to be met for the next 20 years. Then, in the 115th year, the Tsembaga would find themselves with insufficient food to meet their own needs. With continued growth in human population, the food shortage grows increasingly severe until the end of the simulation.[10]

Figures 10 and 11 show the adverse impacts of a prohibition on the Tsembaga practice of warfare. Eliminating this ritual behavior would cause the population to climb past the carrying capacity of the gardening system. The impacts would impose huge changes in the Tsembaga way-of-life and would ultimately lead to inadequate nutrition for the Tsembaga people.

On the other hand, the simulation shows the long delays before the adverse impacts of a warfare prohibition would be evident. The prohibition is imposed from the outset of the simulation, but the first, significant indication of a cultivation problem does not appear until the 77th year. Problems that would first appear 77 years in future might not count for much in the minds of those who would impose a prohibition on warfare.

Exercise 7. Onset of food shortages with faster growth in the human population.

The 77- year interval is quite long because the humans' net birth rate is quite low (only 1%/year). Shantzis and Behrens believed the net birth rate is 1.3%/year. Simulate the model with the net birth rate at 0.013/year and generate a graph similar to Fig 11. <u>When do the first signs of a food shortage appear?</u>

Shantzis and Behrens conducted a simulation with the net birth rate at 1.5%/year to represent a scenario with "improved health." Change the net birth rate to represent this scenario and generate a graph similar to Fig. 11. <u>When do the first signs of a food shortage appear?</u>

Shantzis and Behrens also conducted a simulation with the net birth rate at 2.0 %/year to represent a scenario with "more improved health." Change the net birth rate to represent this scenario and generate a graph similar to Fig. 11. <u>When do the first signs of a food shortage appear?</u>

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[10] The model in Figure 9 does not include feedback from food adequacy to either the net birth rate for pigs or for humans. These feedback effects are included in the DYNAMO model by Shantzis and Behrens (1973).

Exercise 8: Feedback Loop Structure.

The model is showing important dynamics, so let's examine the feedback loop structure. Figure 12 shows a good start toward a causal loop diagram of the model shown in Figure 9. Complete the diagram by labeling each arrow as + or -. Then label each feedback loop as (+) or (-). You should see seven feedback loops in the diagram. Assign a number to each loop, and provide a label or description of in Table 3.

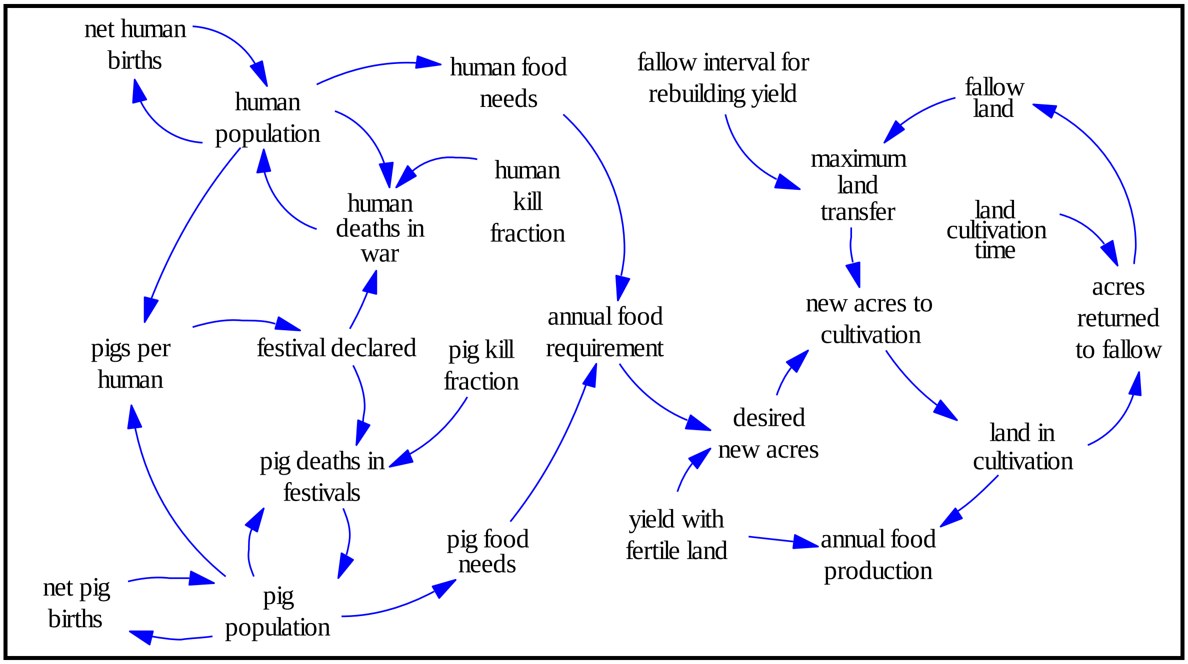

Figure 12. Complete this causal loop diagram of the model in Figure 9.

#	**Loop Label or Description**
1	
2	
3	
4	
5	
6	
7	

Table 3. Fill in this table to label or describe each feedback loop.

Exercise 9. A Separate Model to Simulate Land Use in More Detail

The previous model used two stocks to simulate the land use: one stock for land in cultivation, the other stock for the fallow land. At this stage, it makes sense to take a closer look at the way the land is used. We will simulate the land use in a separate model. It will stand alone from the previous model of human and pig populations. We will test the new model with exogenous inputs for the total food requirement, and we will use the model to see how land uses would change when the food requirement is growing exponentially.

We will start the simulation with annual food needs of 200 MCal/year, a value based on the average needs shown in the first year of Figure 11. The cultivated land would be 200/4.4 or approximately 45 acres. The cultivated slice of land is depicted in white in Figure 13. This diagram shows the entire 1,350 acres of land as it might appear after decades of sustained use to meet a food requirement of 200 MCal/year. This year's cultivation is 45 acres; last year's cultivation would have been 45 acres; cultivated land 10 years ago, 20 years ago, and 30 years ago would have been 45 acres. This constant pattern from the past makes sense if the population were kept in check by Tsembaga rituals (as shown in Figure 6) and the yield were maintained by a proper rotation period.

These assumptions about the past lead to the pattern of 45-acre slices of fallow land in Figure 13. For example, the purple slice to the northwest of the cultivated slice is land in the first year of fallow state. This land was under cultivation one year prior to the start of our simulation. The green slice (to the northwest of the purple slice) is in the 2nd year of a fallow state (but under cultivation two years prior to the start of our simulation.) Following this pattern in a clockwise direction, we arrive at the 45 acres in the north-north-east, land in the 14th year of a fallow state at the start of our simulation (but under cultivation 14 years prior to the start of our simulation).

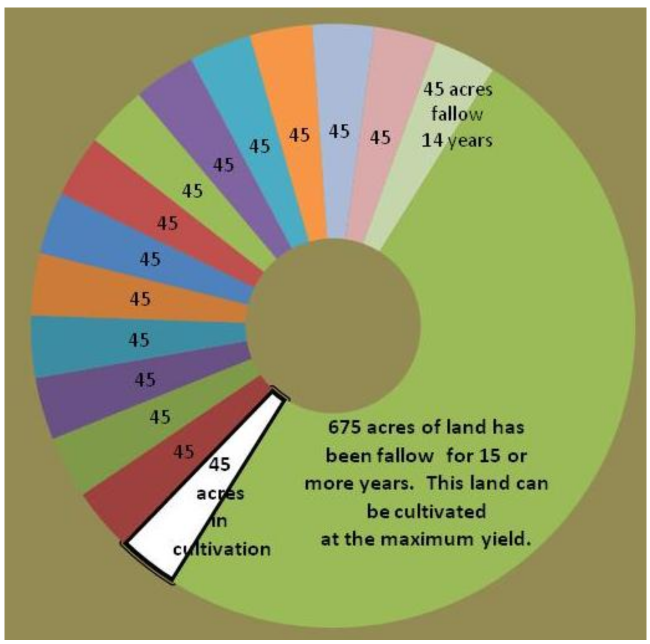

Figure 13. Land use at the start of a simulation with the separate model.[11]

All told, we have 15 slices, each 45 acres in size. They occupy 675 acres or half of the arable land. The other 675 acres is the large, green area in Figure 13. This land has been in the fallow state for 15 or more years. The Tsembaga can count on this huge land reserve to yield 4.4 MCal/year per acre.

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[11] The initial land use model will be similar to the model of forested land on page 69 of the book. A donut diagram helped us picture land use categories on page 69 and a similar diagram will help us imagine the land uses by the Tsembaga. Currently cultivated land is the white slice at the 7 o'clock position. The white slice will move in a counter-clockwise direction over time. In one year, for example, the white slice will be to the right of the position in Figure 13. If food needs were constant over time, the white slice will be half way around the circle in 15 years and all the way around in 30 years. With growing food needs, however, the white slice will become larger and larger over time

Figure 14 shows a model to implement the ideas in Figure 13. There are 16 stocks with initial values based on the donut diagram: "Fallow 15 or more" is initialized at 675 acres; land in cultivation is 45 acres; and the Fallow 1 through Fallow 14 stocks are each set to 45 acres. The food requirement stock is initialized at 200 MCal/year, and the "food req growth rate" is set at 0.01/year. The yield is 4.4 MCal/year per acre, so the desired new acres is 45 acres at the start of the simulation. As food requirements grow over time, the desired new acres will grow as well. The desired new acres is ghosted to the lower left part of the diagram to get L15 to C, a flow to lower the land remaining in fallow state and add to the land in cultivation. The equation would use the minimum (MIN) function:

L15_to_C = MIN(Fallow__15_or_more,desired__new_acres)

Food production will be the product of land in cultivation and the yield.

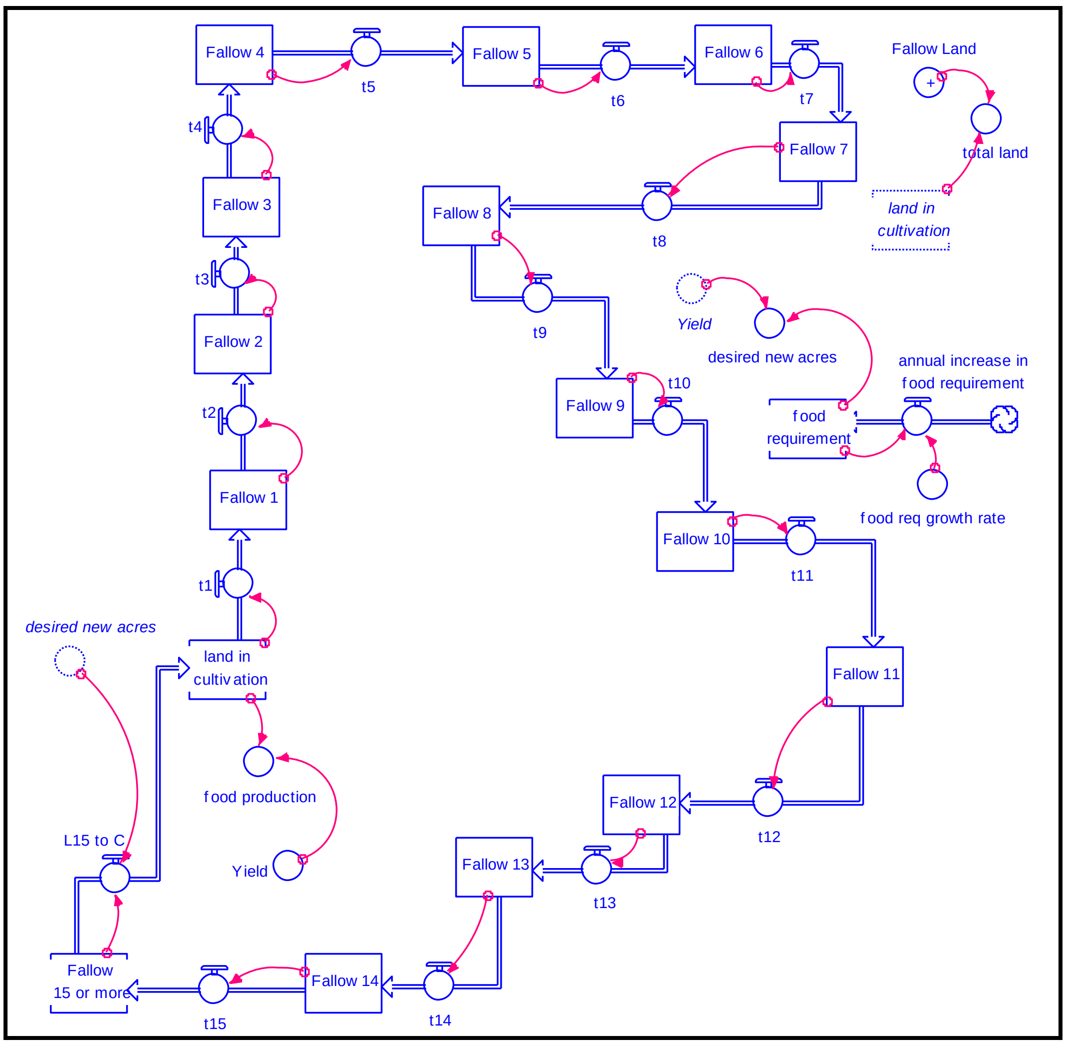

Figure 14. New model based on the land use categories in Figure 13.

Fig 14 shows 15 flows with the short names: t1, t2, t3…..t15. The t stands for transfer; these flows transfer land from one category to another based on the average time (1 year) spent in each stage. The t1 flow is the first of the transfer flows; it moves land out of cultivation into the first fallow stock. The flow t2 moves land from Fallow 1 to Fallow 2. Working around the loop, the t15 flow moves land from Fallow 14 to Fallow 15 or more. The average time interval for each of these stocks is one year, so each of the flows is the value of the stock divided by 1 year. The equations[12] can be written as:

t1 = land_in__cultivation
t2 = Fallow_1
t3 = Fallow_2
…
t15 = Fallow_14

Fig 14 shows a "summer" "+" for the fallow land (i.e., the sum of 15 stocks of fallow land). Adding the fallow land to the land under cultivation gives the total land, a variable which should remain constant at 1,350 acres. You now have sufficient information to build the model in Fig 14. Build the model and simulate if for 160 years with DT = 0.125 years. Create a time graph to verify that your results match the results in Figure 15.

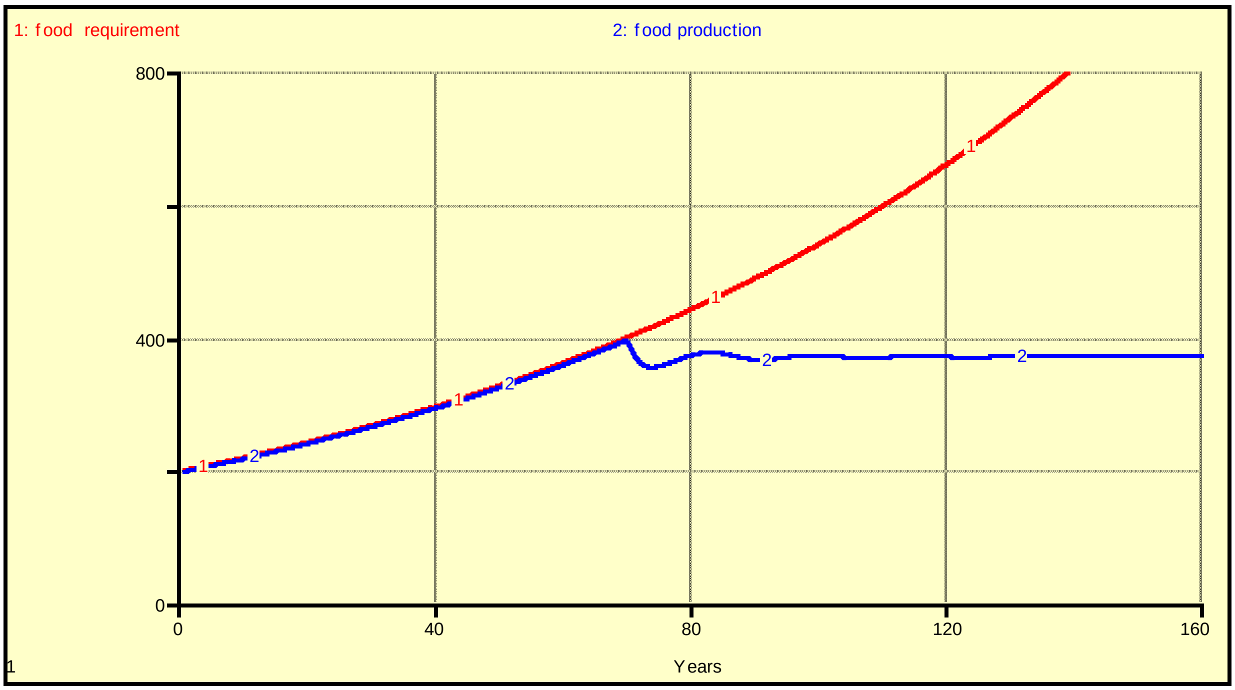

Figure 15. Food requirements are met for the first 70 years in the new land-use model.

The red line in Fig 15 grows at 1%/year; it will double every 70 years, reaching 400 MCal/year by the 70th year, 800 MCal/year by the 140th year. The blue line shows food production keeping pace for 70 years. However, in the 70th year, the goal is for 91 acres under cultivation. But the stock Fallow 15 or more is insufficient to meet the total need, and the cultivated land is only 88 acres. This small deficit is the first sign of problems meeting food needs. These problems grow increasing severe during the remainder of the simulation since the food needs continue to grow at 1%/year.

[12] Some might complain that the units of these equations are incorrect since the flows are in acres/year and the one-year time interval does not appear explicitly in the equation. To make sense of the units, think of the 1-year variable as implicit in the equation. I did not include an explicit variable since the value of 1 year is clear from the variable names, and I wanted to avoid using up space in the diagram. (The open space in Figure 14 will be valuable when we expand the land-use model in the next exercise.)

After the 70th year, land under cultivation declines for several years. Then, after some minor oscillations, it finds its way to an equilibrium value of 84.4 acres. The model shows that each of the fallow land categories will also find their way to 84.4 acres in equilibrium. If we were to redraw the donut diagram, there would be 16 slices, each of which is 84.4 acres in size.

This equilibrium state is quite different from the land use at the start of the simulation. The most dramatic change is the loss of the huge green area. The 675 acres of high-yield, fallow land is reduced to 84.4 acres by the 140th year of the simulation. By this time, the system is cultivating 84.4 acres year after year. The system is operating with only one year's worth of high-yield land in reserve. When this is brought into cultivation each year, the food production is 84.4 acres times 4.4 MCal/year per acre = 371 MCal/year. This annual production is sustained over time because the land use policy guarantees a 15-year fallow period and, therefore, a constant yield.

With 1%/year growth in the human population, the demand for food grows at 1%/year. The 1% annual growth rate leads to a doubling time of 70 years (see Appendix B). In the absence of warfare, the population and their food needs will double in the first 70 years and then double again in the next 70 years. Figure 15 shows the first sign of food production problems in the 70th year. The model is teaching us that the population is only "one doubling time away" from food production problems when the simulation begins.

This is a startling result given the relatively large reserve of high-yield land shown in Figure 13. A quick glance at Figure 13 might leave you with the impression that this system is far, far below its carrying capacity. But the dynamic model tells a different story. The population is only one doubling time away from hitting the limit on food production. The model has revealed the tendency for exponential growth to overpower a fixed resource in a surprisingly short period of time.[13]

The Figure 15 results may be compared with the results in Figure 11 to learn the value of the more detailed land use model. Whether we use 1 stock or 15 stocks for the fallow land, we see similar results. For example:

- Both models show the same equilibrium value at the end of the simulations; there can only be 84.4 acres under cultivation.
- Both models show similar results for when the first food shortages appear: in the 77th year with the simple model, in the 70th year with the stand-alone model.

These similarities confirm the value of the simple portrayal of land use (in Figure 9) to deliver plausible results while operating within the model of the Tsembaga system. At this stage, the detailed model (Figure 14) serves a supporting functions --- to confirm the general patterns and to help one visualize the land use in more detail (as in the donut diagrams). However, the simulations conducted so far assume that the Tsembaga would enforce the 15-year fallow period. For the next exercise, we ask if the Tsembaga would be better off if they relaxed the 15-year requirement.

[13] This result reinforces the findings from many of the other models published in *Toward Global Equilibrium* and the global simulations published in *The Limits to Growth*.

Exercise 10. Would it Help to Relax the Land Use Restriction?

Suppose the yield follows the pattern shown in Figure 16. The maximum yield is 4.4 MCal/year per acre. This can be achieved if the land is fallow for 15 years or longer. The yield curve is very similar to the logit function (see page 80 of the book), so the "s-shaped" pattern should be familiar. The midpoint of the curve shows a rapid decline if the fallow period is less than 8 years.

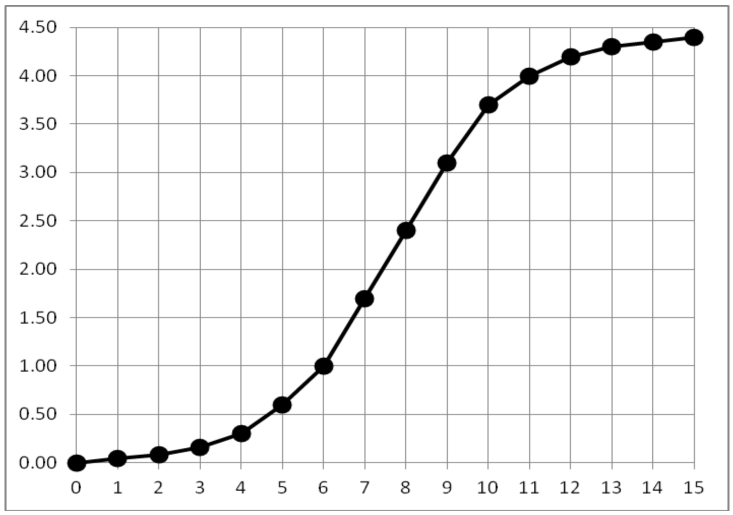

Figure 16. The yield of a new acre put into cultivation depends on the length of of fallow period for that acre.

Let's use the yield curve to think about the problems encountered around the 80th year in Figure 15. The constraint on cultivation allowed for only 84.4 acres to guarantee maximum yield. But imagine that the Tsembaga also make use of the 84.4 acres that have been fallow for 14 years. This land yields 4.35 MCal/year per acre, only slightly below the full yield. The food production from tapping into both categories of land would be nearly twice as large before. Perhaps that is exactly what the Tsembaga population should do to deal with the doubling in their population.

Figure 17 shows an expansion of the previous model to address this question. It introduces 7 new flows to transfer lower-yield lands into cultivation if the food production needs cannot be met by the high-yield land.   The new flows are shaded in black, with the previous variables in blue. For example, the flow L8toC would transfer land in the 8th year of fallow state into cultivation. This land has a yield of 2.4 MCal/year per acre, well below the maximum yield. We assume that this is as low as the Tsembaga would go in their descent down the yield curve.[14]   Other flows transfer land from the stocks Fallow 9, Fallow 10, Fallow 11, Fallow 12, Fallow 13 and Fallow 14.

[14] The yield for 8 years of fallow time is on the steeply declining portion of the curve in Fig 16. We assume that the Tsembaga would be unwilling to go further down the yield curve. To do so would be a lot of work with very little additional food production, and it would use land that might be left in reserve for high-yield cultivation in the future. For these reasons, we do not include an L7to C flow, an L6toC flow, etc. etc.

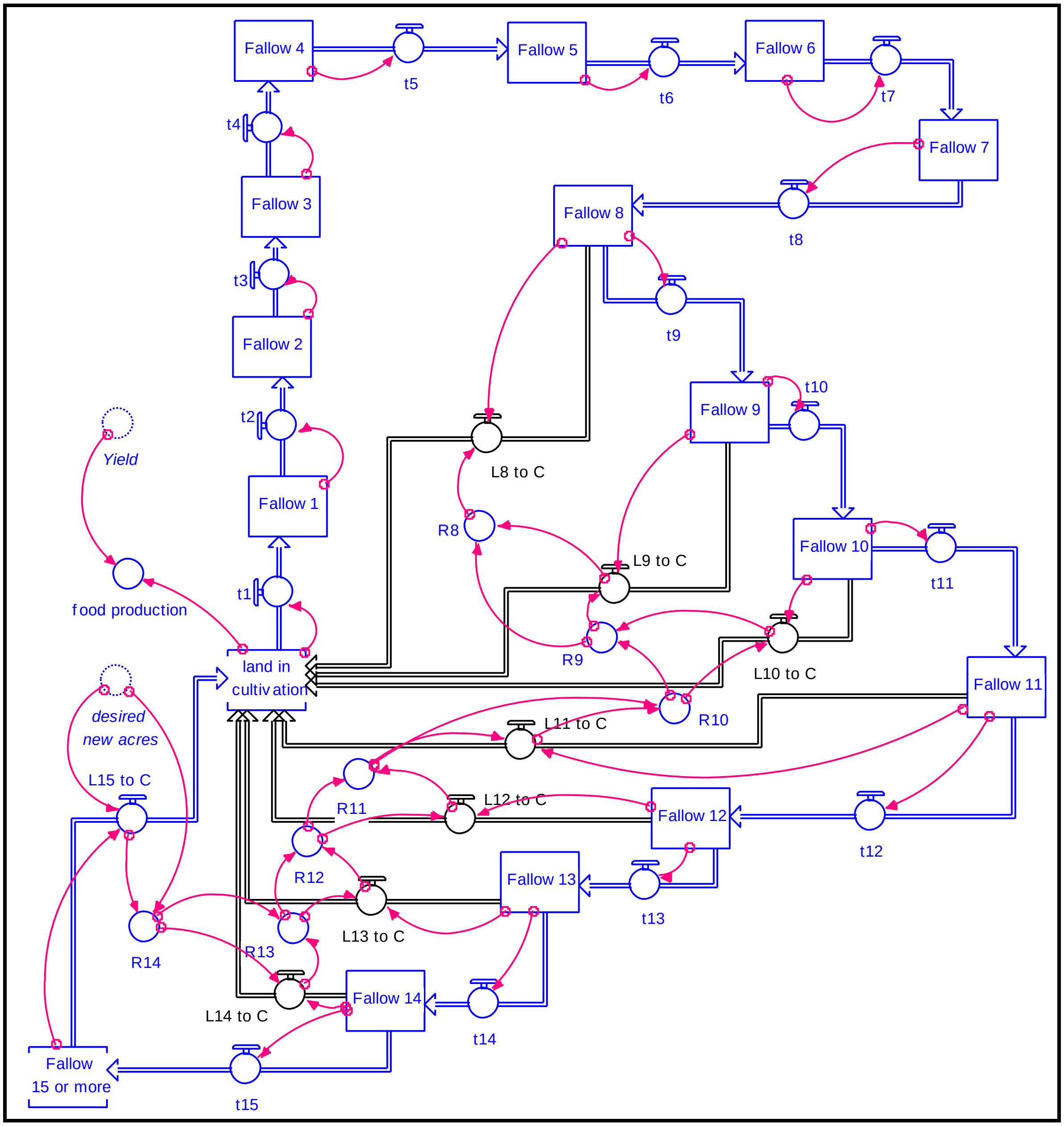

Figure 17. Expanded model with opportunities for cultivation of less productive land.

The new flows in Figure 17 are calculated sequentially based on the assumption that the Tsembaga would only turn to the lower-yield lands after they have taken full advantage of the higher-yield lands. Starting at the transfer from Fallow 15 or more, the flow L15 to C is the same as before:

L15_to_C = MIN(Fallow__15_or_more,desired__new_acres)

We then calculate R14, the cultivation acres remaining for the 14-year fallow land.

R14 = desired__new_acres-L15_to_C

The transfer of land from Fallow 14 can be calculated as:

L14_to_C = MIN(R14,Fallow_14)

And we then find R13, the cultivation acres remaining for the 13-year fallow land:

R13 = R14-L14_to_C

The transfer of land from Fallow 13 can be calculated as:

L13_to_C = MIN(Fallow_13,R13)

This sequential process is continued until we have transferred land into cultivation from Fallow 8, the lowest-yield stock for which cultivation is allowed in the model.

The yield of land in cultivation is based on the weighted average yield of the lands transferred to cultivation. The Stella diagram is shown in Figure 18; the equation is as follows:

*Yield = f8*Y8+f9*Y9+f10*Y10+f11*Y11+f12*Y12+f13*Y13+f14*Y14+f15*Y15*

The "f" variables are the fraction of each type of fallow land put into cultivation.

The "Y" variables are the yields, with the values from Figure 16:

Y8 = 2.4
Y9 = 3.1
Y10 = 3.7
Y11 = 4.0
Y12 = 4.2
Y13 = 4.3
Y14 = 4.35
Y15 = 4.4

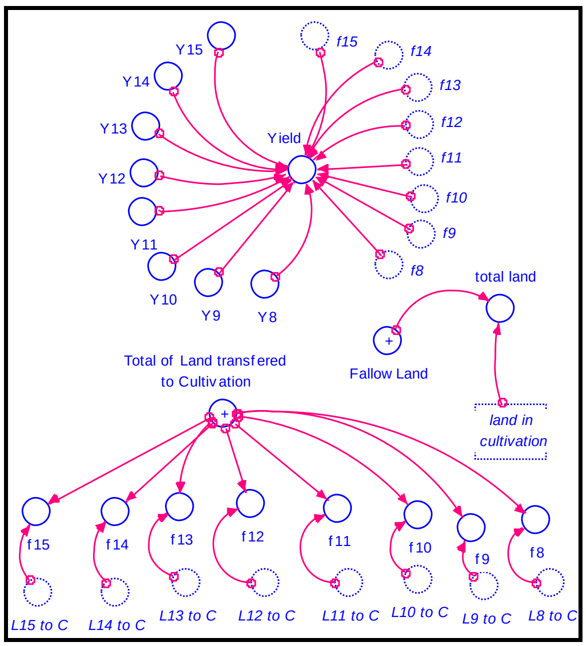

Figure 18. Yield calculation.

As in the previous model, the total land is the sum of the land in cultivation and the fallow land. This variable can be displayed in graphs, where we expect to see it remain constant at 1,350 acres.

The final part of the new model is shown in Figure 19. The food requirement stock is initialized at 200 MCal/year, the same as before. We will simulate the model with the food requirement growth rate at 0.01/year. The standard yield is 4.4 MCal/year per acre. And the desired new acres is the food requirement divided by the standard yield.

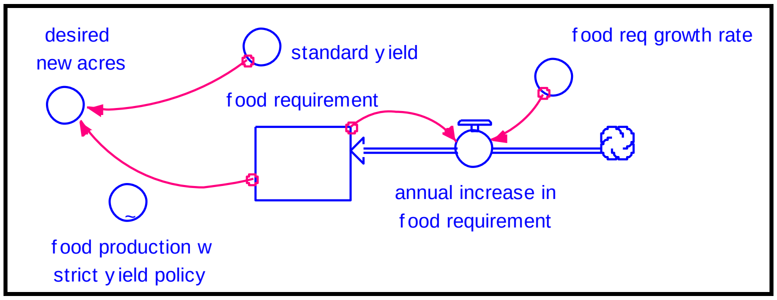

Figure 19. Remaining part of the new land use model.

We will use the land use model shown in Figures 17,18,19 to simulate food production if the Tsembaga can relax the 15-year fallow rule on land use. To make comparisons easy, we add a new variable in the lower-left corner of Figure 19: "food production w strict yield policy." This is a time-dependent variable with a graphical look-up for the food production shown previously in Figure 15.[15]

Build the model shown in Figures 17,18,19 and simulate it for 160 years with DT=0.125 years. Create a time-graph to verify the results in Figure 20. It shows the food requirement (in red) growing at 1%/year, the same as before. The requirement will double from 200 to 400 MCal/year in the first 70 years. Then it will double again and climb off the chart by the 140th year.

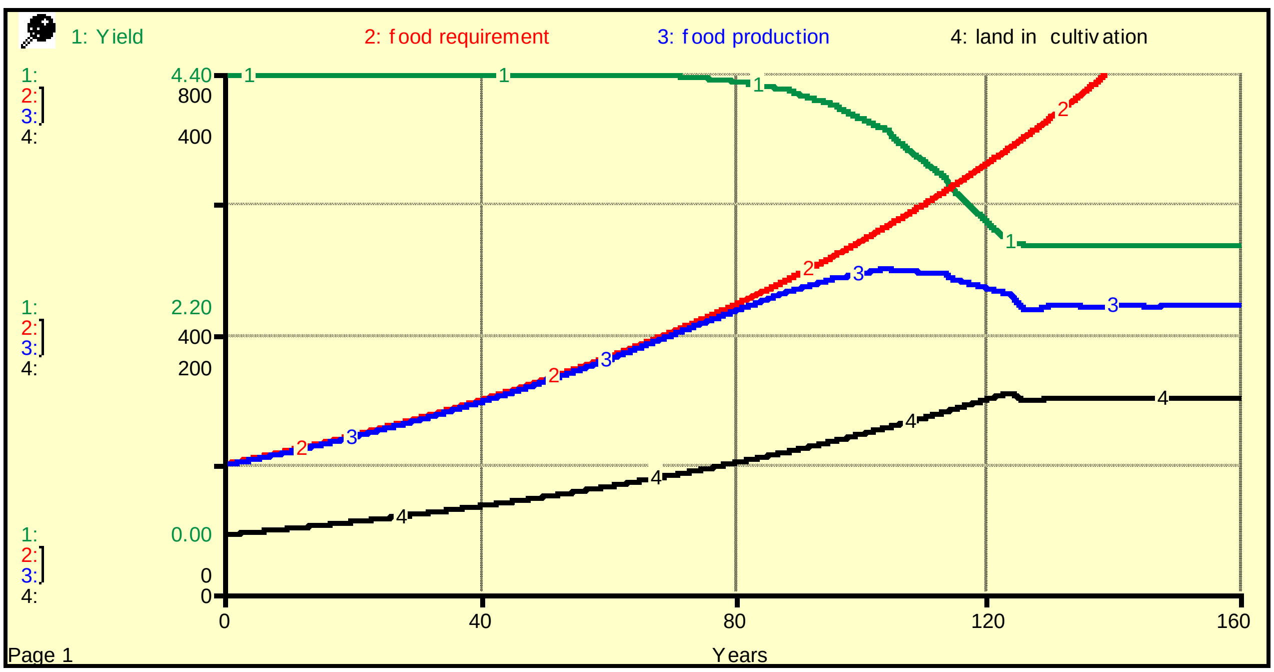

Figure 20. Food production and yields when the 15-year fallow rule can be relaxed.

[15] A convenient way to transfer the results from Figure 15 is to ask for a table to report the food production for each year of the 160-year simulation. Pin the table to the screen; use the cursor to highlight the food production column; then use Edit-Copy to copy the results to the clip board. Then open the new model and create the variable in the lower-left corner of Figure 19. Type the word Time and click on become a graph. Ask Stella for a minimum time of 0, a maximum time of 160 and for 161 entries. Click on the title of the entries column, and Stella will respond by highlighting all 161 entries. Hold down the CTRL key and tap V (Control-V). Stella will respond by pasting the contents of the clip-board into the designated position.

The green curve in Figure 20 shows that the yield is held constant at 4.4 MCal/year per acre for the first 70 years of the simulation. At this point, a small amount of Fallow 14 land is put into cultivation. The yield of the combination of Fallow 15 and Fallow 14 land drops to 4.39 MCal/year per acre. The small decline in the 71st year is indiscernible in Figure 20, but the benefit in food production is clear: food production comes much closer to keeping pace with food production for the next decade. Food production continues to grow because more and more land is put into cultivation, as shown by the black curve in Figure 20. Food production peaks around the 105th year and begins to decline. Cultivated land is still growing at this point, so the decline in yield must be greater than the increase in area cultivated. The system reaches an equilibrium around the 130th year with 150 acres under cultivation and annual production of 443 MCal/year.

Figure 21 compares the new food production with the production in the previous model. The previous model (with the strict policy on yield) shows food shortages in the 70th year. The new model shows the benefits of relaxing the 15-year fallowing constraint. Food production can keep pace with the growing need requirement for several more decades and it can deliver more production when the system reaches equilibrium. By transferring the lower-yield lands into cultivation, the Tsembaga will deal with smaller food shortages and buy more time to deal with the inexorable increase in the demand for food.

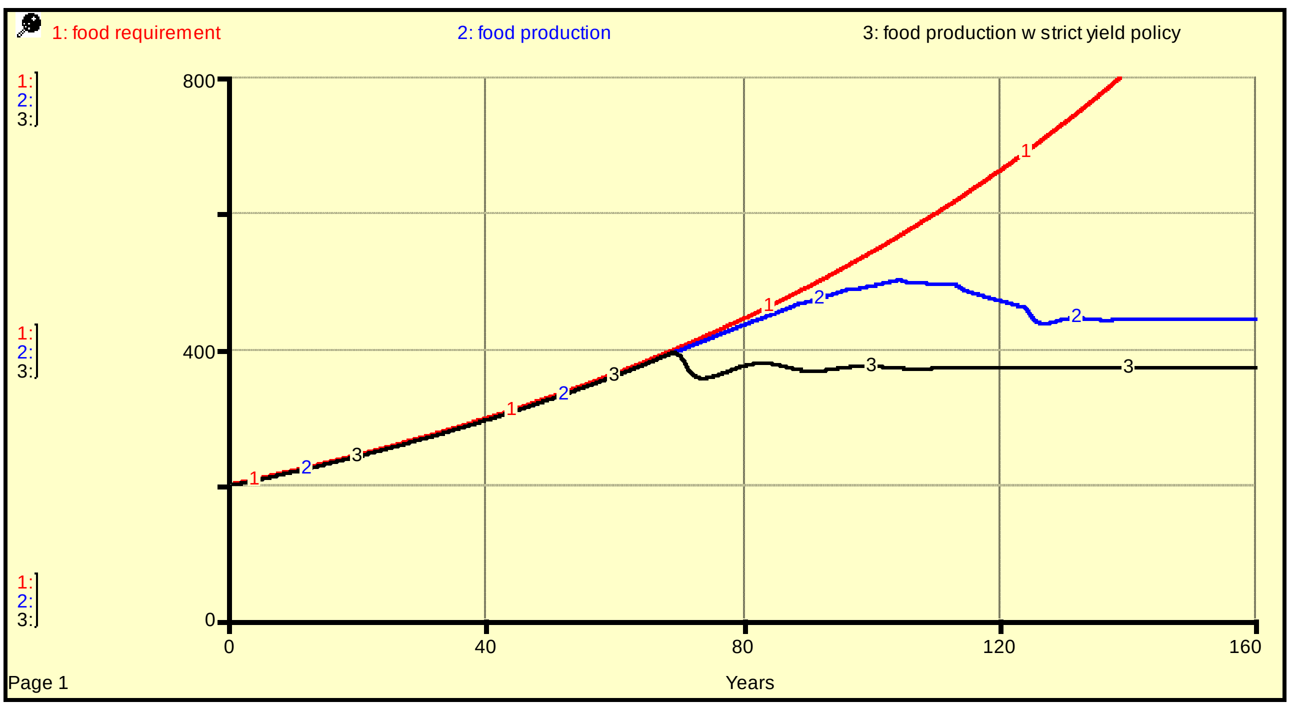

Figure 21. Comparison of food production in the new model with the previous model.

Figures 22 and 23 provide a different perspective on the equilibrium conditions at the conclusion of simulations with the strict yield policy (Fig. 22) and the relaxed yield policy (Fig. 23). As in the previous donut diagram, land under cultivation is depicted by the white slice at the 7 o'clock position. The green slice to the right of the cultivated land is the fertile land that can be brought into cultivation next year at the maximum yield. The simulation in Figure 15 reached an equilibrium state with each and every slice diagram at 84.4 acres.

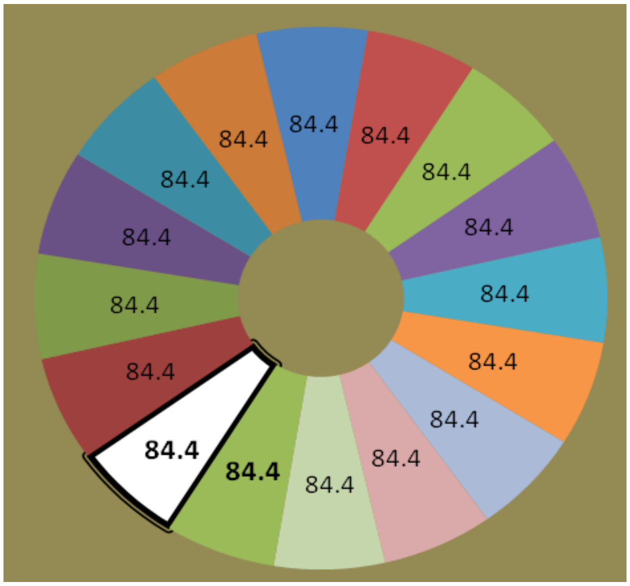

Figure 22. Land use diagram for the equilibrium conditions at the end of the strict-yield policy simulation.

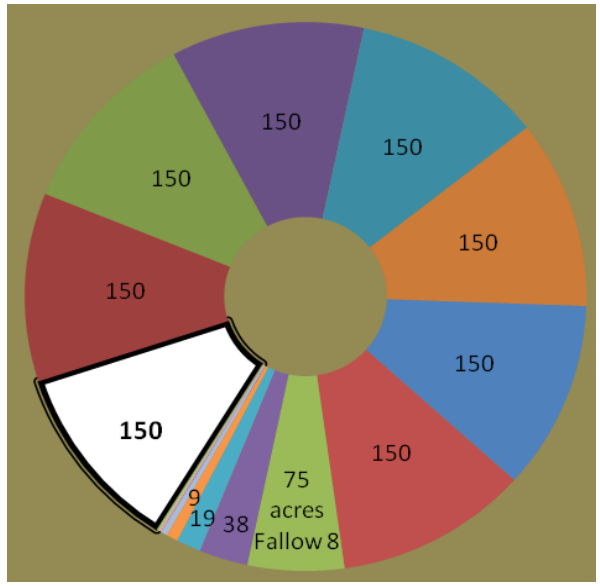

Figure 23. Land use diagram for the equilibrium conditions at the end of the relaxed yield policy simulation.

Figure 23 shows a much different picture when gardening is permitted in the lower-yield lands. There is 150 acres of cultivated land shown in white. Working in the clock-wise direction we see seven 150 acre slices. These represent the cultivated land from the previous year, from 2 years ago, 3 years ago, 4 years ago, 5 years ago, 6 years ago and 7 years ago. All of this land has yields on the lower half of the yield curve, so it is not eligible for cultivation in this simulation. Figure 23 shows 75 acres of land that has been fallow for 8 years. This is the first of the low-yield lands that can be transferred into cultivation. It would account for half of next year's cultivation. The remaining acres have higher yields, but there is less and less acreage available in the higher- yield categories:

38 acres of Fallow 9 land,
19 acres of Fallow 10 land,
9 acres of Fallow 11 land,
5 acres of Fallow 12 land,
2 acres of Fallow 13 land
1 acre of Fallow 14 land, and
1 acre of Fallow 15 land.

The total available for next year's cultivation is 150 acres.

Let's conclude with a comparison of cultivation activity in the two simulations around the 140th year (when both simulations have reached equilibrium):

- Production = 84.4 acres*4.40 MCal/year per acre = 371 MCal/year (Strict Policy on Yield)
- Production = 150 acres *2.95 MCal/year per acre = 443 MCal/year (Relaxed Policy on Yield)

The relaxed policy increases food production by 19%, but it requires 78% more area under cultivation. Would the extra 19% in calories intake be sufficient to cover the extra calories expended tending to 78% larger gardens? Answering this question is left to you as a modeling exercise.

Discussion and Advanced Exercises

These exercises have been adapted from the system dynamics model by Shantzis and Behrens (1973). They believed that the Tsembaga system had evolved into a homeostatic mode of behavior that controls the population at levels that could be sustained indefinitely. Their simulations without warfare showed an unsustainable situation, and they questioned the wisdom of those who would intervene to disallow warfare.

Your work on the exercises will reinforce some of their findings. The exercises will also raise questions about improvements to expand the power of the model. The following exercises build from ideas by Shantzis and Behrens (1973) and from project ideas by previous students.

Calories Assessment:
The final exercise concluded with a situation with 78% more land under cultivation to produce 19% more food. The calories expenditure tending to 78% more land makes one wonder if the extra food production is a net gain for the Tsembaga. The model could be expanded to account for calories expended in various activities (basic metabolism, gardening, caring for pigs, etc.). Useful information can be found in Rappaport's study.

Food Shortages Reduce the Net Birth Rate:
The separate land-use models assume a constant growth in food requirements of 1%/year. Food shortages appear around the 70^{th} year, but they do nothing to slow the growth in the human or the pig populations. The model could be expanded to represent the allocation of shortages among the pigs and humans and to make the population growth rates endogenous. Useful information can be found in the model by Shantzis and Behrens (1973).

Descending the Yield Curve:
The model in Figure 17 does not allow transfer of land from the low-yield lands (Fallow 1 through Fallow 7). However, Figure 23 shows these lands could provide 1,050 acres that might be cultivated. The model in Figures 17, 18, 19 could be expanded to allow these lands to be transferred into cultivation. Simulations with the expanded model would show yields descending further and further down the yield curve. The results might be compared with the results by Shantzis and Behrens (1973, Fig 9-16) in which the yield can descend completely to zero under extreme conditions.

Advance Planning and Food Storage:
The abrupt changes in cultivated land in Figures 8, 10, 11 are not plausible, as explained in footnote #6. The model in Figure 9 could be expanded to include year-ahead planning of land cultivation. The new model could also include storage, with food production adding to storage and food consumption drawing from storage. The expanded model should eliminate the abrupt changes in land cultivation shown in Figure 10.

More Detailed Picture of the Human Population:
The human population in Figure 9 could be expanded to distinguish between young, mature and elderly people. It could be further expanded to keep track of the males and females and their different sources of mortality. Model results might be checked against the age and sex observations by Rappaport (1984).

External Food Aid—Shifting the Burden:
The model in Figure 9 could be expanded to represent external sources of food assistance. The external food might be provided by the PNG or an NGO. The extra food could compensate for the shortages appearing in Figure 11. The new model could be used to study the "shifting the burden" dynamic that would appear when the system lacks the built-in population controls of the Tsembaga rituals.

Interaction with Neighboring Clans:
The final suggestion is the most ambitious and perhaps most potentially rewarding of the model expansions. It would require a broad understanding of the history and rituals of the Maring people. The model in Figure 9 could be expanded to simulate neighboring clans and their interactions with the Tsembaga. The new model would simulate the human populations, pig populations and land use of each clan. The interactions between the clans could include sharing of pigs at festivals, formation of alliances and engagement in warfare. The expanded model could be used to learn if the system view of the Maring clans reinforces or contradicts the findings from the "Tsembaga Only" modeling.

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