

Model 5: Farming with Dynamic Technology

Narrative

Sometimes hunter-gatherers undertake activities that increase the productivity of otherwise wild plants and animals. For example, the Paiute of Nevada dug ditches to divert storm water onto fields where desirable wild food plants grew. California people planted tobacco if it was not easily collectable nearby. Nut bearing walnuts were rare in California but are often found near old village sites, probably because they were deliberately planted there.

Hunter-gatherers are good natural historians, and the idea that you could deliberately plant desirable ones would not have been a big leap. Similarly, people often kept orphan animals as pets and the idea of doing this on a systematic basis may have occurred quite often. As the climate stabilized after about 11,700 years ago, people tended to become more sedentary and to use local resources more intensively. Near Eastern people had already started on this trajectory before the Younger Dryas interrupted them and, after it was over, they got into cultivating fields and planting desirable seeds, like wild wheat and barley, in them rather shortly.

They also began to select for desirable traits in the plants and animals they were nurturing. For plants, a key trait is non-shattering. Most wild plants scatter their seeds as soon as they are ripe. Grass seed-heads fall apart (shatter). Legume pods typically pop explosively as they dry, flinging seeds in all directions. To harvest shattering seeds, early farmers had to go over their fields several times as they ripened. They were tempted to pick unripe seeds that they judged would shatter before they have time to come back for them. Rare mutant plants that didn't shatter were sure to be collected whereas only a portion of those that did shatter ended up in our incipient farmers' grain bins. As non-shattering genotypes become more common in farmer's seed stock, farmers might have started to notice them and select them deliberately for next year's planting seeds. Eventually, fields of non-shattering crops could be harvested in one pass after the entire crop was ripe. Threshing and winnowing to separate seeds from other flower parts could now be done on a large scale.

Animal proto-domesticates came under selection for docility early in the domestication process. The wild relatives of cattle, sheep, pigs, and goats had survived the late Pleistocene extinction by being wary of people. They would run away if given a chance and might put up a fight rather than being easy to manage. Some of this selection was partially inadvertent.

In 1908, President Theodore Roosevelt established the National Bison Range in Montana to assist in the recovery of this then near-extinct animal. The Range hired cowboys and bought a starter herd of privately owned animals originally established by Flathead Indians. Since bison are closely related to domestic cattle, cowboys could manage bison using their customary procedures, albeit with difficulty, since bison had little respect for horses and fences. Working large livestock is inherently dangerous under any circumstances, but the danger is compounded when individuals are aggressive. Bison bulls were large and often exceptionally bad tempered, but even cows were far from docile. However, after a few decades of operation, the long-time Superintendent of the Range noticed that, even though the objective of the Range was to produce animals fit for reintroduction into the wild where docility might translate into vulnerability to predators or hunters, the herd was becoming noticeably more docile.

The cause of this increased docility was easy to understand, however. The scariest bulls had a tendency to be culled along with any cow that put a cowboy in the hospital with a brutal kick. Similarly, the aurochs, ancestors of cattle, were large belligerent beasts and it is easy to imagine why early herders also selected for smaller size and docility. The size reduction is, in fact, evident in the archaeological record.

In addition, domestic animals generally have smaller brains than their wild ancestors, as if human herders did much of the thinking their now-dependent stock had to do for themselves in the wild. Even today, Western North American ranchers have a dilemma. Tame cattle are easier and safer to work, but on the open range cattle have to contend with coyotes, mountain lions and, increasingly wolves. Tame, okay, but not too tame!

It took about 2,000 years for Near Eastern proto farmers to evolve the crops, animals, and techniques sufficiently to become nearly wholly dependent on domesticates. Then populations of farmers spread west and east so that by 7,000 years ago they reached the British Isles in the West and Central and South Asia in the east. In Asia, they met farmers moving east from the foci of farming innovation in the Far East. Farming was slowly spreading and very gradually leading to increases in the population of people and their domesticates. Similar developments were occurring in the Americas and in Africa as simple agricultural systems evolved there and spread.

Agriculture is supposed by some to have resulted in a demographic revolution, an early Holocene population explosion. There is no good evidence that this happened. Rather, agricultural innovations came slowly when population sizes were small and, accordingly, populations grew slowly. Growing populations did provide some feedback to increase the rates of innovation, but this effect built up very slowly throughout most of the Holocene. Still, rapid population growth and high rates of innovation had occurred by the end of the Holocene (but not at the beginning). Note that in our models, the parameters are fixed and only the state variables evolve. The same process is operating from the initial steps through the period of slow growth and the final rapid acceleration in the Holocene, giving a hockey stick shaped curve.

Agriculture resulted in a *conflagration*, not an *explosion*. In a proper explosion, as in a dynamite explosion, the entire chemical energy in the explosive, triggered by a fuse, is converted to heat and light in a fraction of a second. A conflagration is like a house fire that begins when a pile of oily rags slowly heats up, and eventually, due to spontaneous combustion, starting a small fire in the garage that then begins to spread to the rest of the house at a moderate pace. Once the whole house is nice and hot, the rate of combustion becomes quite high. The time from the first flames to the collapse of the house is a matter of an hour or so rather than a fraction of a second if it were blown up. The origin of agriculture 10,000 years ago initiated a conflagration not an explosion. Agriculture and agricultural innovation are burning the hottest ever right now. About half of the earth's habitable land area is devoted to the production of domesticated animals and plants.

Models like ours are useful tools to school our intuitions about things like the difference between explosions and conflagrations. In our simple model it just boils down to the rate of human creativity. If you make that high, you get an explosion. If you make it realistically small you get a conflagration. Historians and archaeologists typically don't understand this distinction. They are prone to see history as a succession of revolutions as if there were a succession of fundamental structural changes in the processes driving change in the Holocene—an agricultural revolution, an urban revolution, a commercial revolution, and an industrial revolution. Perhaps, but also it could have been the same processes operating all along with positive feedbacks building at first slowly but at a smoothly accelerating pace.

Our model does useful work in simply teaching us that such a pattern is logically quite possible. The revolutions picture would look quite different. It would be a series of explosions followed by little change until the next explosion, producing a staircase pattern instead of a hockey stick. The real data, such as it is (historical demography is a hard business), is more consistent with the hockey stick model (Figure 1). Perhaps there is a stairstep pattern (Figure 2), given the uncertainties of the data generating Figure 1, but there is no reason to accept the revolutions account without further evidence.

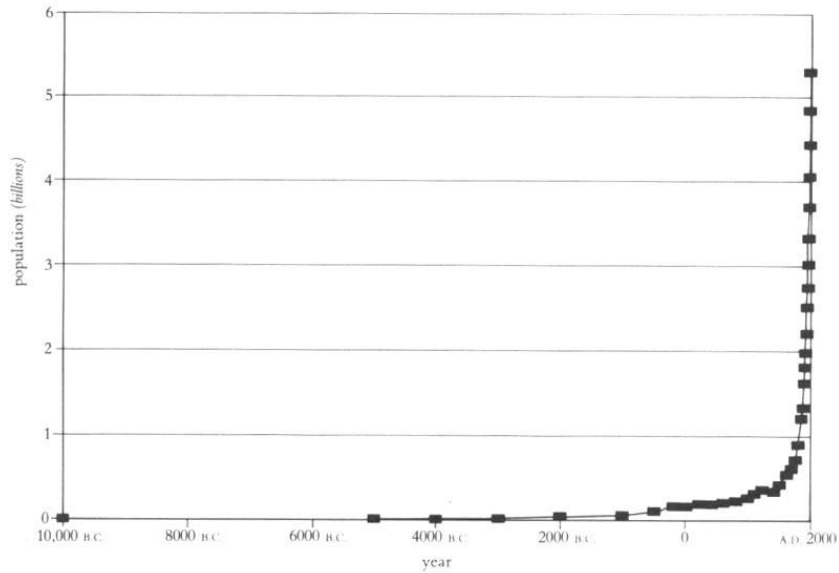
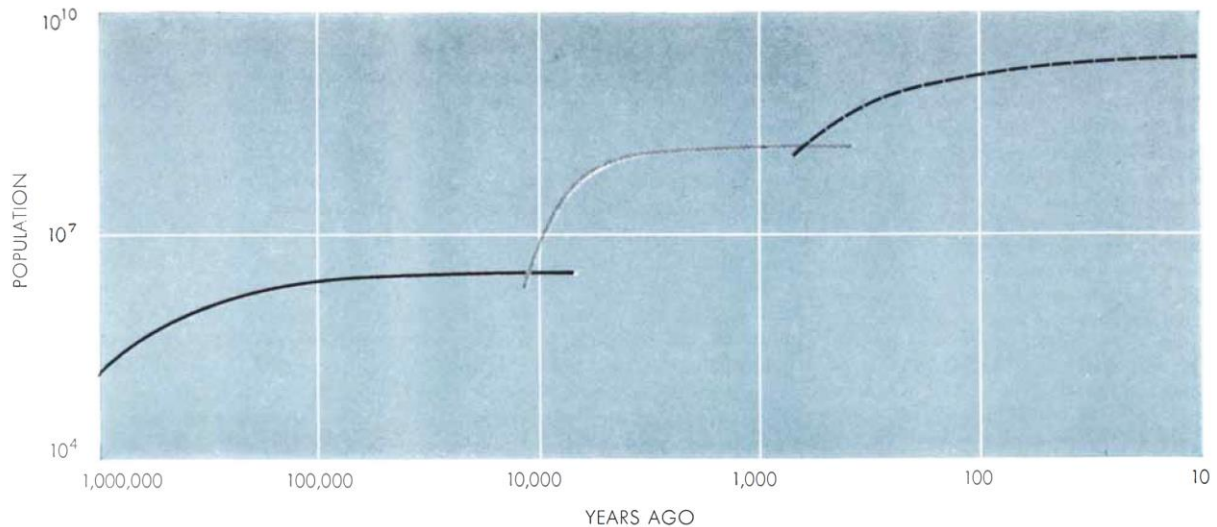


FIGURE 5.2 Estimated human population from the last ice age to the present.
SOURCE OF DATA: Appendix 2

Figure 1. From Joel Cohen 1995



LOGARITHMIC POPULATION CURVE makes it possible to plot, in a small space, the growth of population over a longer period of time and over a wider range (from 10^3 , or 10,000, to 10^{10} , or 10 billion, persons). Curve, based on assumptions concerning

relationship of technology and population as shown in chart on page 196, reveals three population surges reflecting toolmaking or cultural revolution (*solid line*), agricultural revolution (*gray line*) and scientific-industrial revolution (*broken line*).

Figure 2. Hypothetical stairstep pattern of population growth. E.S. Deevey, 1960.

The “hotter burning” of agricultural populations is due to a vast train of innovations in the domesticates themselves as well as in the management and use of them. So-called “secondary products” were developed. Sheep, goats, and cattle were selected for higher milk yield to support the production of dairy foods. Sheep, goats, and alpaca were selected to produce wool. Fruit trees were selected and techniques for vegetative reproduction of desirable varieties were perfected. Fiber crops like flax, hemp, and cotton were developed. Animal traction evolved to use livestock to plow fields, pull carts, carry packs, and carry soldiers.

Deserts and semi-arid prairies tend to have large expanses of good soil, but without water they are only suitable for light grazing. Water, however, is often available in large quantities in the form of rivers flowing from high, well-watered mountains across the warm dry plains on their way to the sea. In the Near East, the Tigris and Euphrates rivers are good examples of such river-fed plains, not coincidentally close to the center of origins of agriculture.

The Nile, another example, flows out of the East African highlands across the eastern edge of the Sahara Desert. Similarly, China has big rivers near the centers of agricultural evolution. In Peru, twenty or so miniature Niles flow down the western slope of the Andes across their fertile but hyper-arid lowlands. Central Mexico has no large rivers but many small and medium-sized ones in a generally semi-arid landscape. Small-scale irrigation works were constructed by individual farmers and at the village scale. Later, large scale, professionally engineered, state managed irrigation systems were constructed to take advantage of large rivers.

Some irrigation systems are quite ingenious. Take the qanat “horizontal wells” originally built in Arabia and Iran perhaps as early as 5000 years ago. These are usually village scale systems built by specialist engineers. Often, in dry mountainous terrain, streams build alluvial fans where they issue onto a valley floor from the well-watered mountains. Coarse sedimentary fractions are deposited at the top of the fan while finer, farmable sands, silts, and clays are deposited toward the toe. The fan stores ground water throughout but it generally outcrops only as springs at the toe of the fan, below the best soils for agriculture. Engineers dig a qanat, a mother well near the head of the fan, and from there construct a gently sloping tunnel with a series of vertical shafts to ventilate the tunnel and make it accessible for maintenance. The tunnel emerges at the surface at the point where the good soils start. Contour ditches then distribute the water to villages and fields. The underground tunnel protects the flowing water from evaporation and contamination and gravity does the entire work of delivering the water, obviating the need for expensive pumping. Most qanats are fairly short, on the order of 5 km long but a few are several tens of km long. Qanats spread west to North Africa and Spain and east into South and Central Asia.

In parts of the Americas, large areas of raised fields were constructed to convert wetlands into farmlands. Farmers dug mud up from wide ditches and piled the spoil in long broad rows ten or twenty cm above the water level so that crops could be planted on them. Wetland muds are high in nutrients and the ditches could produce fish and aquatic plants. In Highland Peru, the open water, raised field ditches retained heat for frost protection at night. Lake Titicaca has large areas of fossil-raised fields around its shore and pre-Hispanic Mexico City was supported by raised-field agriculture. Western European engineers learned how to dyke and drain salt marshes to create agricultural land, most famously on the Rhine Delta in the Netherlands.

Trade in agricultural products was historically fairly limited because foodstuffs are heavy in relation to their value. Townspeople drew their food supplies from their immediate countryside and many farmers ate largely what they grew. This meant that regional famines were common because food could not be

brought from afar in sufficient quantity to relieve them. The early exceptions were where farm commodities could be moved by sea, rivers, or canals. Rome famously imported most of its grain by sea from Egypt. The Chinese Grand Canal's main function was to transport grain. Water transport is still the most economical way to ship bulk commodities like grain.

The American Mid-West plays a large role in the global grain trade in part because it is well supplied with water transport routes connected to the Mississippi-Missouri-Ohio river system. Nowadays, rail and truck transport of farm commodities is more practical, but to this day more expensive than by water. Siberia is at a competitive disadvantage in the world market because its grain has to be transported long distances to ports by rail. Rich countries consume luxury foods transported by air!

Famine risk generated pressure for local solutions to food shortages. One answer was open field systems. Instead of each farmer cultivating a compact plot, they had a number of small plots scattered about the landscape. This made farm operations cumbersome, but a compact field was vulnerable to being wiped out by flood, frost, drought, or pest attack, whereas many scattered fields took advantage of the variability in field orientation, slope, soil type, and elevation. If the rains were heavy, a low-lying field's crop might drown, but a ridgetop could yield a bumper crop. In a drought the opposite. Plot dispersal was a common risk reduction strategy everywhere.

By the Medieval period, the growth of agricultural technology was steady if still slow. For example, Western Europeans adopted the mouldboard heavy plow to deal with heavy, wet, but fertile, soils. This plow rolls over a strip of soil to bury weeds and any trash from the previous crop. Horse collars and horseshoes increased the efficiency of using horses and mules for traction. Improved crops and regular rotations with nitrogen fixing peas and beans improved yields.

The modern period generated a sharp increase in the innovation rate in agriculture. Science and industry were harnessed to plant and animal breeding, to understanding plant and animal nutrition, and to creating innovative farm machinery. The US Land Grant agricultural colleges and agricultural experiment stations were established by the federal Morrill (1862) and Hatch (1887) acts. Similar institutions were established all over the world, for example, the Rothamsted Experiment Station in England (1843) and a national network of experiment stations in Japan (1893).

Agriculture, historically a labor-intensive business, gradually became ever more capital intensive. For example, California, mid-19th century, focused on the extensive cultivation of commodities for the world market, especially wheat. But as the list of crops grew, farm size shrank as farmers concentrated on labor intensive but valuable fruit, nut, and vegetable crops, mainly shipped east by rail. By 1900, speculators began laying out farm subdivisions as small as 5 acres per parcel on the assumption that this trend would continue. Then came the cheap gasoline- or diesel-powered tractor that individual farmers could use to multiply their labor. Farm sizes started to increase again even though California was making ever more sophisticated use of its favorable climate. As with everywhere in the industrialized world, less and less labor was needed on the farm, while jobs in manufacturing and commerce increased their demand for labor in proportion.

Agricultural innovations eventually came to support a vast human population, but the increase is most dramatic quite late in time. On the eve of agriculture, 10,000 years ago, the world human population was perhaps 5 million. The Roman and Chinese empires around 2000 years ago numbered in the vicinity of 50 million people each. The world population on the eve of the Black Death 700 years ago was around a half a billion, reaching a billion around 200 years ago. Today there are close to 8 billion of us.

Further Reading

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- Zahid, H. J., E. Robinson and R. L. Kelly (2016). "Agriculture, population growth, and statistical analysis of the radiocarbon record." *Proceedings of the National Academy of Sciences* 113(4): 931-935.

https://en.wikipedia.org/wiki/History_of_agriculture

<https://en.wikipedia.org/wiki/Trade>

https://en.wikipedia.org/wiki/State_formation

<https://en.wikipedia.org/wiki/Qanat>

https://en.wikipedia.org/wiki/Agricultural_experiment_station

<https://en.wikipedia.org/wiki/Irrigation>

<https://en.wikipedia.org/wiki/Polder> (Dutch style dike-and-drain field systems)

<https://en.wikipedia.org/wiki/Lock>

https://en.wikipedia.org/wiki/History_of_science_and_technology_in_China

White Box Graphical Model

The under-the-hood white box model description sections below can be skipped, and you can proceed directly to the Black Box Simulations if you just want to operate the simulator and skip the model diagram and equations.

The graphic Stella model, shown in Figure 5-1 (below), is broken into three major sections, the Farm, the Humans who run them, and the evolving Technology. Each major section of the model is discussed below.

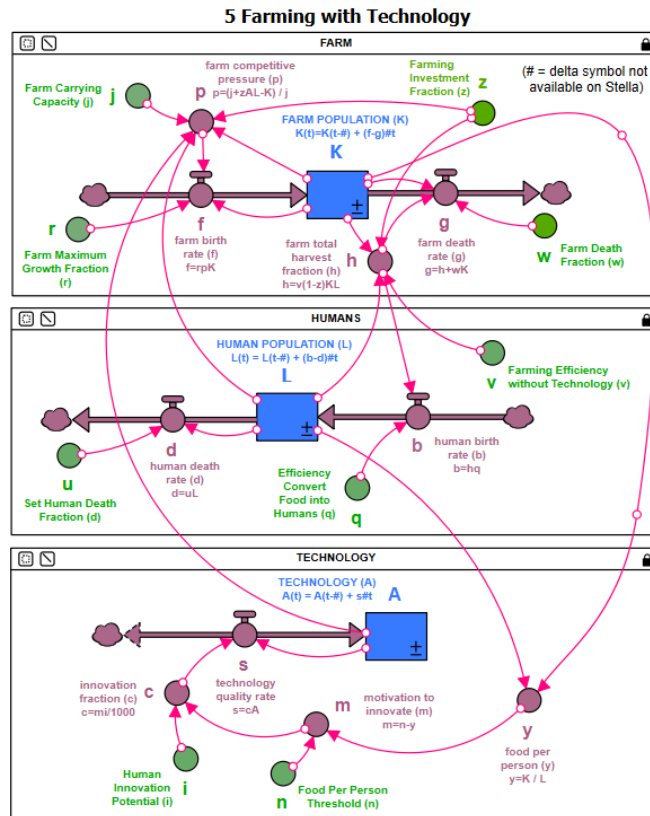


Figure 5-1: Stella Farming with Technology model.

For the FARM section of the model, the **FARM POPULATION (K)** is a state variable (i.e., a “tank”) whose value can change during the simulation for each tiny iteration of the Stella model with each small step in time. The amount of change is the rate of input, the **farm birth rate (f)** minus the **farm death rate (g)** times the small increment of time, Δt (shown as #t in the model because Stella does not have the Δ symbol). Thus, for each step in time, the simulation makes the calculation

$$K(t) = K(t-\Delta) + (f-g)\Delta t$$

The **farm birth rate (f)** is the product of the **Farm Maximum Growth Fraction (r)**, the **farm competitive pressure (p)**, and the **FARM POPULATION (K)**, i.e.

$$f = rpK$$

The **Farm Maximum Growth Fraction (r)** is the per individual growth rate of the farm population in the absence of any competition from other members of the population. It represents the per-capita birth rates in the absence of harvesting of competition. Mathematically, **r** is the population growth rate when K is very near but not quite 0.

The **farm competitive pressure (p)**, is, in essence, the farm animals competing against themselves for a limited supply of what they eat to stay alive and reproduce. When K is small relative to j, p is approximately 1 and the farm population is free to grow exponentially. As K approaches j, p approaches 0 and competition alone stops the prey population from growing. For a grazing herd of goats, for

instance, it would be the grass in the meadows, knee deep when $K \ll j$, grazed tight to the ground as $K \rightarrow j$. This competition for a fixed resource is calculated, for each simulation step as

$$p = (j - K) / j$$

From this equation it can be seen that when K is zero or very small, then p is essentially equal to 1.0. This is the green light (excuse the pun) to the goats that the meadows are green with grass. However, as K gets larger, i.e. the number of goats increase, then there is less uneaten grass in the meadows. As K gets larger and larger, p approaches 0.0 and the number of goats is limited by the **Farm Carrying Capacity (j)**. If there weren't any humans eating goat meat, the **FARM POPULATION (K)** would, over time, asymptotically approach the **Farm Carrying Capacity (j)** and then stay at the number forever.

$$g = h + wK$$

The **farm total harvest fraction (h)** is the fraction of the goats (or other farm animals or plants) that humans kill. w is the per capita non-harvest death rate, so g is the total loss rate of the farm population to death plus harvest.

$$h = v(1-z)KL$$

z is the fraction of the human time budget that is devoted to nurturing and protecting the farmed or herded population, so $1-z$ is the proportion of effort devoted to harvesting the crop or herd ($z + (1-z) = 1$). *This is the key difference between hunting and gathering and farming.* In effect, in a hunting and gathering system $z = 0$, so our models of farming become the same as our hunter-gatherer models when z is set to zero, as you can verify.

This equation simply suggests that the more goats there are, the more humans there are to tend and eat them, and the greater the efficiency of the humans, the more goats that can be eaten.

Farming Efficiency without Technology (v) represents the farming efficiency of early, essentially static farming (so slowly changing we can ignore the technological advances). Even today neglecting the rapid evolution of farming technology would make sense if our interest is in a short-term prediction. An economist wanting to estimate next year's global wheat harvest could safely neglect the evolution of technology. One could model a more realistic approximation of actual early farmers by introducing a plant resource. This could look just like the existing sub-model of K except that we would assign v a substantially larger value for the plant resource. Even if our ultimate objective is to build a more complex, more realistic model, applying the KISS rule at this point focuses our attention on building it sub-model by sub-model. To have insight into the behavior of a complex model, an understanding is required of each piece that goes into it. Even with this knowledge in mind, complex models with non-linear feedbacks can be a challenge to understand!

For the HUMANS section of the model, **HUMAN POPULATION (L)** is a state variable (i.e., a "tank") whose value can change, during the simulation, for each tiny iteration of the Stella model, each small step in time. The amount of change is the rate of input, the **human birth rate (b)** minus the **human death rate (d)** times the amount of time, Δt (shown as $\#t$ in the model because Stella does not have the Δ symbol). Thus, for each step in time, the simulation makes the calculation

$$L(t) = L_{(t-\Delta t)} + (b-d)\Delta t$$

The **human birth rate (b)** is the product of the **prey total harvest fraction (h)** and the **Efficiency Convert Prey into Humans (q)**. The more goats that the farmers eat, and the more efficiently they use this food (cooking all the parts) to produce more humans, the more baby humans will be born.

$$b = hq$$

The **human death rate (d)** is the product of the **Human Death Fraction (d)** and the **HUMAN POPULATION (L)**.

$$d = uL$$

human death rate (d) is the number of humans that die of old age, diseases, accidents, etc., each year.

Human Death Fraction (u) is the fraction of humans that die each year.

For the TECHNOLOGY section of the model, **TECHNOLOGY (T)** is a state variable (i.e., a “tank”) whose value can change, during the simulation, for each tiny iteration of the Stella model, Δt , i.e., each small step in time. The amount of change can be positive or negative (but is usually positive) times the amount of time. This ability to add to or subtract from the state variable, T, i.e., to fill or drain the tank, is denoted in the model by having arrows on *both* ends of the flow into or out of the “tank.”

For each step in time, the simulation makes the calculation.

$$A(t) = A(t-\Delta t) + s\Delta t$$

The **technology quality rate (s)** is

$$s = cA$$

where **c** measures the innovation fraction (how enthusiastically people innovate), and **A** is the previous level of technology.

The **innovation fraction (c)** measures the innovation fraction (how enthusiastically people innovate), and **A** is the previous level of technology.

$$c = mi$$

The **motivation to innovate (m)** is a function of **w** a hunger threshold and **y** a hunger index.

$$m = w - y$$

The **prey per person (y)** is the size of the prey population relative to the human population. In the spirit of “necessity is the mother of invention” when prey get scarce enough, hungry hunters turn their attention to ways to hunt more effectively.

$$y = K / L$$

Model Variables and Equations

The visual flow diagram “white box” model, described above, can be reduced to a set of initial conditions and independent (and intermediate) variables which, through mathematical relationships (equations), provide the results (the independent variables). These are given in the table below:

Key: STOCKS; Parameters, intermediate variables

FARMS	Units	Stella Equations
FARM POPULATION (K)	Farm unit	$K(t) = K(t-\Delta t) + (f-g)\Delta t$
Farm Carrying Capacity (j)	Farm unit	
Farm Maximum Growth Fraction (r)	1/year	
Farming Investment Fraction (z)	Unitless	
Farm Death Fraction (w)	1/year	
farm birth rate (f)	farm unit/year	$f = rpK$
farm competitive pressure (p)	unitless	$p = (j + zLA - K)/j$
farm death rate (g)	farm unit/year	$g = h = wK$
farm total harvest fraction (h)	farm unit/year	$h = v(1-z)KL$
HUMANS		
HUMAN POPULATION (L)	People	$L(t) = L(t-\Delta t) + (b-d)\Delta t$
Set Human Death Fraction (d)	1/year	
Efficiency Convert Food into Humans (q)	People/farm unit	
Farming Efficiency Without Technology (v)	1/(people*year)	
human death rate (d)	people/year	$d = uL$
human birth rate (b)	people/year	$b = hq$
TECHNOLOGY		
TECHNOLOGY (A)	Unitless	$A(t) = A(t-\Delta t) + s\Delta t$
Human Innovation Potential (i)	People/(per unit*year)	
Food Per Person Threshold (n)	Farm unit/person	
technology quality rate (s)	1/year	$s = cA$
innovation fraction (c)	1/year	$c = mi/1000$
motivation to innovate (m)	farm unit/person	$m = n - y$
food per person (y)	farm unit/person	$y = K / L$

Table 5-1: Model variables and equations.

Equations without Intermediate Variables

$$K' = rK[(j-K + zLA)/j] - v(1-z)AKL$$

$$L' = qv(1-z)AKL - uL$$

$$A' = iA(n-K/L)$$

Black Box Simulations

As suggested in the course Introduction, when using a black box model, you are just concerned with the model's inputs, not its internal workings which can be extraordinarily complex. To run the Farming with Technology model from this black box perspective, bring it up at:

<https://exchange.iseesystems.com/public/cherylgenet/farming-with-technology/index.html#page1>

This is what you should get:

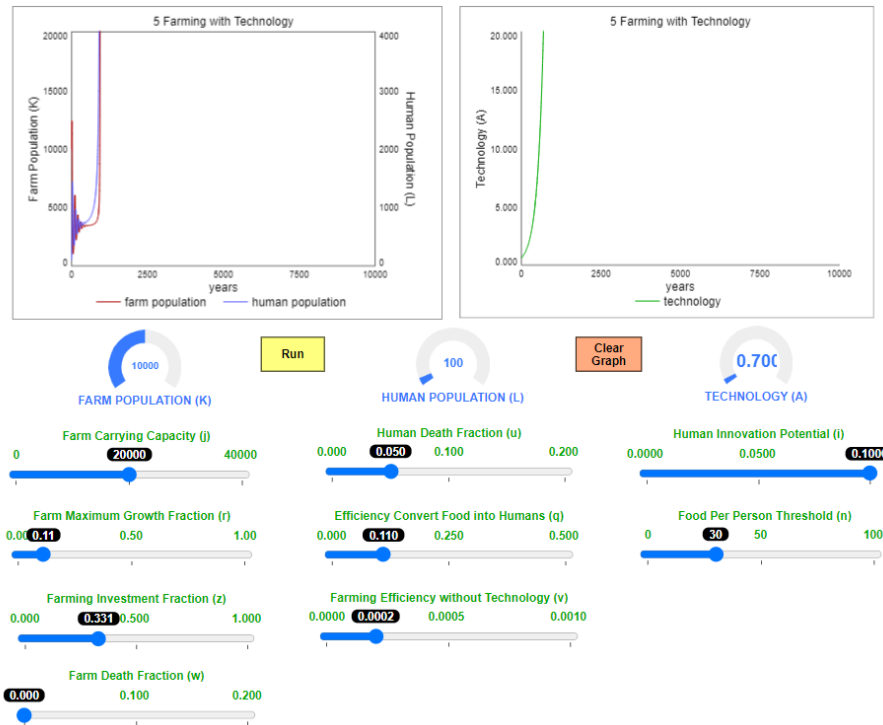


Figure 5-2: Simulation controls for Basic Hunter-Gatherer.

The simulation model has three initial condition knobs:

- FARM POPULATION (K)
- HUMAN POPULATION (L)
- TECHNOLOGY (A)

And nine independent variable parameter adjustment sliders:

- Farm Carrying Capacity (j)
- Farm Maximum Growth Fraction (r)
- Farm Investment Fraction (z)
- Farm Death Fraction (w)
- Human Death Fraction (u)
- Efficiency Convert Food into Humans (q)
- Harvest Efficiency (v)
- Human Innovation Potential (i)
- Food Per Person Threshold (n)

The initial condition knobs and independent parameter sliders require minimum, maximum, increment (resolution), and reset values. These are provided in the table below.

Key: STOCKS; Parameters

	Min	Max	Increment	Reset
FARM POPULATION				
FARM POPULATION (K)	0	20000	100	10000
Farm Carrying Capacity (j)	0	40000	100	20000
Farm Maximum Growth Fraction (r)	0	1.0	0.01	0.11
Farm Investment Fraction (z)	0	1.0	0.001	0.331
Farm Death Fraction (w)	0	0.2	0.001	0.0
HUMAN POPULATION				
HUMAN POPULATION (L)	0	2000	1	100
Human Death Fraction (u)	0	0.2	0.001	0.05
Efficiency Convert Food into Humans (q)	0	0.5	0.01	0.011
Farming Efficiency Without Technology (v)	0	0.001	0.001	0.0002
TECHNOLOGY				
TECHNOLOGY (A)	0	20.0	0.001	0.7
Human Innovation Potential (i)	0	0.1	0.0001	0.1
Food Per Person Threshold (n)	0	100	1	30
OUTPUT GRAPHS				
human population	0	20000		
farm population	0	400		
technology	0	20		
years (t)	0	10000		

Table 5-2: Simulator interface values.

Each simulator control has a minimum and maximum value. Each control also has an increment (resolution) and default reset values that will be in place if you press Clear Graph. These values cannot be changed by the model user and have been set by the model designers to allow the model to be exercised over a useful range of values while avoiding extreme values that would be confusing. While they are “fixed” values in the simulation program, the table is provided not only as background information, but as a starting point for those who would like, on their own, to modify the Stella model.

Explosion Scenario

Our first scenario has the Human Innovation Potential (i) slider set at 0.1. This might seem like a large value, but in the model we have divided it by 1000, so its actual value is 0.0001. This value is enough to head both the farmers and their domesticates off to infinity on year 945. The model simply crashes at this point because the numbers have become too large to compute any longer.

Compared to the historical record, this explosion in less than 1000 years, a millennium, quite different from what actually happened! Technology fueled agriculture could have counted as an explosive revolution, but that is not what actually happened. To get a revolution followed by a long stable period until the next revolution we'd need a model that experienced a carry capacity effect at some point. If you are sufficiently ambitious you can give this a try. You might imagine that there is a normal, slow innovation rate but that rarely a revolutionary innovation is discovered that abruptly jumps the carrying capacity. That might produce a staircase successive revolutions trajectory with a fairly simple model.

Building models schools our intuitions. People speculating verbally about collapses of societies spoke in terms of what sounds like the logistic model in which overshooting the carrying capacity caused a crash. But the logistic regulates population growth smoothly to the carrying capacity. To get overshoots and crashes, you need a more complex model, as we'll see in our next model. In our model in this section we can get explosions and conflagrations but a staircase model is going to need something. Just knowing that is a small step forward!

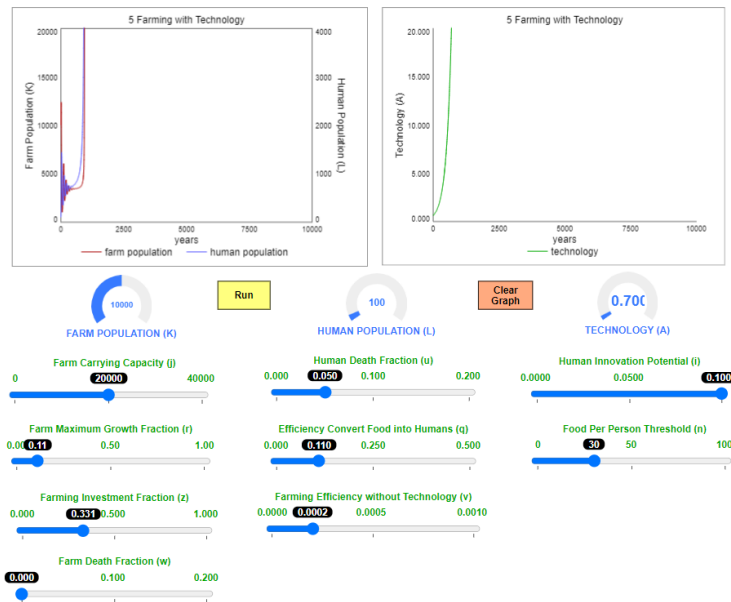


Figure 5-3: Explosion scenario for Farming with Evolving Technology.

Conflagration Scenario

If we reduce the Human Innovation Potential (i) (even further below 0.0001 by setting the Human Innovation Potential (i) slider to 0.0188), we stretch out the time before the model takes off toward infinity, giving us “hockey stick” shaped results. This set of parameter values fits the empirical data on human population growth rather well, qualitatively speaking. The key insight is that in non-linear models, multiple positive feedbacks all sorts of counter-intuitive behavior can occur. The same parameters that dictate slow evolution near the beginning are consistent with much higher rates later in the evolution of the system. There may have been revolutions in various senses in human history, but it is not clear that we need them to explain the overall trajectory of human evolution over the last 10,000 years. This should be a revelation to historians and social scientists who often suggest that humans are far too complex to “reduce” to simple models. Even in the case of very complex phenomena, the KISS

principle applies. As Einstein put it, “Models should be as simple as possible, but no simpler!” The main trend of human evolution can be fit with a pretty simple model. Wild eh!

Of course, we don’t claim that this is the best possible model of human history. It is just a challenge to others to come up with competing models we can formally test against today’s data and, perhaps, better data in the future. Keep the successive revolutions-stairstep verbal model in mind, for example. Better data might end up requiring it.

It is interesting to think about a model that would produce the simplest trajectory of all, a linear growth of people, technology, and farms. With all the non-linearities inherent in coupled population-based systems it is not clear how we’d produce such a simple pattern!

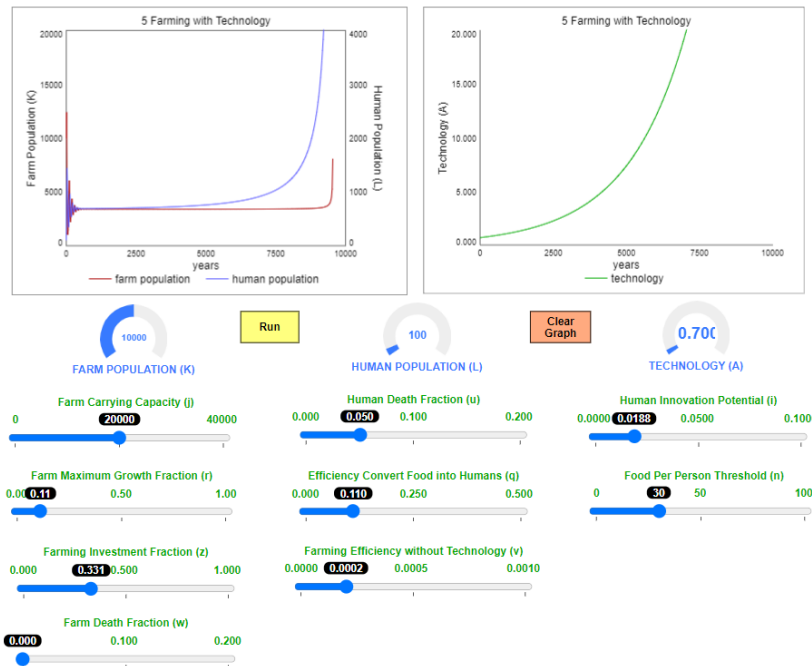


Figure 5-3: Just changing on slider, the Human Innovation Potential (i) the human (farmer) population does not head upwards sharply until almost 10,000 years, a good match for the historical record. We can switch this model to produce an explosion or a conflagration just by adjusting one parameter!

Conclusions

On the one hand, the agricultural conflagration and allied developments in industry, commerce, medicine, and science are spectacular achievements. Not only do they support large numbers of people, but support many of them in comfort and reasonable health and happiness. On the other hand, the agricultural conflagration threatens to burn the world up! Observers have long pointed to the problem that recent achievements are based on the exploitation of non-renewable resources and that this fact will eventually bring the party to a halt. So far, we have engineered our way around this problem by myriad innovations in the utilization of lower grade ores, efficiency in the use of scarce resources, and substitutions.

The impact of our activities on climate and other ecosystems services at this point seems like the more urgent threat. The models with dynamic technology that we analyze in this module and in the hunting

and gathering case, suggest that human dominated systems are not inherently stable. Evolving technology tends to turn us into super-predators that drive their prey and themselves to extinction, and to super mutualists who tend to farm our way to and beyond the limits of our planet. In principle we can use our capacity for cooperation to engineer stability of the global ecosystem. Impressive efforts have been made to regulated fisheries, forestry, endangered species, climate warming, and other forms of human impacts on the global ecosystem. Impressive, but so far not enough!

There is one more bit of bad news to deal with in the next module about the dynamics of civilizations. The human management of our collective affairs has also historically been subject to instability. That human societies function at all is one of the wonders of natural history. Cooperation at the scale of even a few families is rare in nature, yet humans started with tribes and worked our way up to generally effective states and empires. But states and empires are prone to boom-and-bust dynamics. Our tools for dealing with global scale issues have, so far, proven rather ineffectual.

While advances in technology are often thought to have created an explosion of farming and humanity, a much slower conflagration fits the historical data much better. Exponential growth is such that even a very small increase will, eventually, gather steam and take off—heading toward infinity in our simple model. Could another, still relatively simple, model illustrate the cycling, the ups and downs known to have occurred with civilizations over time? We turn to this issue in our next model.

Appendix / Stella Top Level Model Code

Stella's top-level code for the Farming with Technology model is given below. It is useful for determining what the model is actually doing (and hence for trouble shooting the model). It could also be useful for those who want to understand the model in more detail or to use this model as a starting point for their own Stella model.

Top-Level Model:

$$A(t) = A(t - dt) + (s) * dt$$

$$\text{INIT } A = 0.7$$

UNITS: unitless

INFLOWS:

$$s = A * c$$

UNITS: 1/year

$$K(t) = K(t - dt) + (f - g) * dt$$

$$\text{INIT } K = 10000$$

UNITS: prey unit

INFLOWS:

$$f = r * K * p \text{ {UNIFLOW}}$$

UNITS: prey unit/years

OUTFLOWS:

$$g = h + w * K \text{ {UNIFLOW}}$$

UNITS: prey unit/years

$$L(t) = L(t - dt) + (b - d) * dt$$

$$\text{INIT } L = 100$$

UNITS: people

INFLOWS:

$$b = h * q \text{ {UNIFLOW}}$$

UNITS: people/years
 OUTFLOWS:
 $d = u * L$ {UNIFLOW}
 UNITS: people/years
 $c = m * i / 1000$
 UNITS: 1/year
 $h = v * (1 - z) * K * L$
 UNITS: prey unit/year
 $i = 0.2$
 UNITS: people/(prey unit*year)
 $j = 20000$
 UNITS: prey unit
 $m = n - y$
 UNITS: prey unit/person
 $n = 30$
 UNITS: prey unit/person
 $p = (j + z * A * L - K) / j$
 UNITS: unitless
 $q = 0.11$
 UNITS: people/prey unit
 $r = 0.11$
 UNITS: 1/year
 $u = 0.05$
 UNITS: 1/year
 $v = 0.0002$
 UNITS: 1/(people*year)
 $w = 0.0$
 $y = K / L$
 UNITS: prey unit/person
 $z = 0.331$
 { The model has 22 (22) variables (array expansion in parens).
 In root model and 0 additional modules with 3 sectors.
 Stocks: 3 (3) Flows: 5 (5) Converters: 14 (14)
 Constants: 9 (9) Equations: 10 (10) Graphicals: 0 (0)
 }