

Model 4: Basic Farming

Narrative

When high resolution cores from the Greenland Ice Cap were drilled in the early 1990s, paleoclimatologists made a stunning discovery. These cores could resolve events that lasted as little as 15 years some 80 thousand years ago, and the seasons back to 15 thousand years ago. Ice cores build from the top as new snow is added each winter creating a physical and chemical record of temperature, atmospheric gas concentrations, dust in the air, and so forth. The climates of the last ice age had large fluctuations between warm and cold climates on time scales of a century to a few millennia. The cold periods were dustier and lower in greenhouse gasses than the warm periods. The transitions from cold to warm, particularly, were often very abrupt, near the resolution of the cores even toward the top of the cores. Recent evidence suggests that the large, thick North American ice sheet was unstable, frequently collapsing and releasing lots of light fresh water into the North Atlantic, shutting down the formation of deep water, the sinking of which otherwise draws subtropical currents into the high North Atlantic, warming the whole Northern Hemisphere's climate.

The last big cold excursion of the Pleistocene climate was the "Younger Dryas" cooling from 12.9 to 11.7 thousand years ago. The end of the Younger Dryas abruptly brought a warmer, wetter and much more stable climate. Geologists declared a new geological Epoch, the Holocene in the 19th century for the post-glacial period, not realizing how dramatic the change really was. The Holocene climate was rather more conducive to plant growth than the last ice age. At the same time, technologically advanced hunters had overexploited game resources as we remarked in the previously module. Already, in the warm period before the Younger Dryas, people in the Middle East had turned to harvesting wild grass seed to replace the scarcer game in their diets.

Thus, the ameliorating climate that made farming possible and also diminished game resources both pushed people to find alternate sources of food. As people intensified their use of plants after 11.7 thousand years ago and coped with lower game populations, in a number of cases they found plant and animal species that responded to artificial selection and became domesticates. Large seeded grasses like wheat, barley, rice, maize, and millet was one important class of plant domesticates. Almost as important were starchy tubers like potatoes, manioc, yams, and taro. One of the dietary limitations of plants is that they are typically low in protein, and the quality of the proteins in terms of the amino acid composition humans need is poor. Legumes that fix nitrogen tend to have more and higher quality protein. Hence early domesticates included peas, many types of beans, chickpeas, peanuts, and broadbeans. Plant diets also are often low in micronutrients, vitamins and minerals. Eventually, fruits, nuts, berries, and vegetable crops were also domesticated. Early animal domesticates included cattle, sheep, goats, pigs, llamas, alpaca, chickens and turkeys. Horses and camels were domesticated rather later, about 5,500 years ago.

There were a number of regions where plant domestication happened independently, including Southwest Asia, South Asia, North China, South China, New Guinea, the Horn of Africa, lowland tropical Africa, Meso-America, the Andean region, lowland South America, and Eastern North America. Agriculture tended to spread from these heartlands both because farmers themselves spread and partly because the farming knowledge and domesticates spread. Farming sustains a higher density of people per unit area than hunting and gathering. Farming thus uses land more efficiently. This, in turn, means that farmers can afford to "pay" more for land than hunter-gatherers. "Pay" sometimes means some

kind of freely negotiated economic compensation. Farmers can pay hunter-gathers in farm products like grain in exchange for luxury foods, meat, hides, ivory and furs, and any mineral resources they happen to control like toolstone and gems. In North America, the European fur trade with the Indians of the Western forests and mountains was economically significant until it was overwhelmed by the burgeoning numbers of European farming and ranching settlers. Often it means that farmers just use superior numbers, perhaps supplemented by superior weapons, to murder, subjugate or drive away the hunters, as in the case of Euro-American settlers.

The movements of farming populations have recently become possible to trace using ancient DNA. It turns out, for example, that the first farmers to reach Northwest Europe were genetically largely Southwest Asians. But once people are farmers or herders, they find it comparatively easy to swap in desirable new domesticates. Thus, wheat spread eventually to North China in ancient times largely replacing the original millets there and rice spread from South China to the Mediterranean via South Asia, supplementing the original wheat and barley domesticates. The first globalization by European navigators after 1500, and the more limited, but still very impressive, Austronesian and Chinese navigational achievements, spread some of the regional domesticates worldwide. It is hard to imagine Southern and Southeast Asian food without American hot peppers or Mediterranean food without American tomatoes. Andean farmers contributed potatoes and quinoa and, in return, acquired cattle, sheep, barley, wheat and broadbeans.

Holocene hunter-gatherer populations that did not discover candidates for domestication tended to intensify their consumption of wild plants and broaden their exploitation of animals to include birds, small mammals, fish and even whales. Some such intensification occurred in regions like the Arctic where even today agriculture, aside from reindeer herding, is not practical. Other places are more surprising, such as temperate Western North America and Australia where, today, agriculture is quite successful. The Western US may have lacked agriculture because summer aridity was hostile to the key American crops like corn and beans. These crops can be grown in some regions with summer rains and/or by irrigation but even where practical it was a somewhat marginal system. The corn farming archaeological Fremont Culture in what is today Utah state, an offshoot of the Puebloan peoples of New Mexico and Arizona, was displaced by the invading Numic plant intensive hunter gatherers about 700 years ago. Similarly, the hunter-gatherers of Southern Scandinavia persisted for around 2000 years in the face of agricultural pioneering in the rest of Northwestern Europe from 7,000 to 5,000 years ago before gradually giving way to the farmers.

These cases are a clue that the advent of agriculture did not result in an immediate demographic revolution as many people have thought. Recent attempts to estimate population growth rates, using frequency of archaeological finds per unit time during the early millennia of farming, suggest them to be on the order 0.04% per year. Estimated rates of growth for Western North American hunter-gatherer populations, slowly intensifying their uses of plant resources, are similar. Since maximum human population growth rates are around 3% per year, the very much smaller growth rates estimated suggest that there was no dramatic agricultural revolution around the origins of agriculture, rather just a rather gentle evolution. At least when populations are relatively small, the rate of growth of technology is dominated by what we can think of as raw human creativity, which has to be surprisingly small to come close to being consistent with the observed very slow rate of population growth in the early Holocene, as we'll see in the next module.

Hence, in this module we develop a model with static technology to illustrate the basic effect of switching from hunting and gathering to farming. To make the contrast stark and simple, we want to

think in terms of replacing hunting with herding. This converts the relationship of people to animals from a predator-prey one to a mutualistic one. The only difference between our model here and the one with hunting and gathering with static technology is a sign change. The hallmark of farming is that people invest time and capital in favoring the productivity of their exploited resources. Herders protect their livestock from predators, move them seasonally to exploit flushes of forage and avoid harsh seasons, create shade when it is too hot and barns when it is too cold. Hay and other stored food is often provide in dry or cold seasons. This creates a positive effect of the herders on the growth rate of their herds.

At the same time herders have to eat or sell animals to survive. These predatory effects exert a negative effect on the prey, as in the hunting models. But if the positive effect of care for the herd is sufficiently strong the tendency of high rates of predation to collapse the exploited population is counteracted or even reversed. Plant domesticates are similar. Farmers till fields to suppress competing plants and provide a nice seedbed for the domesticate. They may fertilize the field or build a fence to keep out grazing animals. Fields may be weeded during the growing season. Irrigation is common. Hard toil is the norm. The Meso-American archaeologist, Kent Flannery, remarked once that it made as much sense to think that corn domesticated farmers as that farmers domesticated corn.

Further Reading

Alley, R. B. (2000). *The Two-mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future*. Princeton, Princeton University Press.

Bettinger, R. L. and M. A. Baumhoff (1982). "The numic spread: Great Basin cultures in competition." *American Antiquity* 47(3): 485-503.

Larson, G. and D. Q. Fuller (2014). "The evolution of animal domestication." *Annual Review of Ecology, Evolution, and Systematics* 45(1): 115-136.

Richerson, P. J., R. Boyd and R. L. Bettinger (2001). "Was agriculture impossible during the Pleistocene but mandatory during the Holocene? A climate change hypothesis." *American Antiquity* 66(3): 387-411.

Zohary, D. and M. Hopf (2001). *Domestication of Plants in the Old World: The Origin and Spread of Cultivated Plants in West Asia, Europe, and the Nile Valley*. Oxford, Oxford University Press.

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

[https://en.wikipedia.org/wiki/Mutualism_\(biology\)](https://en.wikipedia.org/wiki/Mutualism_(biology))

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

White Box Graphical Model

The under-the-hood 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 4-1, is broken into two major sections, the Farm and the Humans who run them. Each major section of the model is discussed below.

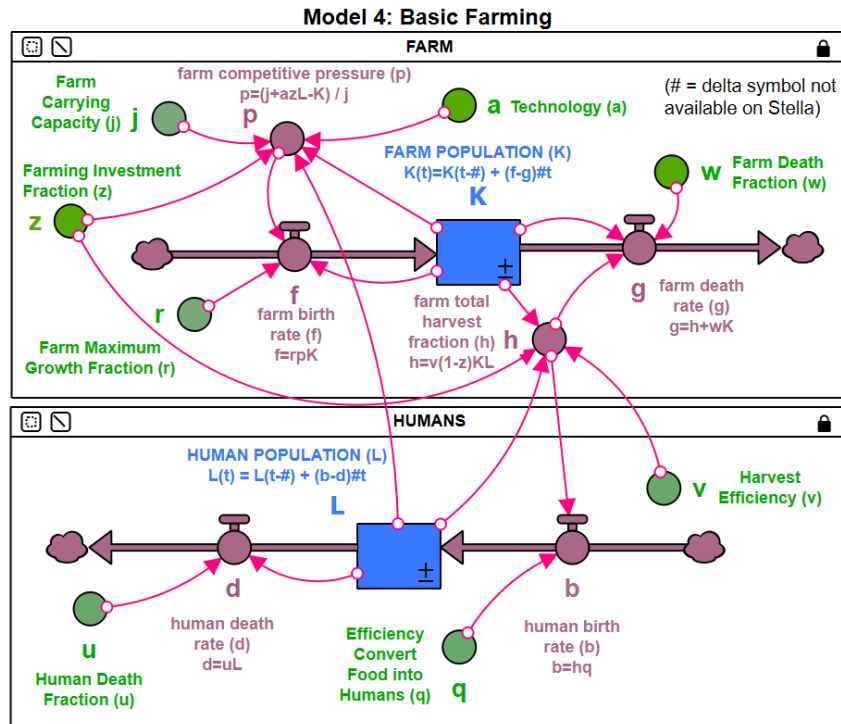


Figure 4-1: Stella Basic Farming model.

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 $\#$ 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.

Harvest Efficiency (v) (without evolving technology) 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 submodel 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 submodel by submodel. To have any insight into the behavior of a complex model you need to have a good understanding of each piece that goes into it. Even with that 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

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

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 (u)** 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.

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	$K(t) = K(t-\Delta) + (f-g)\Delta t$
Farm Carrying Capacity (j)	Farm unit	
Farm Maximum Growth Fraction (r)	1/year	
Technology (a)	Unitless	
Farm Death Fraction (w)	1/year	
Farming Investment Fraction (z)	Unitless	
farm birth rate (f)	farm unit/year	$f = rpK$
farm competitive pressure (p)	unitless	$p = (j + azL - K)/j$
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	$L(t) = L(t-\Delta) + (b-d)\Delta t$
Human Death Fraction (u)	1/year	
Efficiency Convert Food into Humans (q)	People/farm unit	
Harvest Efficiency (v)	1/(people*year)	
human death rate (d)	people/year	$d = uL$
human birth rate (b)	people/year	$b = hq$

Table 4-1: Model variables and equations.

Equations without Intermediate Variables

The intermediate variables can be eliminated by substitution, leaving just the dependent variables as a function of the independent variables. If Δt is made smaller, we reach, in the limit, the differential

$$K' = rK[(j + azL - K)/j] - v(1-z)KL - wK$$

$$L' = vKL - uL$$

Black Box Model

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

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

This is what you should get:

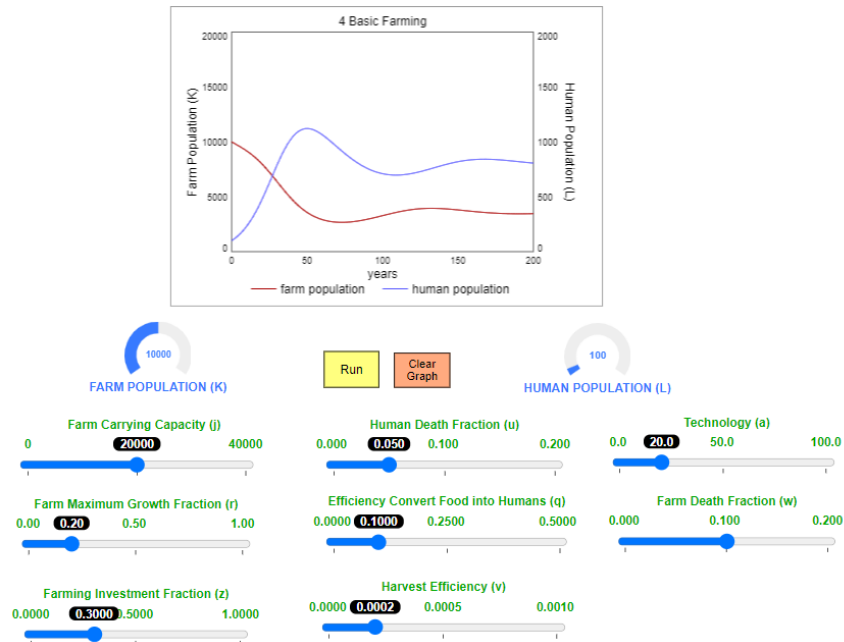


Figure 4-2: Simulation controls for Basic Hunter-Gatherer.

The simulation model has two initial condition Population Control knobs:

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

And eight independent variable parameter adjustment sliders:

- Farm Carrying Capacity (j)
- Farm Maximum Growth Fraction (r)
- Farm Investment Fraction (z)
- Human Death Fraction (u)
- Efficiency Convert Food into Humans (q)
- Harvest Efficiency (v)
- Technology (a)
- Farm Death Fraction (w)

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	0.2
Farm Investment Fraction (z)	0	1.0	0.01	0.3
Technology (a)	0	100.0	1.0	20.0
Farm Death Fraction (w)	0	0.2	0.001	0.1
HUMAN POPULATION				
HUMAN POPULATION (L)	0	2000	1	100
Set Human Death Fraction (u)	0	0.2	0.001	0.05
Efficiency Convert Food into Humans (q)	0	0.5	0.001	0.1
Harvest Efficiency (v)	0	0.001	0.01	0.002
OUTPUT GRAPHS				
farm population	0	20000		
human population	0	2000		
years (t)	0	200		

Table 4-2: 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.

Basic Farming Scenario

In our first scenario, we start with 100 farmers and a vast heard of 10,000 goats, a ratio of 100:1 goats per farmer. The farmers eat goats right and left, have lots of baby farmers, and soon the human population swells while the goat population drops. Eventually things steady out at about 3500 goats and 800 farmers.

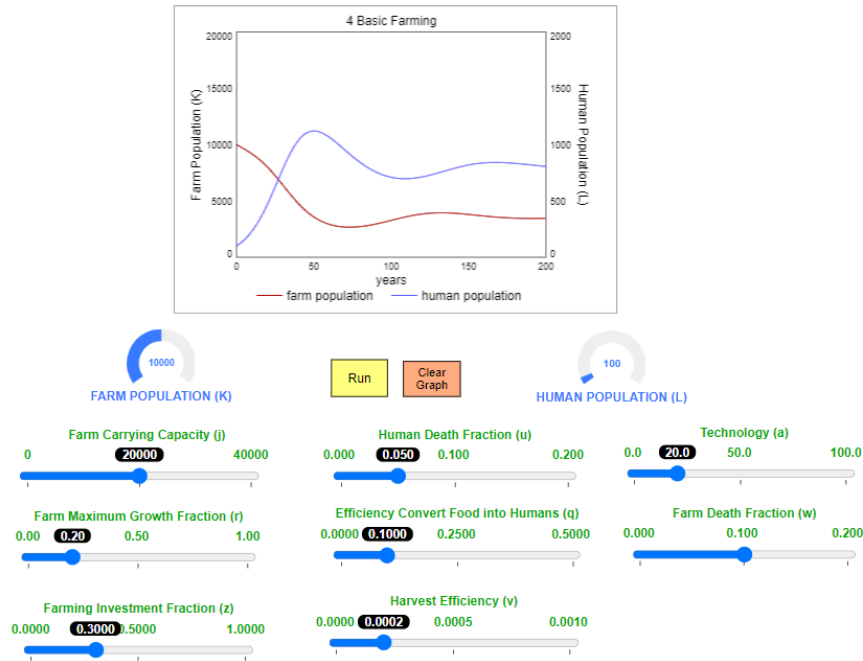


Figure 4-3: Basic Farming scenario (repeat of Figure 4-2).

Increased Initial Technology Scenario

With the initial technology increased but not growing (this is a static technology model), humans will more efficiently care for and utilize their wards which will causes the human population to level out at a higher level, showing the technology (initial, not growing) effect on mutualism. This does provide us with a hint of what might happen if, instead of being static, technology increased dynamically over time.

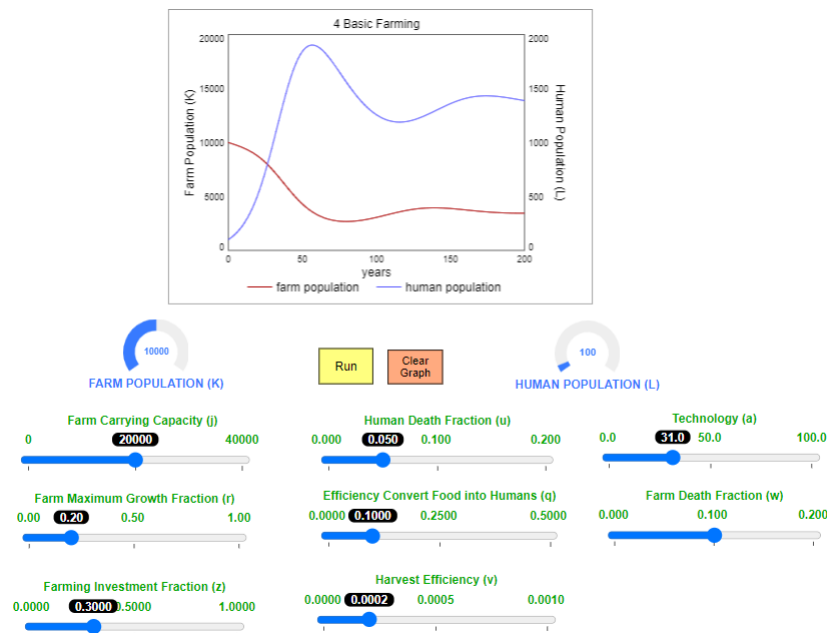


Figure 4-3: Increased initial technology scenario.

Increased Farming Investment

Increasing the farming investment fraction (z) allows farmers to expend more effort protecting the herds and keeping the weeds at bay. As a result, farmers can raise more food on the same amount of land; in other words, they can reduce the farm competitive pressure (p). As can be seen from the run below, with the Farming Investment Fraction (z) increased to 0.72, both the farm animal and human farmer populations head off toward infinity in just a few generations.

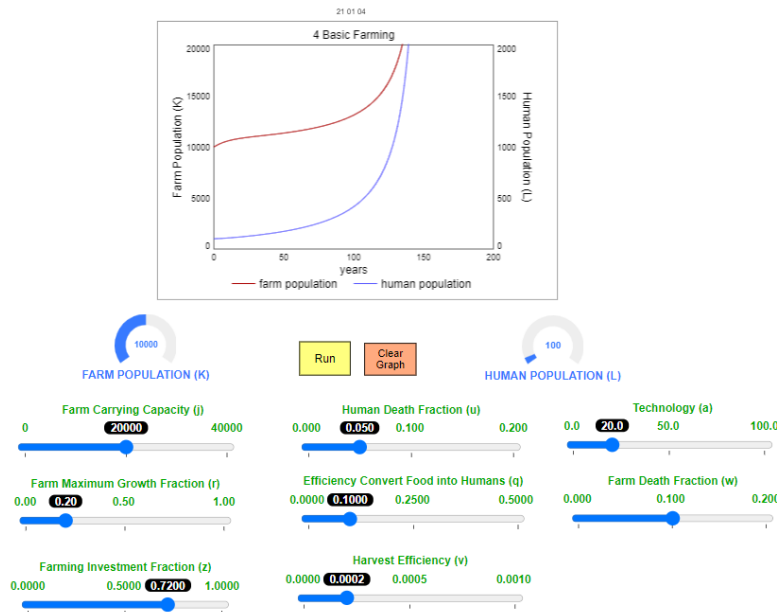


Figure 4-4: Increased farming investment scenario.

Conclusions

The above scenarios drive home the key point that farming is very sensitive to technology and the amount of effort humans devote to applying whatever technology they have at any given point in time. Our level of technology in Basic Farming was set initially and stayed fixed at that level during the simulation run. It does not take a rocket scientist to predict, in general, what will happen if we make technology dynamic, allowing it to grow over time, but let's develop a farming model with dynamic technology and take a closer look at what happens.

Appendix / Stella Top Level Model Code

Stella's top-level code for the Basic Farming 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:

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

INIT K = 10000

UNITS: prey unit

```

INFLOWS:
  f = r*p*K {UNIFLOW}
  UNITS: prey unit/years
OUTFLOWS:
  g = h+w*K {UNIFLOW}
  UNITS: prey unit/years
L(t) = L(t - dt) + (b - d) * dt
INIT L = 100
UNITS: people
INFLOWS:
  b = h*q {UNIFLOW}
  UNITS: people/years
OUTFLOWS:
  d = u*L {UNIFLOW}
  UNITS: people/years
a = 20.0
h = v*(1-z)*K*L
  UNITS: prey unit/year
j = 20000
  UNITS: farm unit
p = (j+a*z*L-K) / j
  UNITS: unitless
q = 0.1
  UNITS: people/prey unit
r = 0.2
  UNITS: 1/year
u = 0.05
  UNITS: 1/year
v = 0.0002
  UNITS: 1/(people*year)
w = 0.1
z = 0.3
{ The model has 16 (16) variables (array expansion in parens).
  In root model and 0 additional modules with 2 sectors.
  Stocks: 2 (2) Flows: 4 (4) Converters: 10 (10)
  Constants: 8 (8) Equations: 6 (6) Graphicals: 0 (0)
}

```