Guided Study Program in System Dynamics

System Dynamics in Education Project
System Dynamics Group
MIT Sloan School of Management[1]

Solutions to Assignment #14
Tuesday, February 16, 1999

All of the explanations of the dynamics of the world model are adapted from Prof. Forrester's *World Dynamics*.

In World Dynamics, Prof. Forrester tests different scenarios with his world model in order to understand how different policies will or will not bring a smooth transition to global equilibrium. In this assignment, you will use Vensim to test out the same scenarios and try to explain why the model generates the behavior you see.

First, run the model as it is, in the base run case that Prof. Forrester first presents in World Dynamics. Then, work through the following exercises one at a time, changing the appropriate parameters and graphing the test run along with the base case, in order to have points of reference from which you can contrast the differences in behavior. After you compare the two runs, provide in your solutions document a verbal explanation of why the policy changes produce the behavior you observed. Feel free to refer to Chapter 3 of World Dynamics for detailed explanation of each variable in the model. You will notice that we have already modeled several components of the world model. Only refer back to Chapters 4 and 5, which contain Prof. Forrester's explanations of the behavior generated by the different scenarios, after you have worked through the model on your own.

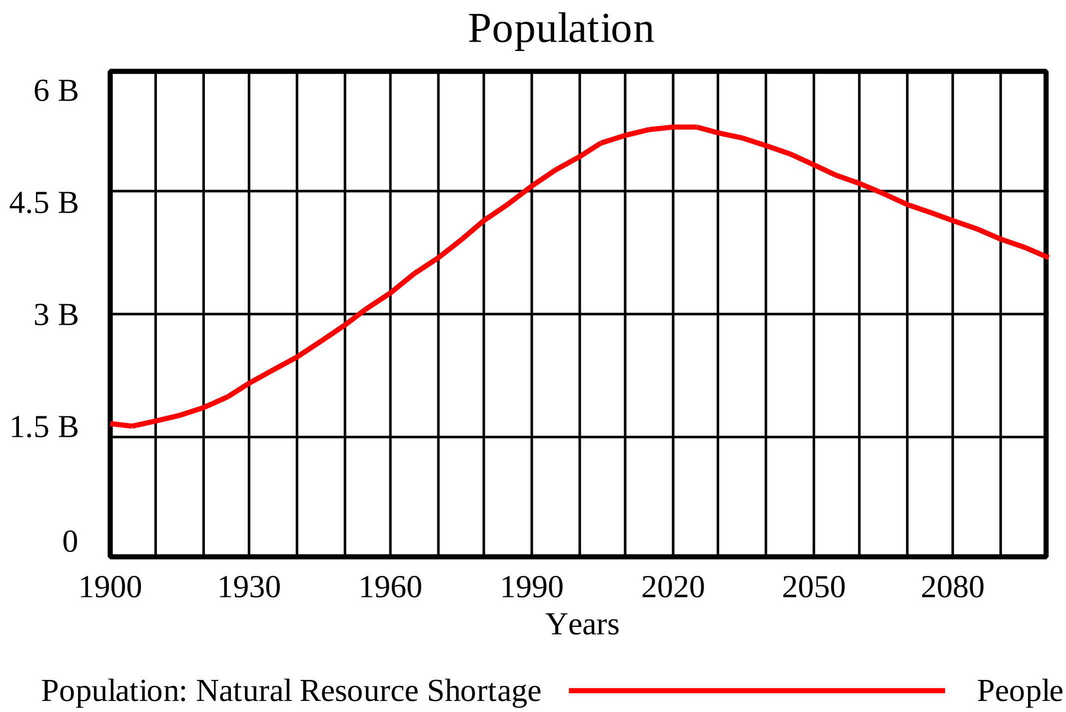
Base Run: Natural Resource Shortage

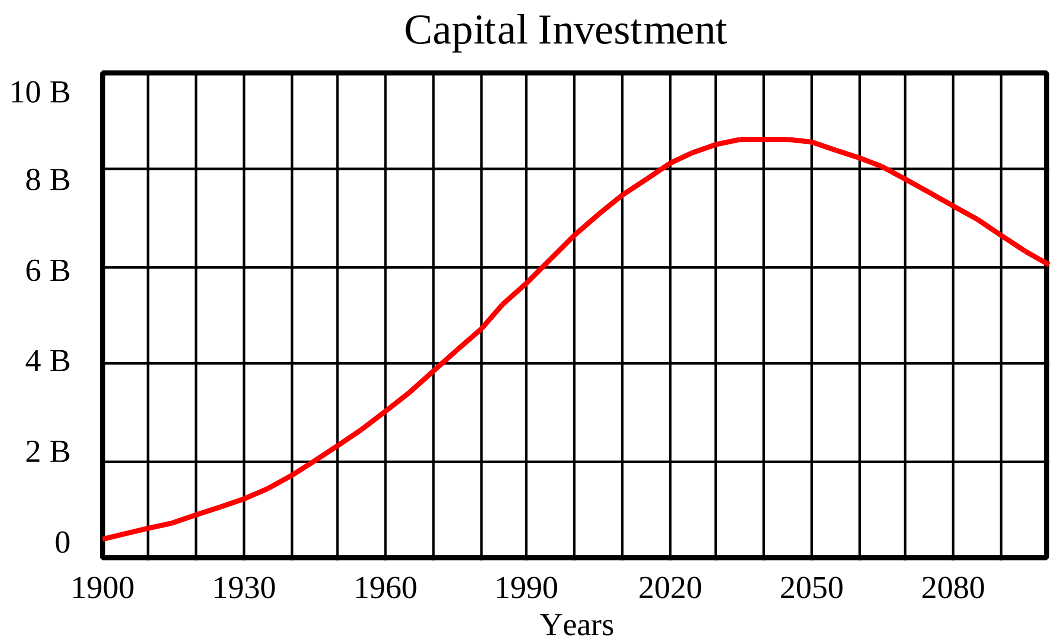
The decline in population is caused by falling natural resources. The falling natural resources lower the effectiveness of capital investment and the material standard of living enough to reduce population. Around year 2000, natural resources are falling steeply. The slope of the curve is such that, if usage continued at the same rate, natural resources would disappear by the year 2150.

In section 3.8 the supply of natural resources was assumed sufficient to last for 250 years at the 1970 rate of usage. In the base run, however, the rate of usage (not plotted) rises another 50% between 1970 and 2000 because of the rising population and the increasing capital investment. Well before natural resources disappear, their shortage depresses the world system because extraction becomes more difficult due to diffused stocks of resources (refer to the description of the natural resource extraction multiplier from section 3.6). Rising demand and falling supply create the consequences of natural resource depletion, not 250 years in the future, but only 30 to 50 years hence.

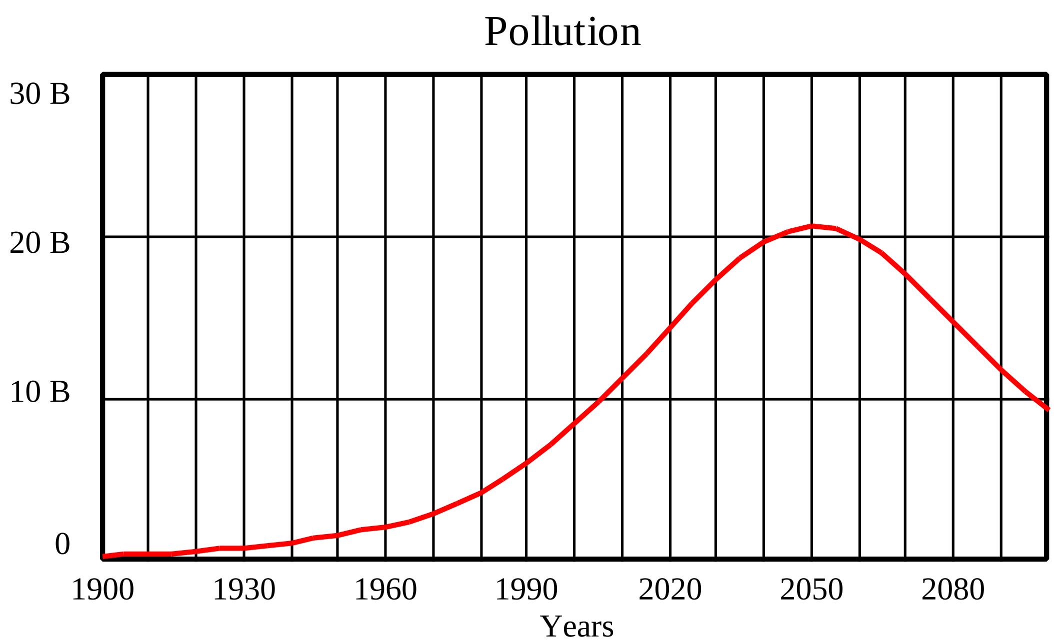
As population starts to decline, so does capital investment after a short time lag, and pollution, after a longer time lag.

The output graphs are as follows:

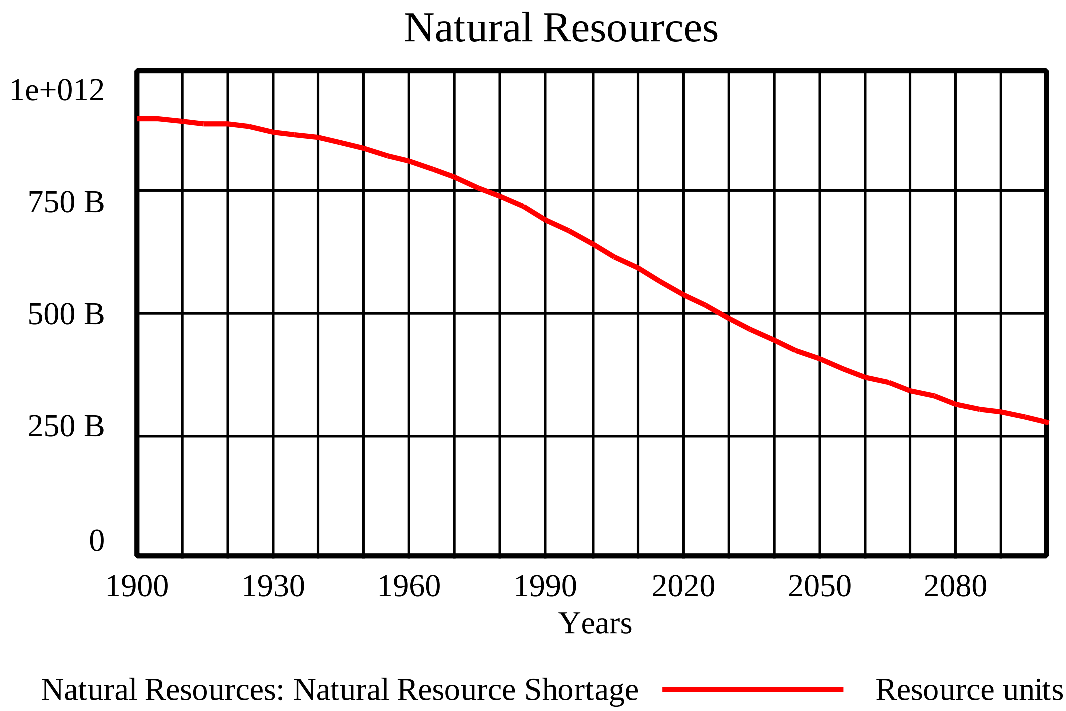




Capital: Natural Resource Shortage —— Capital units



Pollution: Natural Resource Shortage —— Pollution units



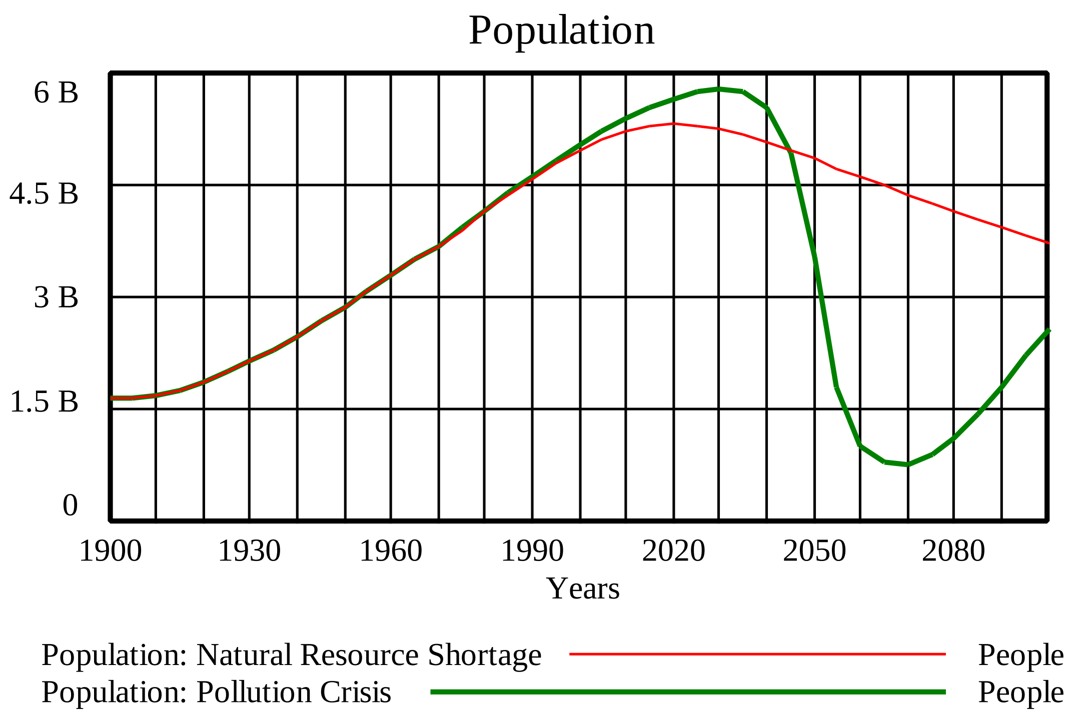
<u>Scenario #1: Pollution Crisis</u>

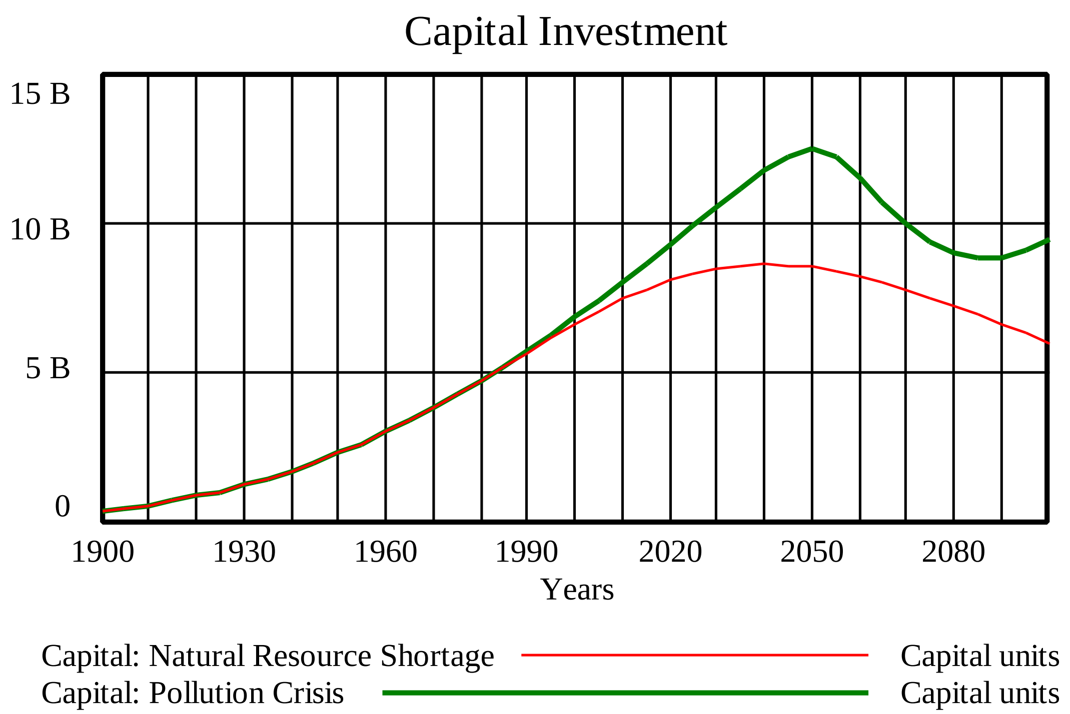
Reduce the "natural resource usage normal" to 25% of its original value.

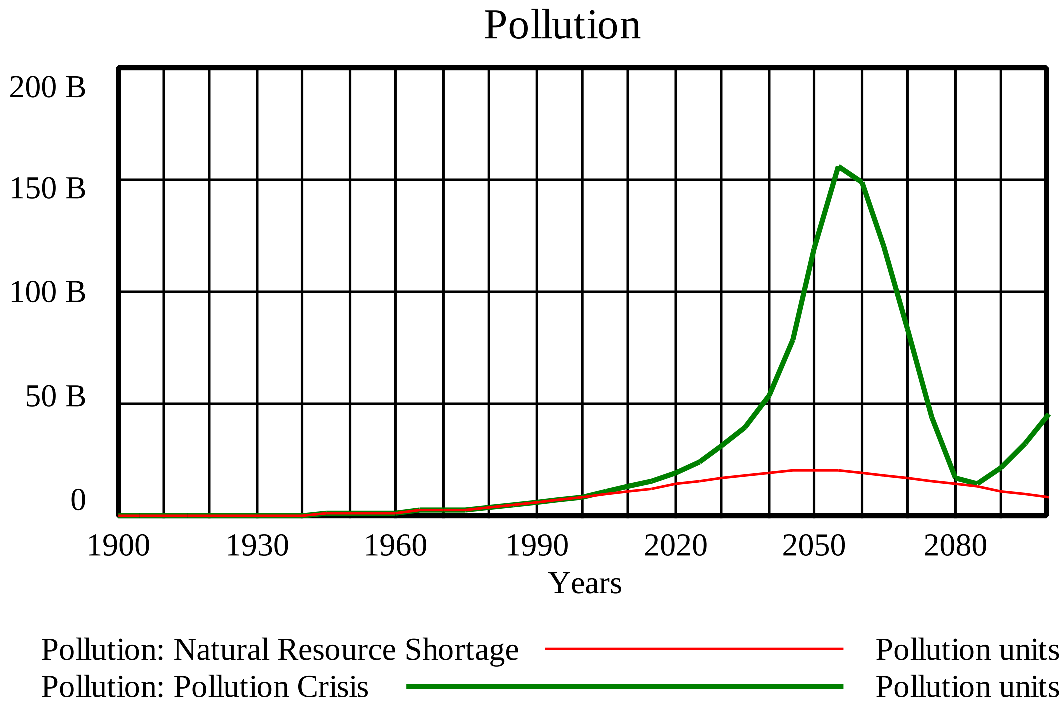
Reducing the demand for natural resources takes one layer of restraint off the growth forces of the system. If natural resources no longer limit growth, the next growth-suppressing pressure will arise within the system.

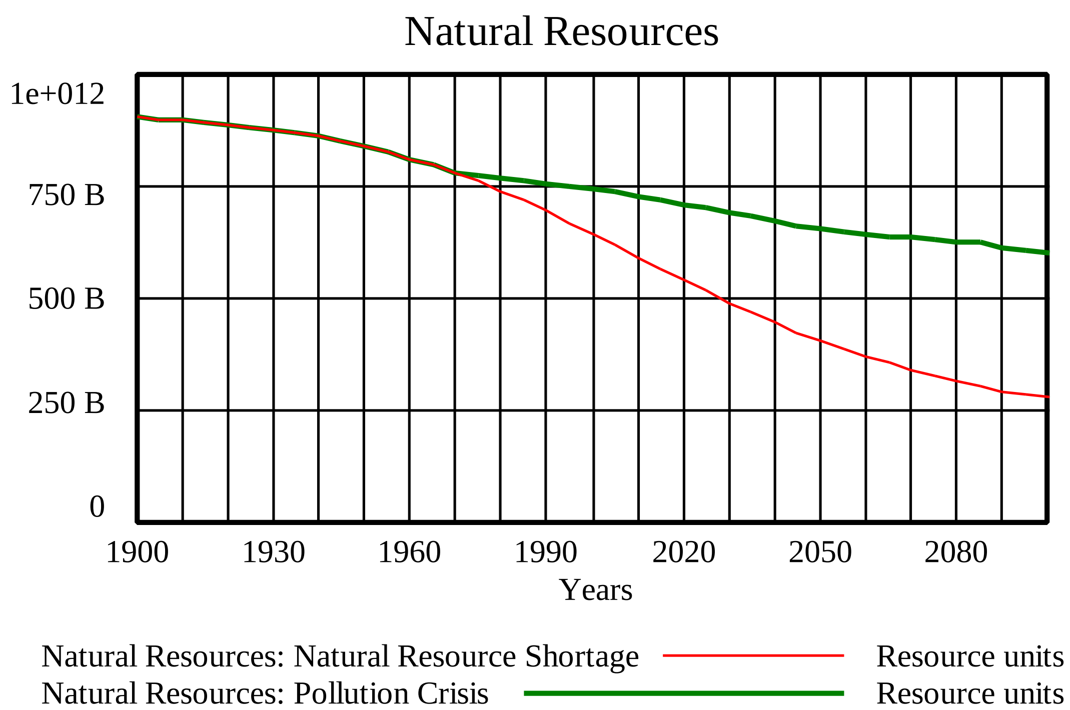
The first scenario simulation runs show pollution as the next barrier to appear. A pollution crisis lurks within the system. The regenerative upsurge of pollution can occur if no other pressure limits growth before pollution does. In this scenario, pollution rises to more than 40 times the amount in 1970. This scenario should be compared with the base run to see the effect of a reduced usage of natural resources, which begins in 1970. Population continues for a longer time along its growth path. So does capital investment. Population and capital investment grow until they generate pollution at a rate beyond that which the environment can dissipate. When the pollution overloading occurs, pollution climbs steeply. As a result, population and capital investment decline until pollution generation falls below the pollution-absorption rate. Population drops in 20 years to one-sixth of its peak value.

The output graphs are as follows:


Population
6 B
4.5 B
3 B
1.5 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Population: Natural Resource Shortage People
Population: Pollution Crisis People


Capital Investment
15 B
10 B
5 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Capital: Natural Resource Shortage Capital units
Capital: Pollution Crisis Capital units


Pollution
200 B
150 B
100 B
50 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Pollution: Natural Resource Shortage
Pollution units
Pollution: Pollution Crisis
Pollution units


Natural Resources
1e+012
750 B
500 B
250 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Natural Resources: Natural Resource Shortage
Resource units
Natural Resources: Pollution Crisis
Resource units

Scenario #2: Crowding

Set the "natural resource usage normal" to 0 and reduce the "pollution normal" to 10% of its original value.

The base run discussed the mode in which growth was suppressed by falling natural resources. In the first scenario the usage rate of resources was reduced enough that pollution appeared as the next limit to growth. Now, if the effects of natural resources and pollution are both eliminated from the model, the third limit to growth can be examined.

Population rises to about 9.7 billion, which corresponds to a crowding ratio of 2.65 times the 1970 world population. By the year 2060 the quality of life has fallen far enough to reduce the rate of rise in population. In the year 2100 population is stabilizing.

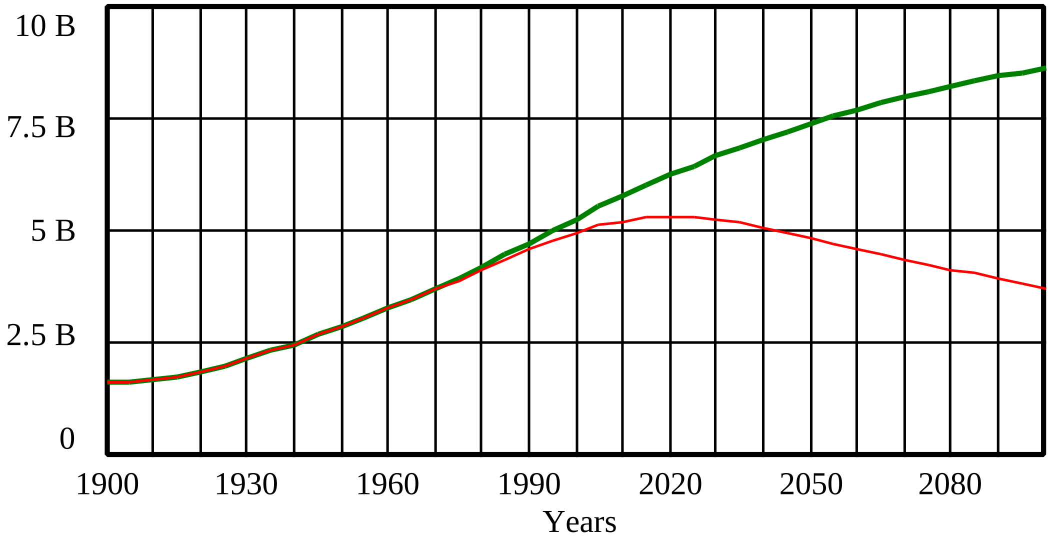
In the second scenario capital investment rises to 38 billion units to yield a capital-investment ratio of 3.9 times the 1970 capital investment per person. This, of course, is possible only because of the assumptions that resources are unlimited and pollution has been suppressed. But the second scenario shows that the high capital-investment ratio is only partly available to raise the material standard of living, which rises to only 2.3 times the 1970 value. Greater crowding and increased demand for food, coupled with the necessity of using less productive agricultural land, has diverted more capital investment to food production. The capital-investment-in-agriculture fraction has risen from 0.28 in 1970 to 0.47 in 2100. In this scenario, the increase in capital devoted to agriculture is able to maintain the food ratio near unity for the entire interval of time.

As capital investment grows, capital-investment discard rate grows proportionately as a result of wear-out and deterioration. At the same time, the incentive to accumulate further capital begins to abate as seen in section 3.26 of *World Dynamics*. The result is an equilibrium above which capital ceases to grow.

A participant commented: "It is interesting to note that although the material standard of life is increasing, the overall quality of life is decreasing. The quality of life cannot be measured by purely counting the amount of stuff you possess."

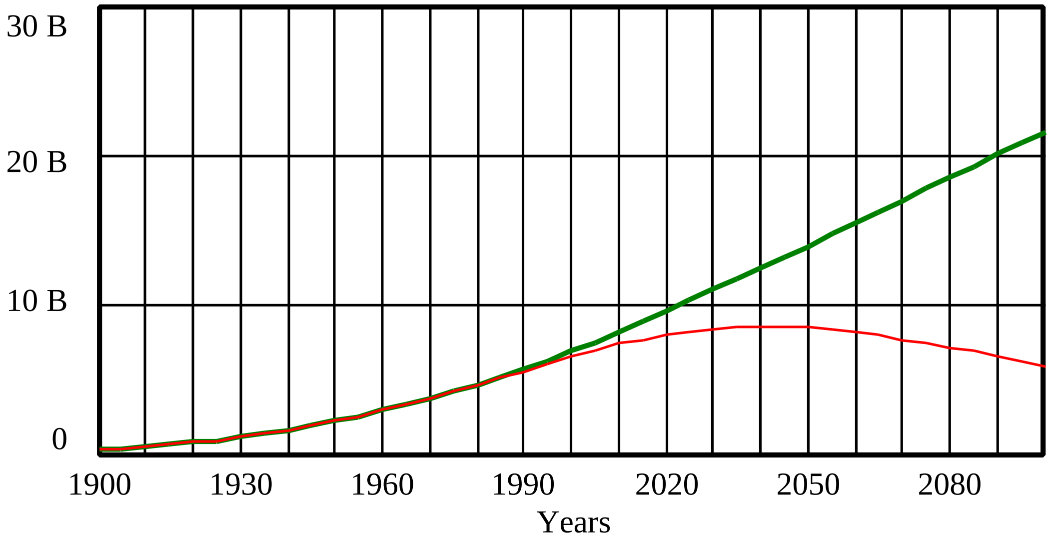
The output graphs are as follows:

Population



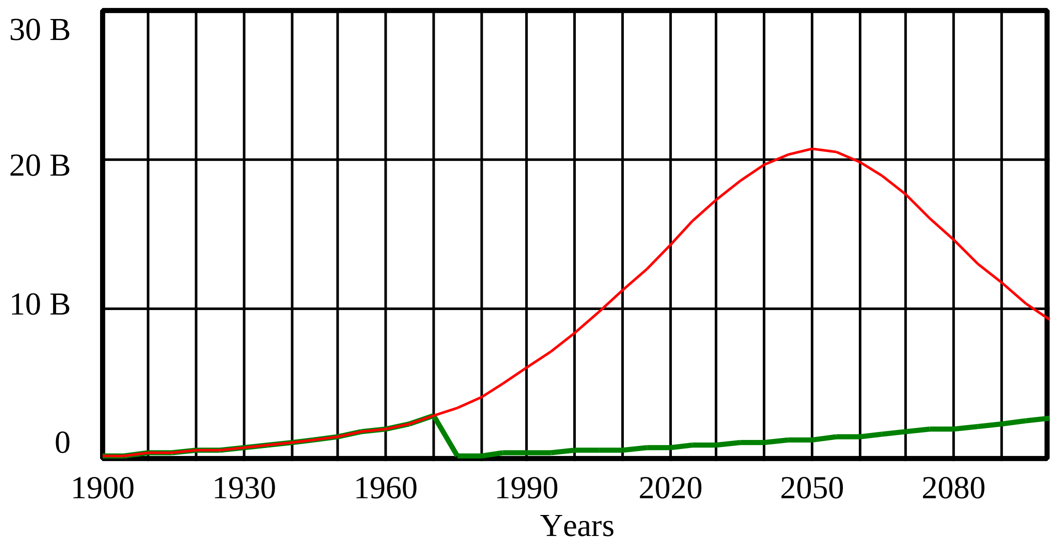
Population: Natural Resource Shortage People
Population: Crowding People

Capital Investment



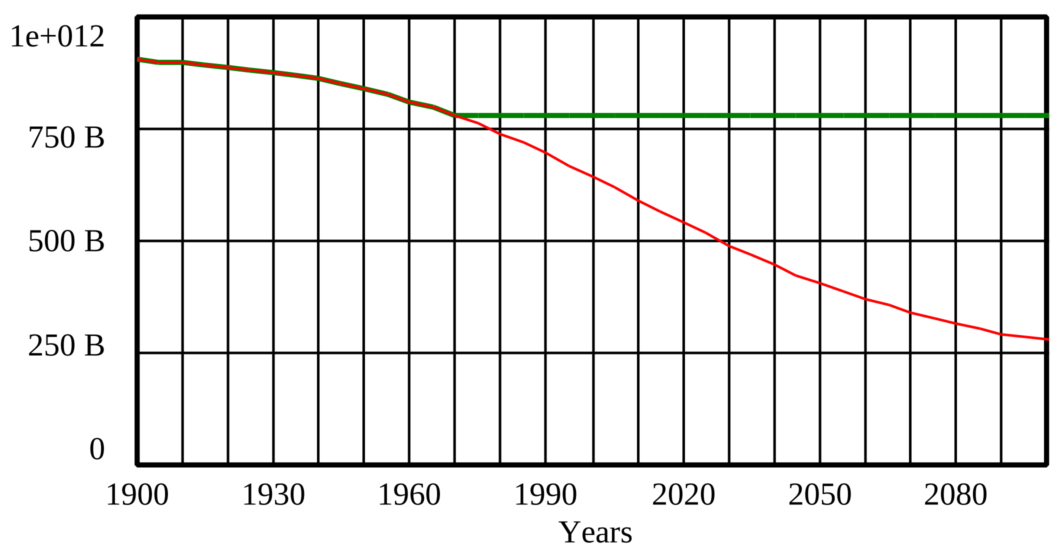
Capital: Natural Resource Shortage Capital units
Capital: Crowding Capital units

Pollution

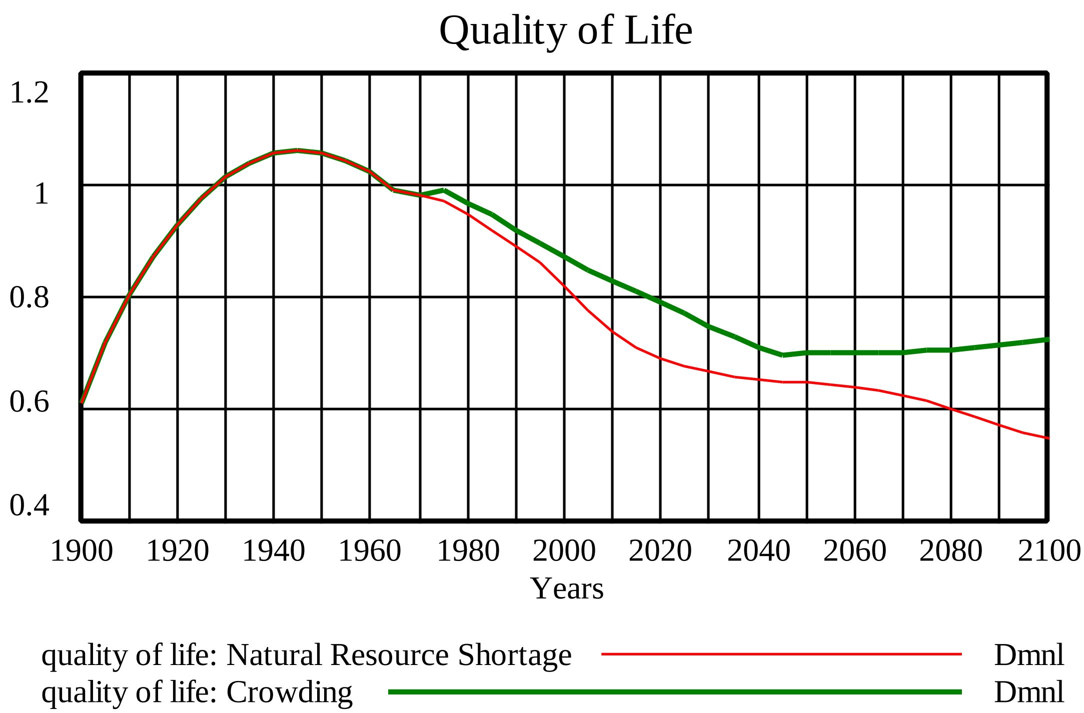


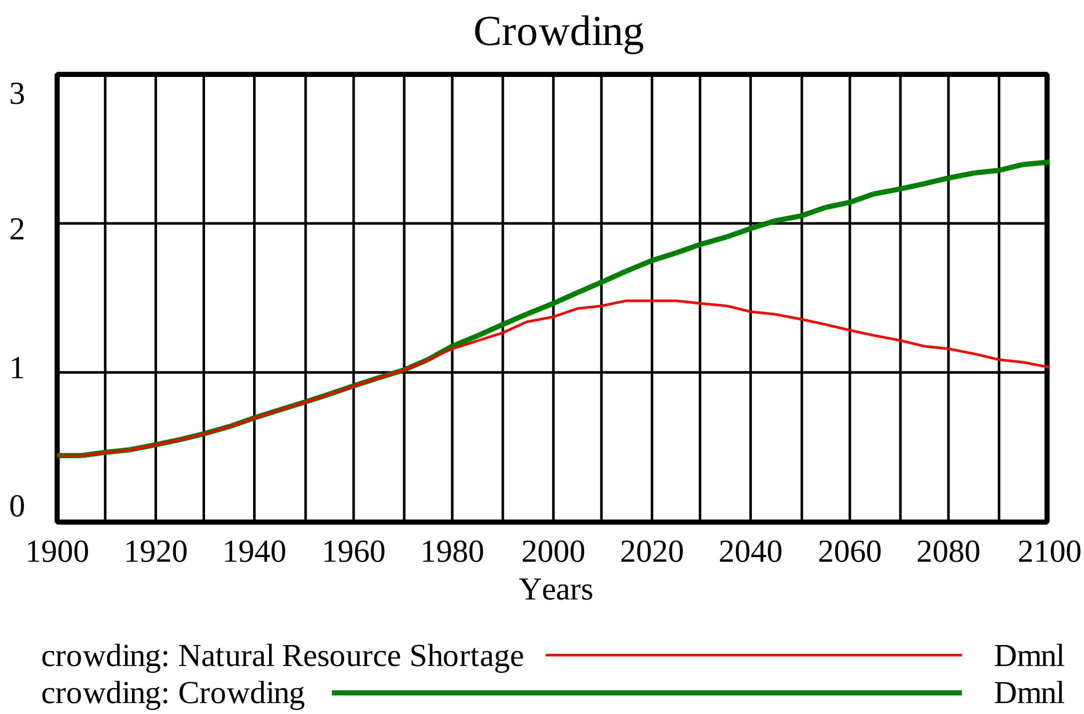
Pollution: Natural Resource Shortage — Pollution units
Pollution: Crowding — Pollution units

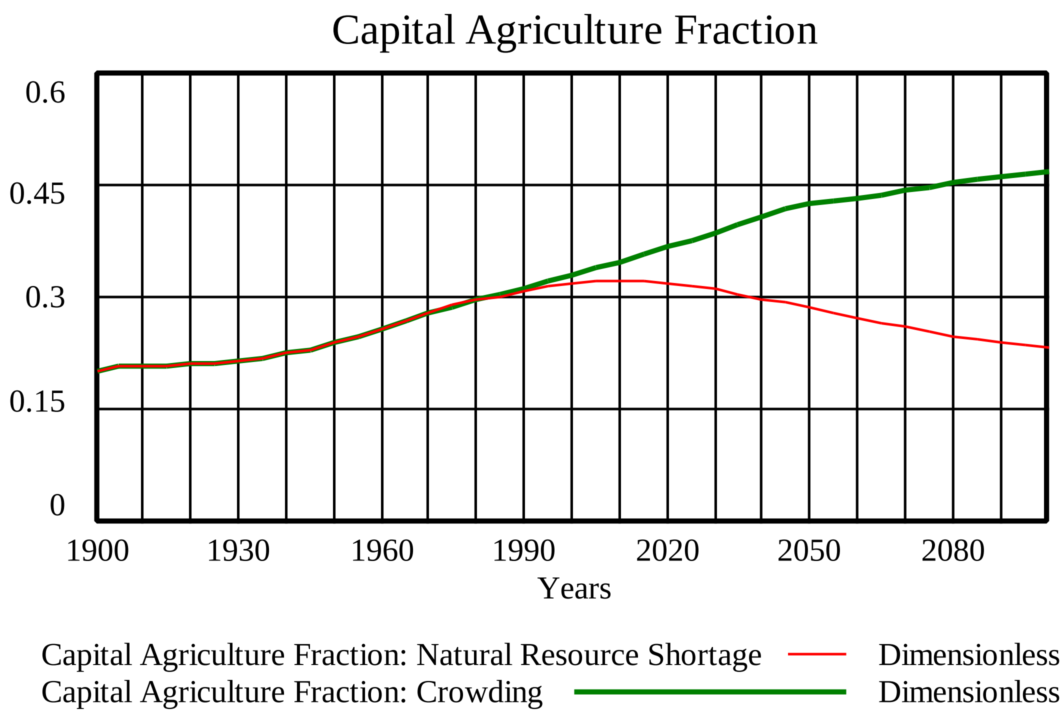
Natural Resources



Natural Resources: Natural Resource Shortage — Resource units
Natural Resources: Crowding — Resource units


Quality of Life
1.2
1
0.8
0.6
0.4
1900 1920 1940 1960 1980 2000 2020 2040 2060 2080 2100
Years
quality of life: Natural Resource Shortage Dmnl
quality of life: Crowding Dmnl


Crowding
3
2
1
0
1900 1920 1940 1960 1980 2000 2020 2040 2060 2080 2100
Years
crowding: Natural Resource Shortage Dmnl
crowding: Crowding Dmnl



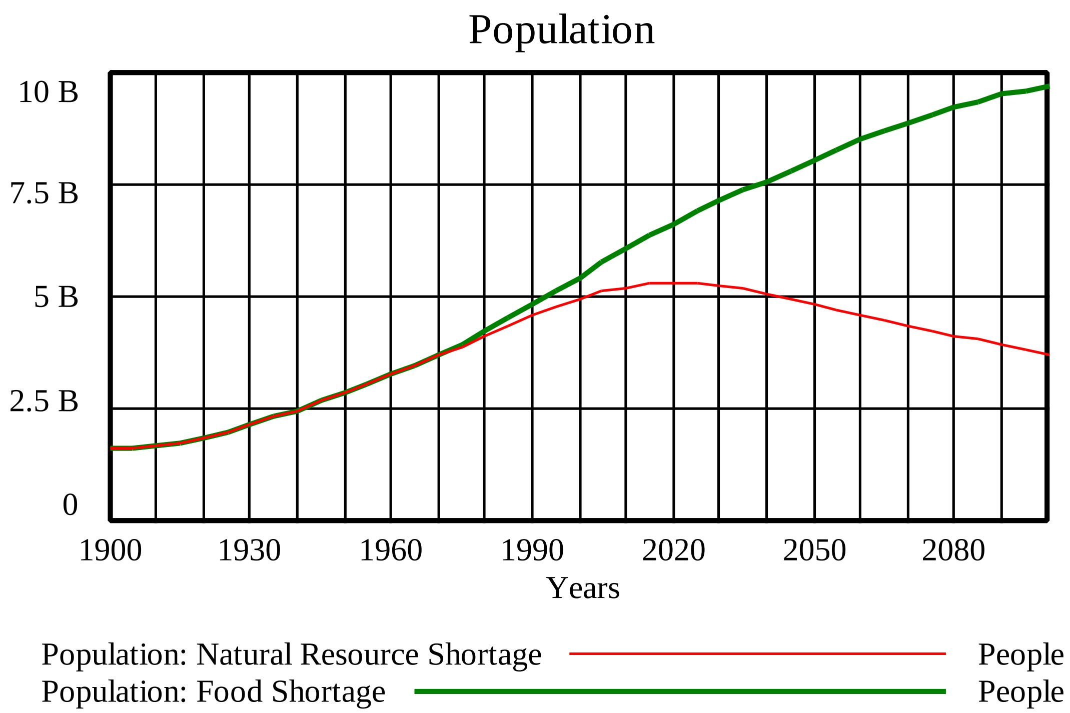
Scenario #3: Food Shortage

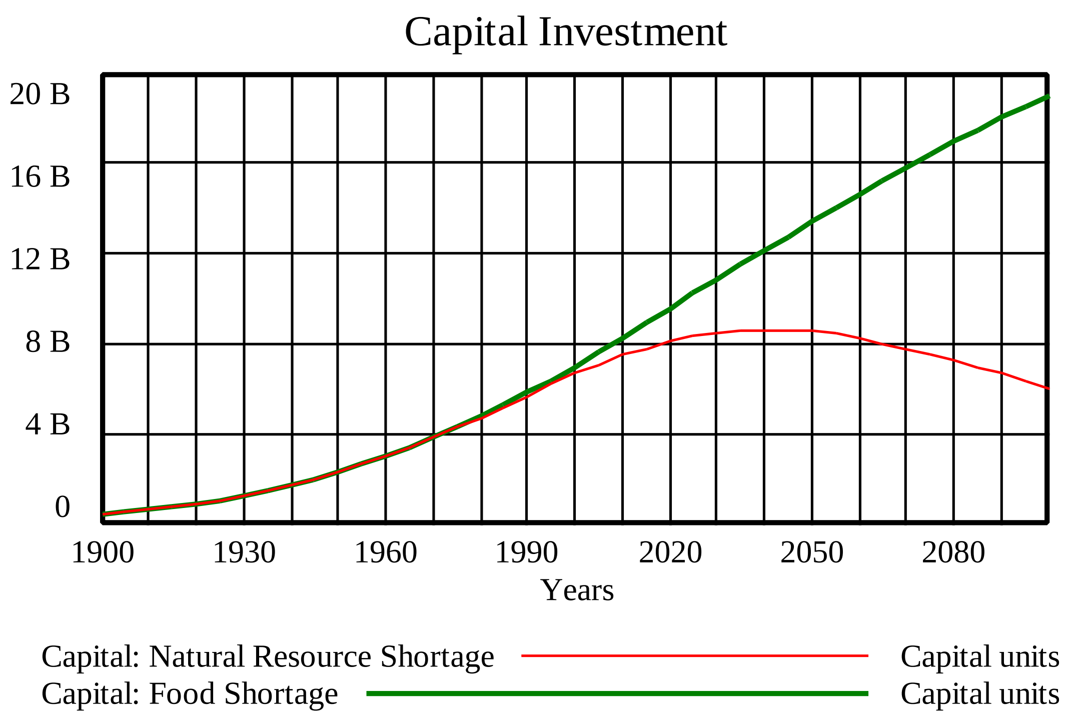
Set the "natural resource usage normal" to 0, reduce the "pollution normal" to 10% of its original value, and change the table functions "death rate from crowding multiplier" and "birth rate from crowding multiplier" so that they level off at 1.0 for any crowding ratios larger than 1.0.

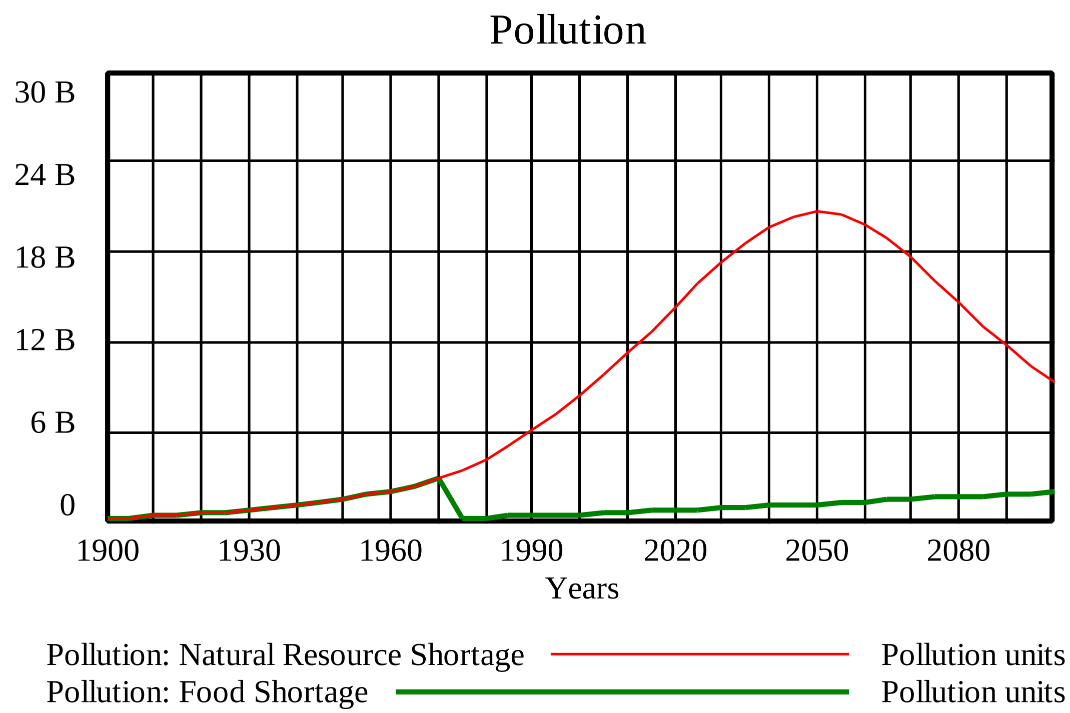
Population rises to 10.8 billion people, which is only moderately higher than the 9.7 billion under the second scenario. A comparison of the simulation runs generated by the second and third scenarios shows a different kind of equilibrium balance between population and capital investment. In the third scenario population rises more steeply at first, lowering the material standard of living and ability to accumulate capital. The demand for food pulls capital into food production, leaving inadequate amounts in the material-standard-of-living sector to regenerate capital to as high a level as in the second scenario.

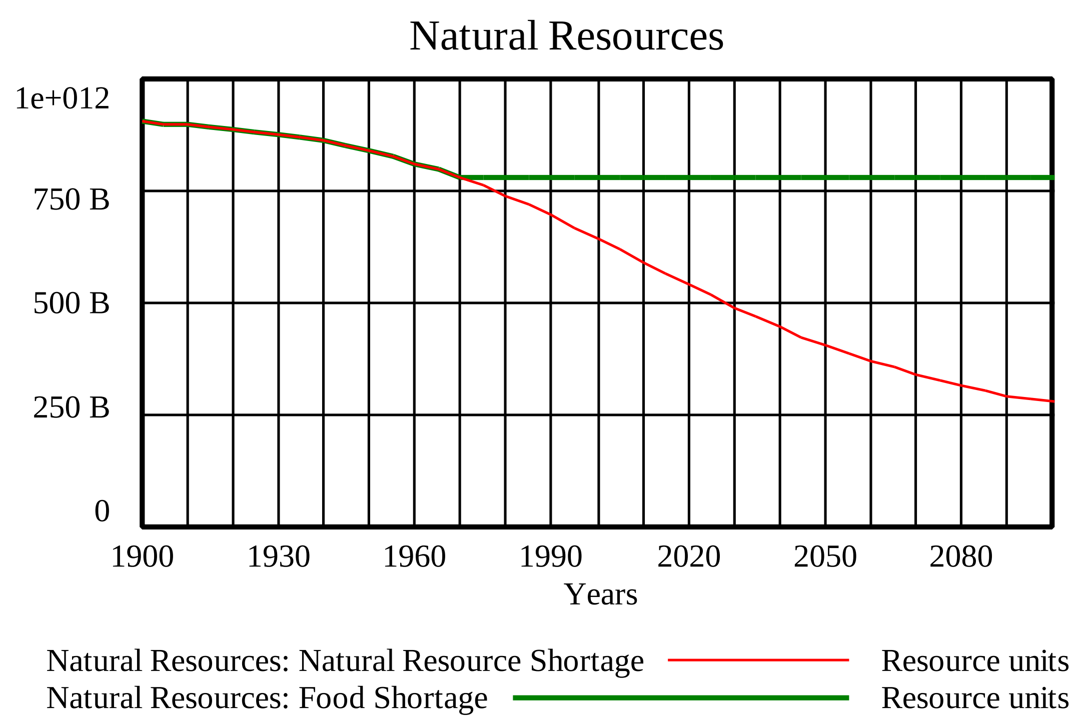
Because crowding no longer directly affects birth and death rates, other unfavorable factors must become powerful enough to compensate in limiting population growth. Here this occurs by a reduction in the food ratio. The material standard of living also falls but has little effect because it causes both birth rates and death rates to increase as it falls, and these nearly compensate. The fall in food ratio is substantial, declining to 0.77. This is sufficient to stop the rise in population. Regardless of the assumptions about the sensitivity of birth and death rates to the food ratio, if all other influences on growth are removed, the population will rise by as much as necessary to generate the degree of food shortage that is needed to suppress growth.

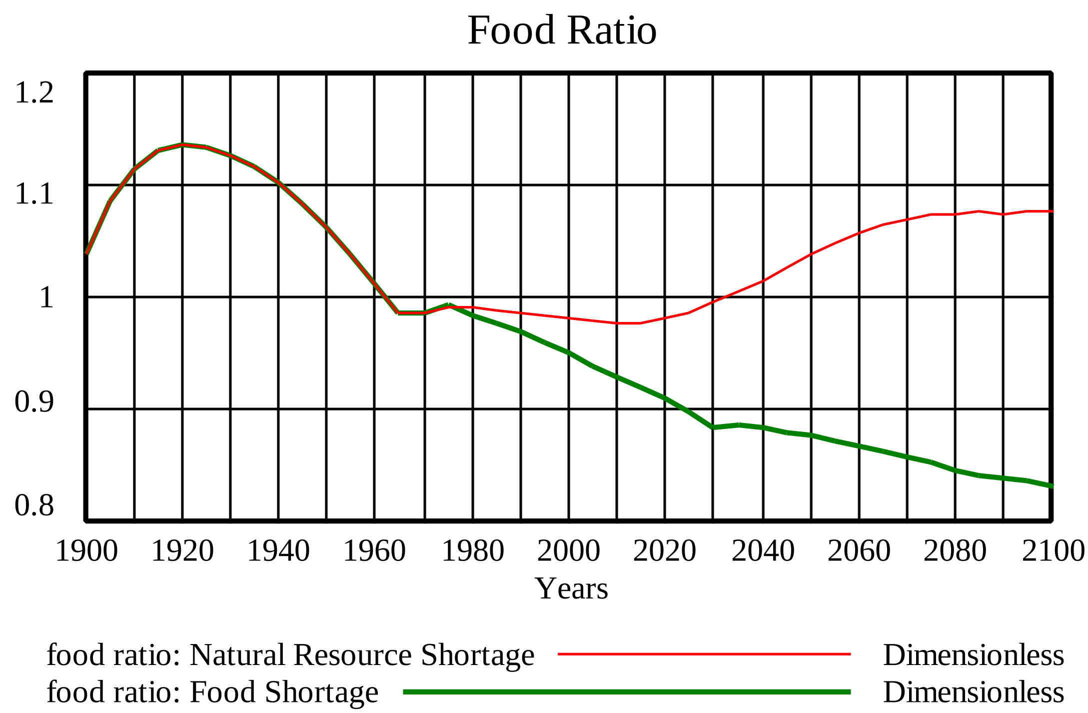
The output graphs are as follows:






Pollution
30 B
24 B
18 B
12 B
6 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Pollution: Natural Resource Shortage
Pollution units
Pollution: Food Shortage
Pollution units


Natural Resources
1e+012
750 B
500 B
250 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Natural Resources: Natural Resource Shortage
Resource units
Natural Resources: Food Shortage
Resource units

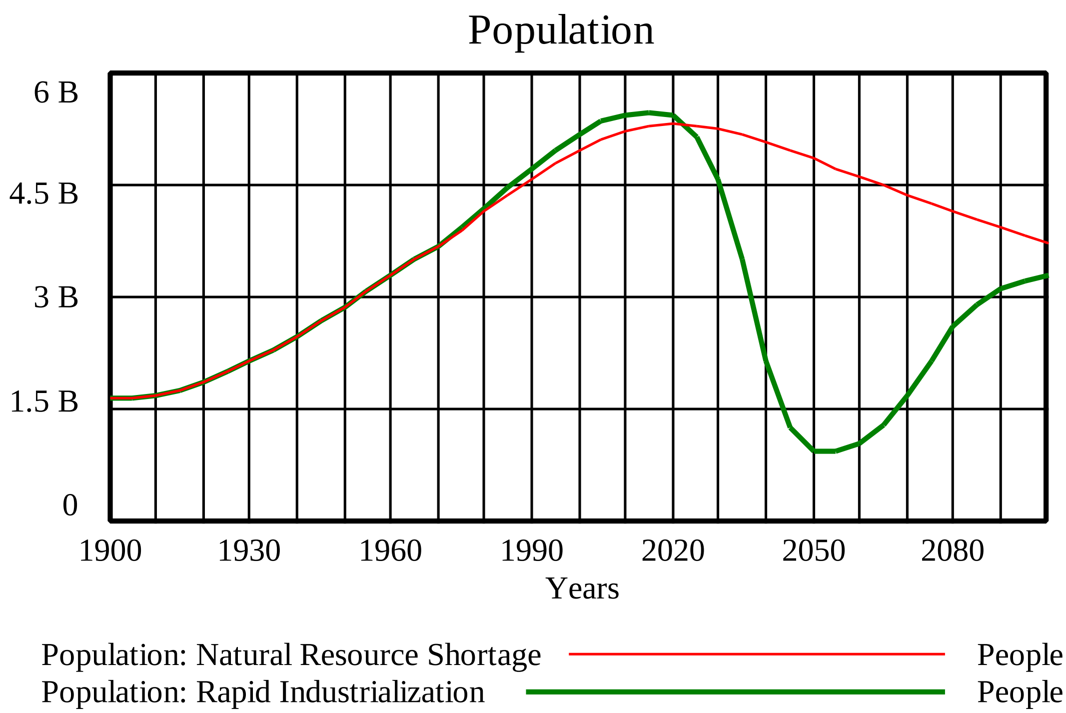


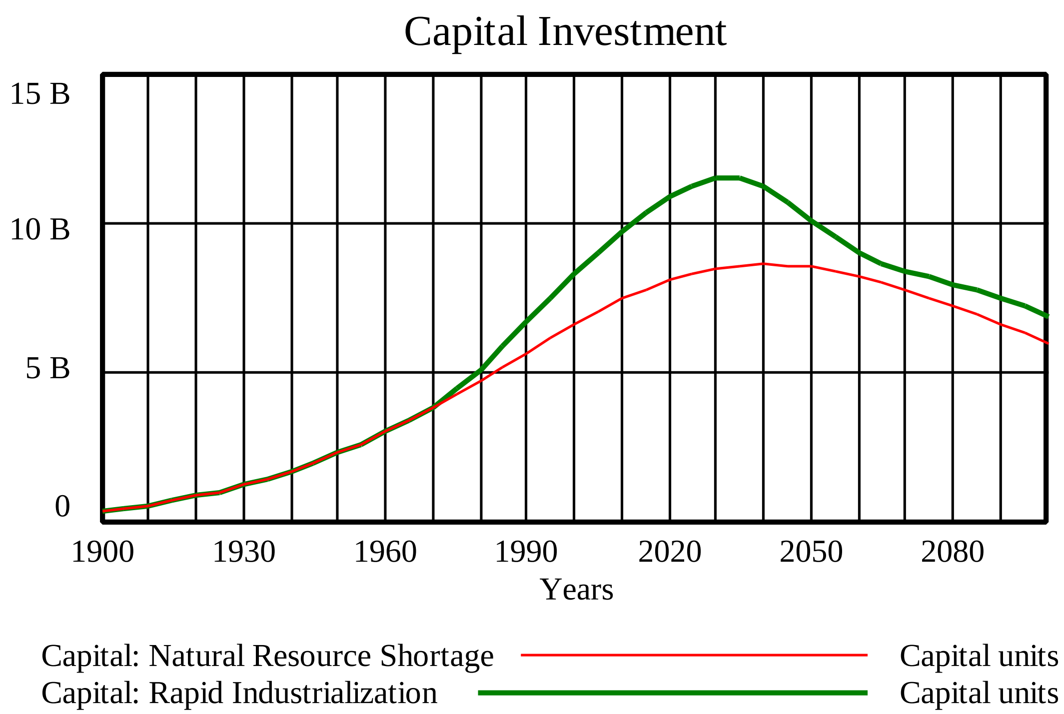
Scenario #4: Rapid Industrialization

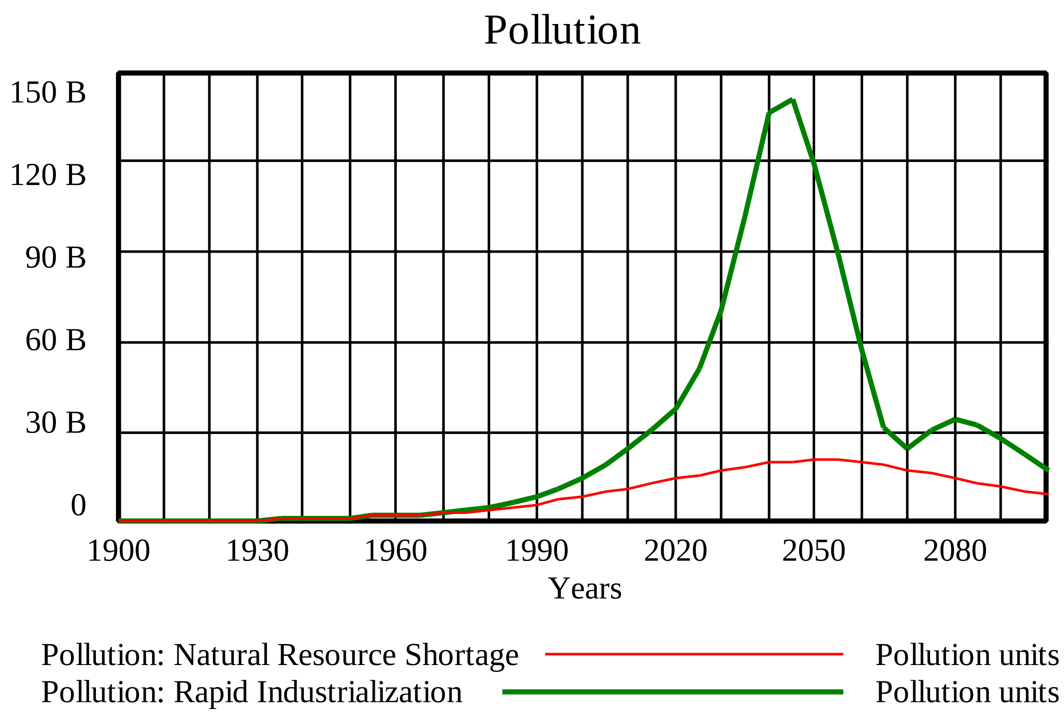
Increase the "capital investment rate normal" by 20%.

The pollution crisis reappears. In the first scenario the pollution crisis occurred because natural resources were depleted slowly enough that population and industrialization exceeded the pollution-absorption capability of the earth. Here in the fourth scenario the pollution crisis occurs before resource depletion because industrialization is rushed and reaches the pollution limit before the industrial society has existed long enough to deplete resources.

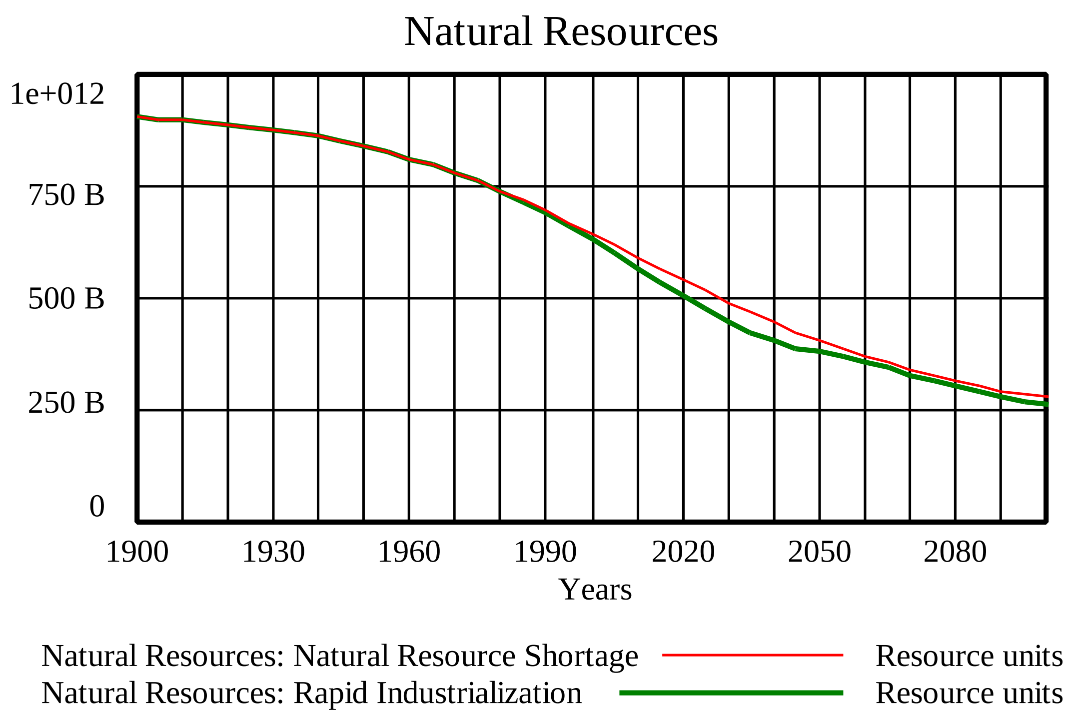
The output graphs are as follows:


Population
6 B
4.5 B
3 B
1.5 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Population: Natural Resource Shortage
People
Population: Rapid Industrialization
People


Capital Investment
15 B
10 B
5 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Capital: Natural Resource Shortage
Capital units
Capital: Rapid Industrialization
Capital units



Pollution
150 B
120 B
90 B
60 B
30 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Pollution: Natural Resource Shortage
Pollution units
Pollution: Rapid Industrialization
Pollution units



Natural Resources
1e+012
750 B
500 B
250 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Natural Resources: Natural Resource Shortage
Resource units
Natural Resources: Rapid Industrialization
Resource units

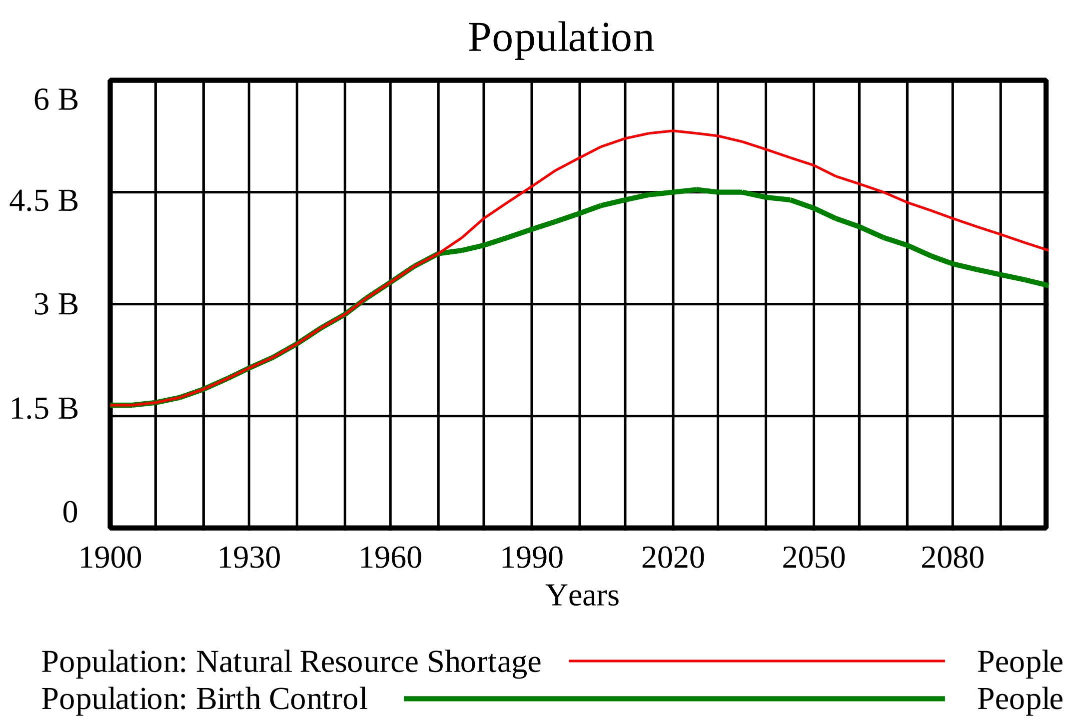
Scenario #5: Birth Control

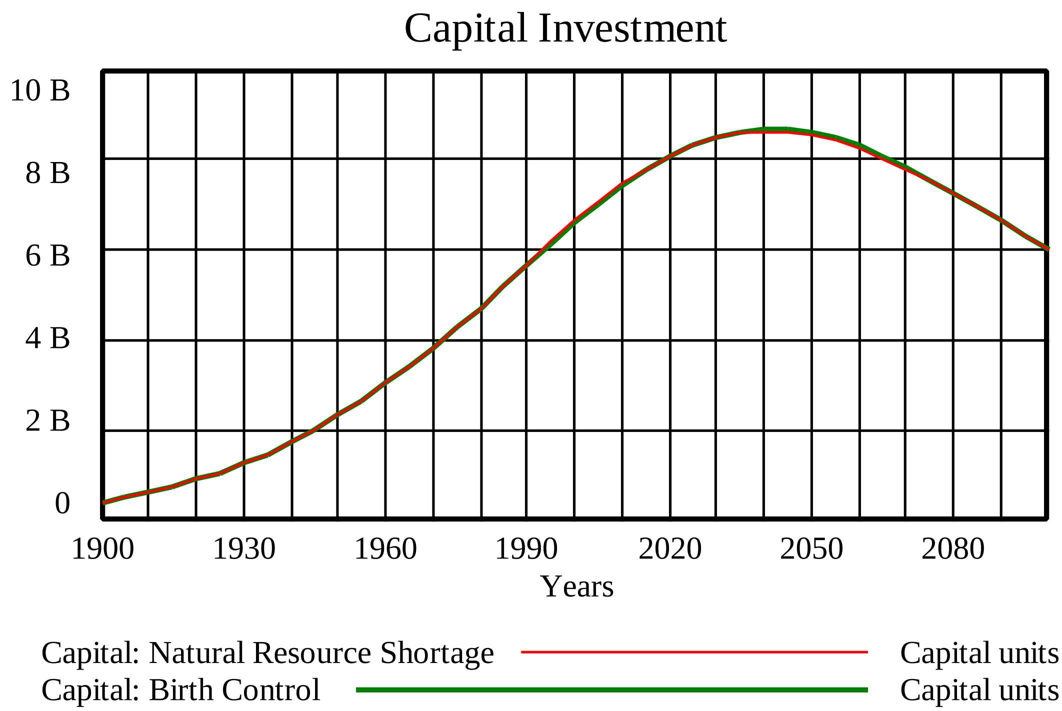
Reduce the "birth rate normal" to 70% of original value.

In the fifth scenario there is a brief pause in population growth after the birth-control program is started in 1970. But during the pause, capital investment continues to increase. A comparison of the fifth scenario with the base run shows that the material standard of living has risen and the food ratio has increased during the decade that population was stable. The quality of life rose during the interval and because the internal system pressures that had previously been limiting the rise of population are now reduced.

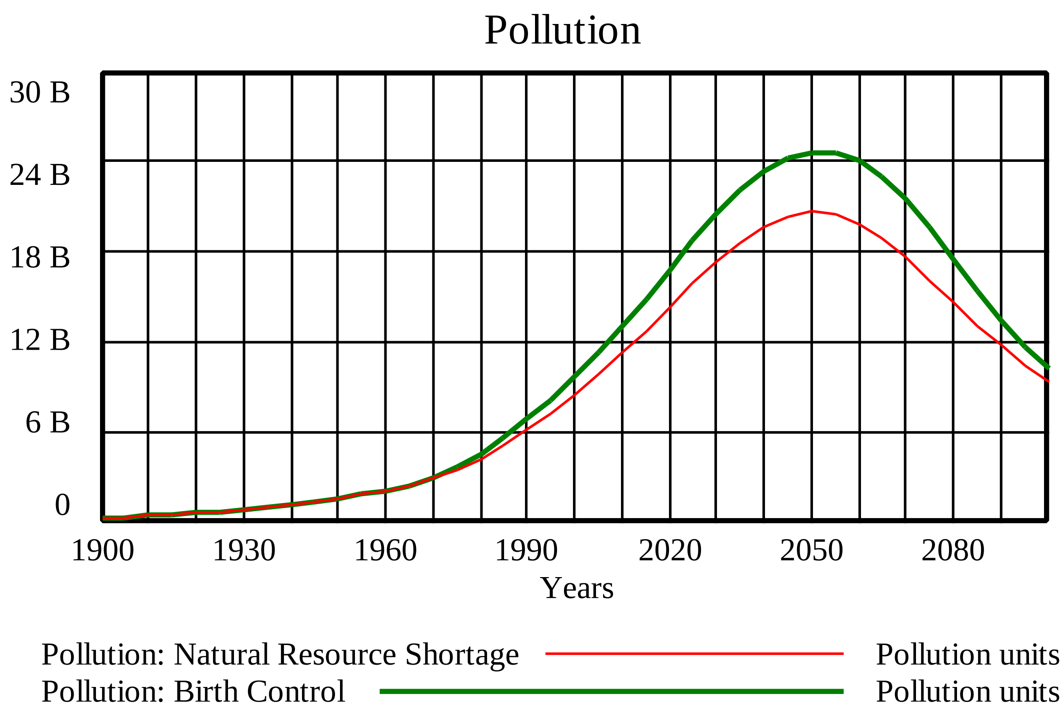
The rate of population growth depends on a combination of many influences. But the influences interact between themselves in such a way that reducing one is apt to cause others to increase and thereby partially compensate for the reduction. A birth-control program is one of many influences on the birth rate. When the emphasis on birth control is increased, the immediate effect may be to depress the birth rate, but in the longer run the other influences within the system change in a direction that tends to defeat the program. The simulation runs of the fifth scenario show that after the system readjusts internally in response to the imposed birth-control program, the population resumes its upward trend. Because the system is still limited by falling natural resources, the population peaks and then declines as before. The program, in effect, delays population growth briefly but leaves the dominant mode of growth limitation, falling natural resources, unchanged.

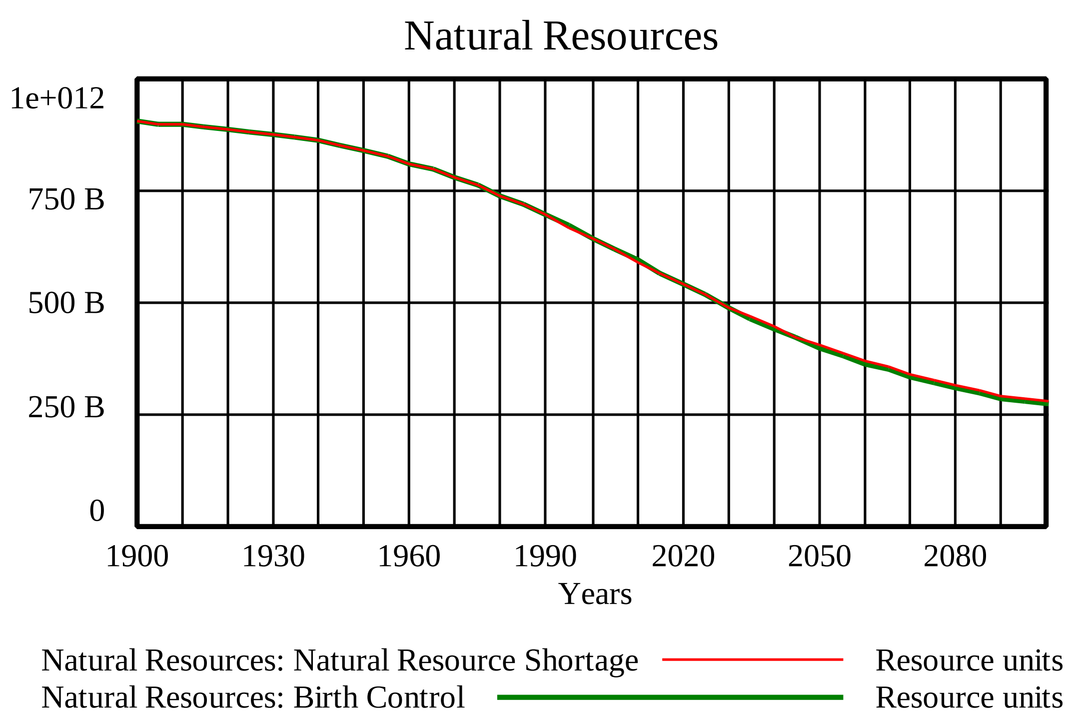
The output graphs are as follows:



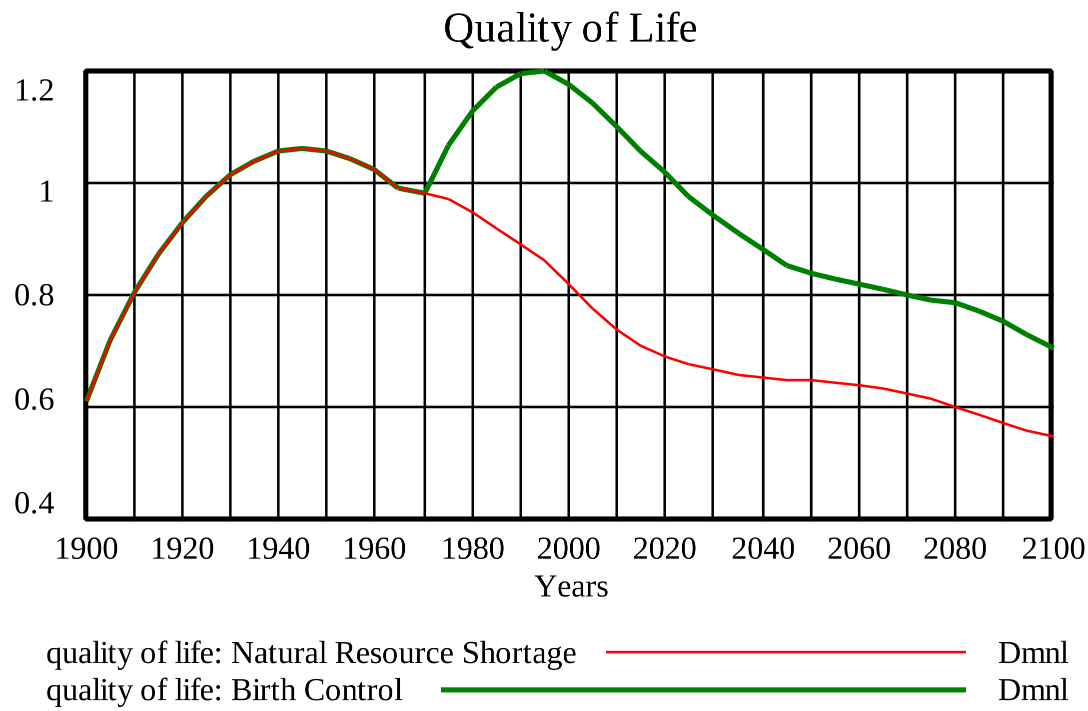


Note that, with respect to capital investment, the two scenarios generate identical behavior.





Note that, with respect to natural resources, the two scenarios also generate identical behavior.


Quality of Life
1.2
1
0.8
0.6
0.4
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100
Years
quality of life: Natural Resource Shortage
Dmnl
quality of life: Birth Control
Dmnl

Scenario #6: Higher Agricultural Productivity

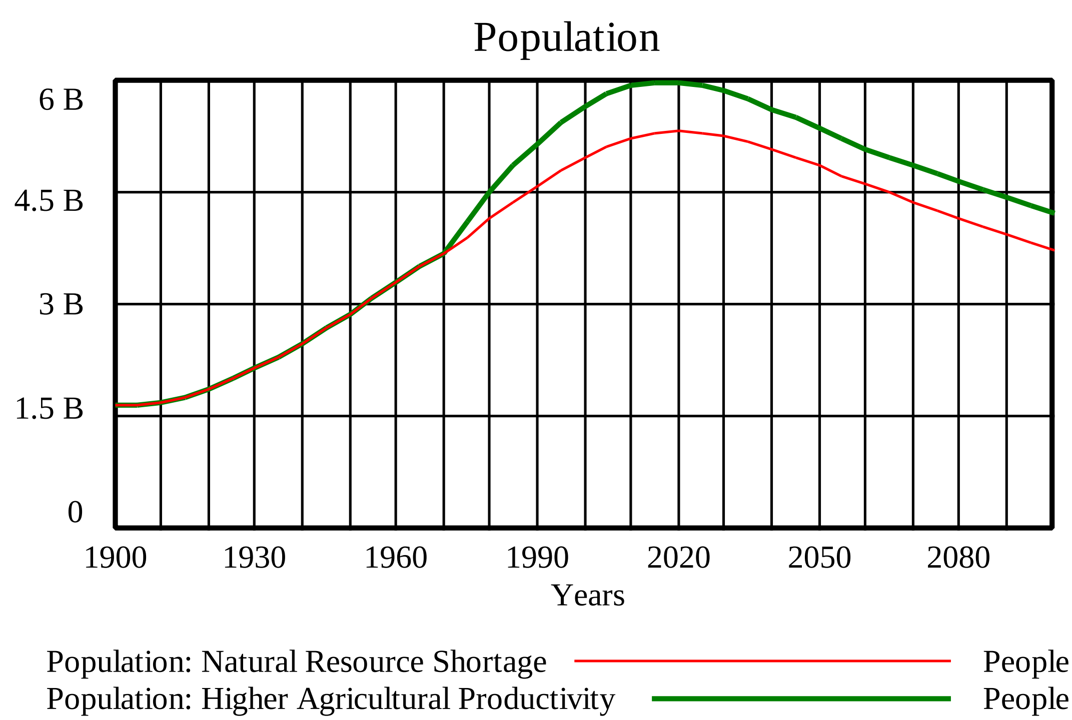
Increase the "food coefficient" by 25%. Explain what the food coefficient represents.

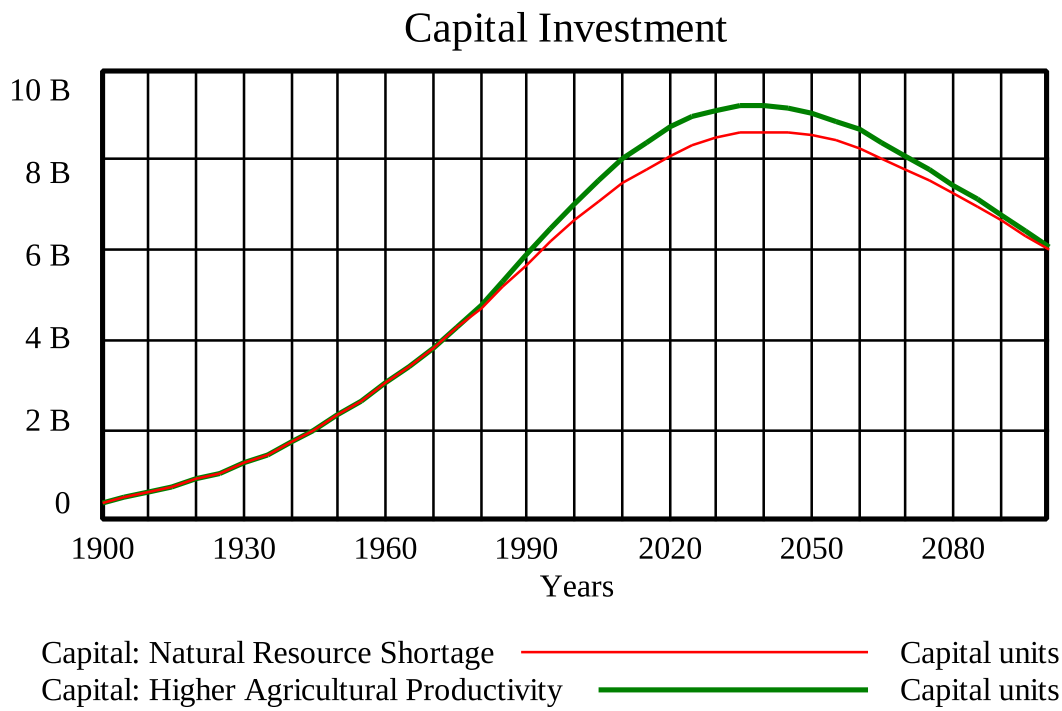
The increase in the food ratio introduces an instantaneous improvement in food availability and causes a rise in quality of life seen in the sixth scenario. Compared with the base run, the effect is to increase the growth rate of population and to bring quality of life back to its original trend in about 20 years.

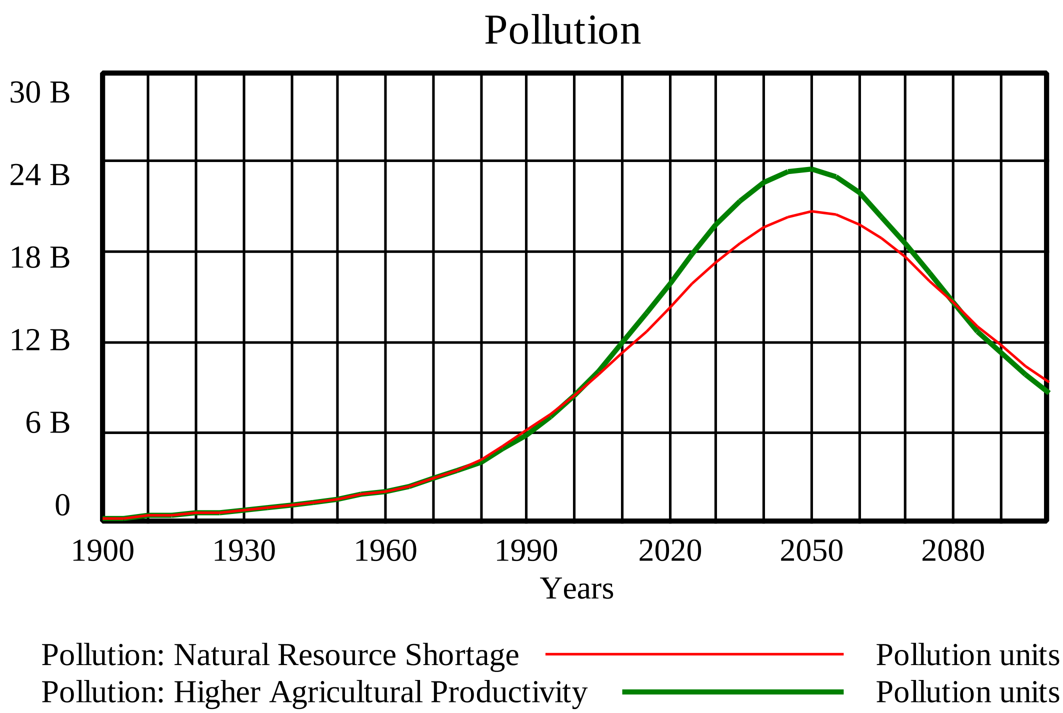
A comparison of the base run and the sixth scenario shows an interesting behavior in the capital-investment-in-agriculture fraction. The increased food productivity has caused a shift of capital investment away from agriculture. Certain criteria in the model give the relative desirability of food versus material standard of living just as criteria for the allocation must exist in the real world. If food productivity increases, the pressure for more food declines, and the capital allocation shifts in the direction of material goods. Even so, the material standard of living is not as high as before because of the increased population. By the year 2020 the quality of life in the sixth scenario is slightly lower with the increased productivity of agriculture than in the base run without the increased productivity.

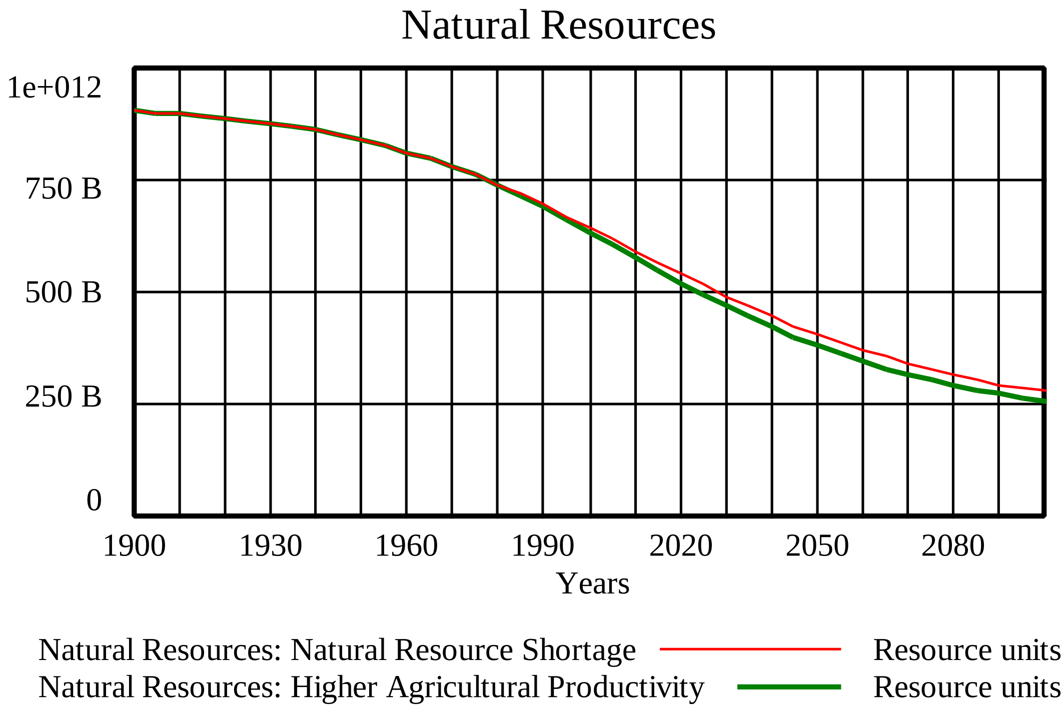
The food coefficient is a multiplier that influences agricultural productivity, which is the food generated per unit of capital investment in agriculture. Developing fertilizers and seeds, implementing crop rotation, and extending irrigation are some ways to improve agricultural productivity.

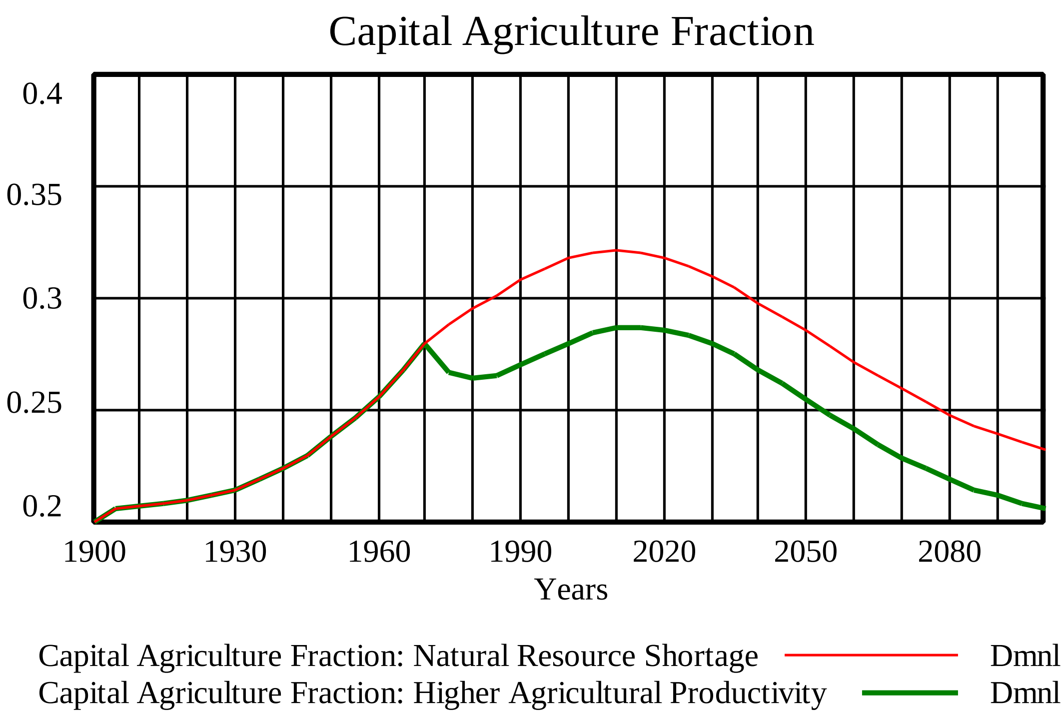
The output graphs are as follows:

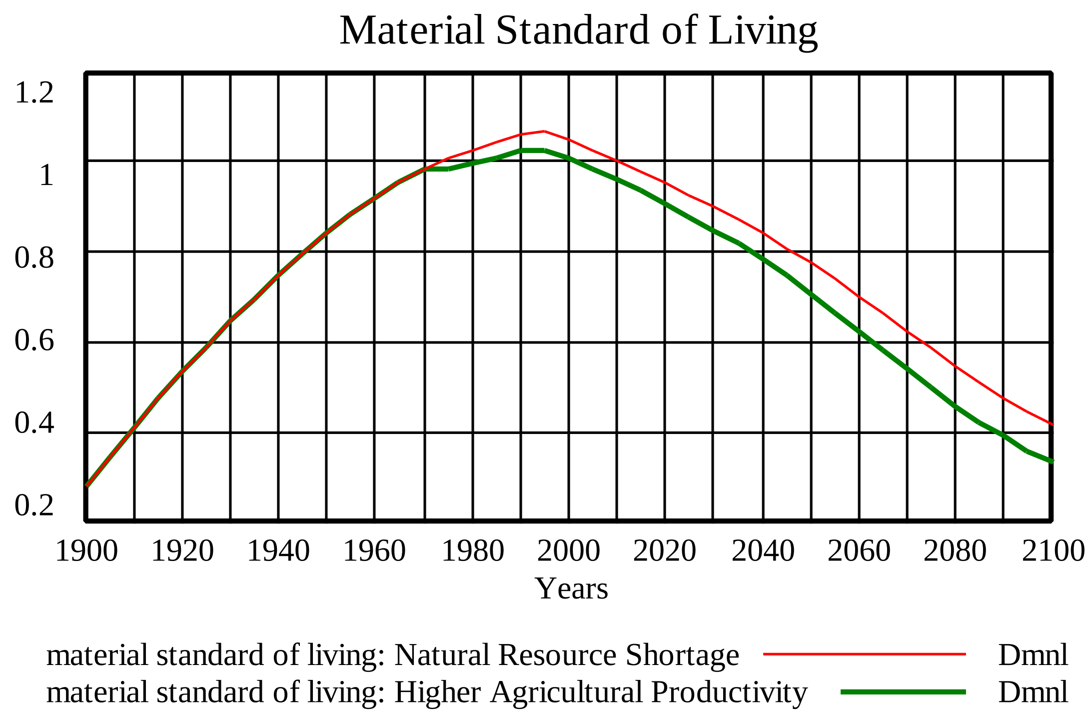


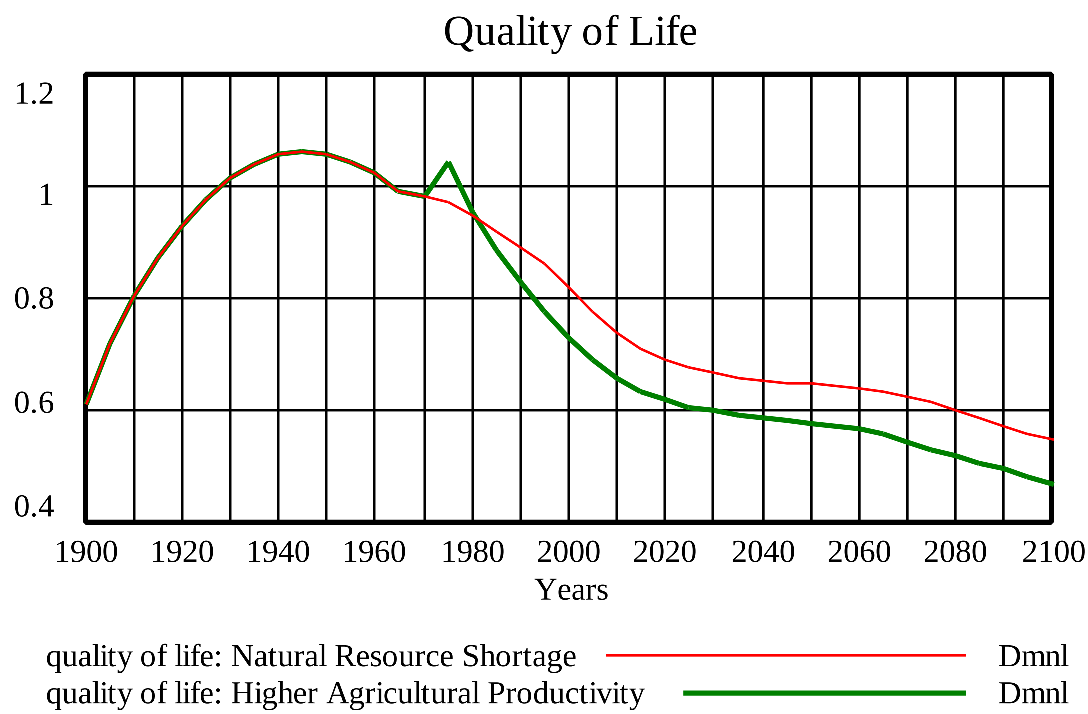

Capital Investment
10 B
8 B
6 B
4 B
2 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Capital: Natural Resource Shortage
Capital units
Capital: Higher Agricultural Productivity
Capital units


Pollution
30 B
24 B
18 B
12 B
6 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Pollution: Natural Resource Shortage
Pollution units
Pollution: Higher Agricultural Productivity
Pollution units


Natural Resources
1e+012
750 B
500 B
250 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Natural Resources: Natural Resource Shortage
Resource units
Natural Resources: Higher Agricultural Productivity
Resource units


Capital Agriculture Fraction
0.4
0.35
0.3
0.25
0.2
1900
1930
1960
1990
2020
2050
2080
Years
Capital Agriculture Fraction: Natural Resource Shortage
Dmnl
Capital Agriculture Fraction: Higher Agricultural Productivity
Dmnl


Material Standard of Living
1.2
1
0.8
0.6
0.4
0.2
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100
Years
material standard of living: Natural Resource Shortage
Dmnl
material standard of living: Higher Agricultural Productivity
Dmnl

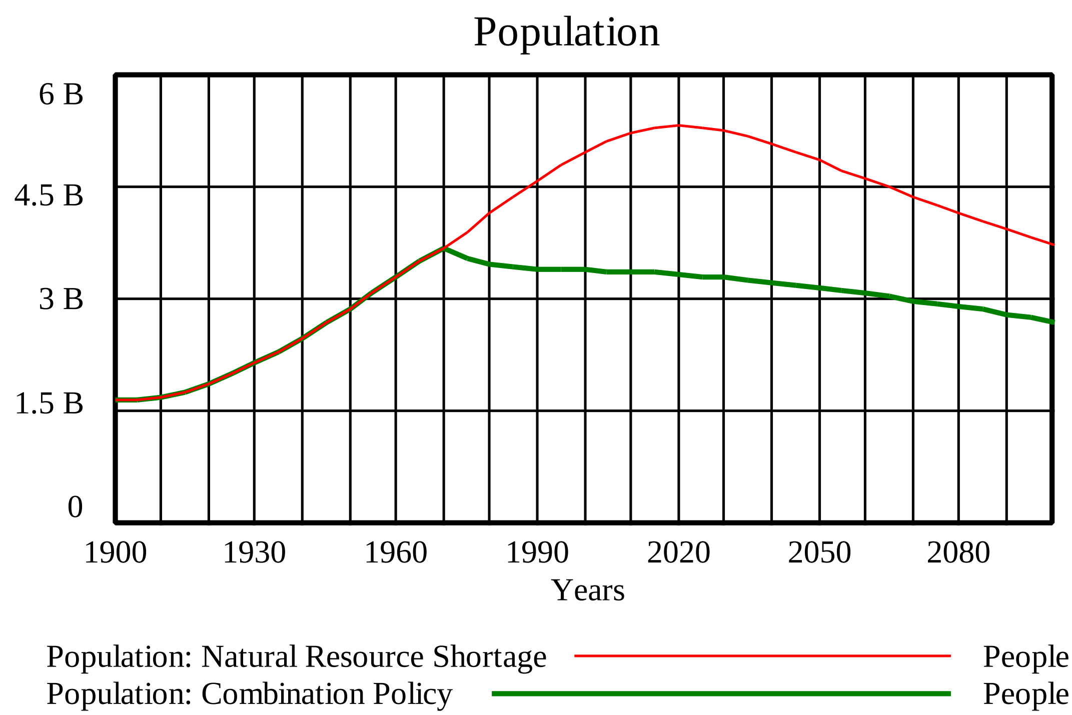

Quality of Life
1.2
1
0.8
0.6
0.4
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100
Years
quality of life: Natural Resource Shortage
Dmnl
quality of life: Higher Agricultural Productivity
Dmnl

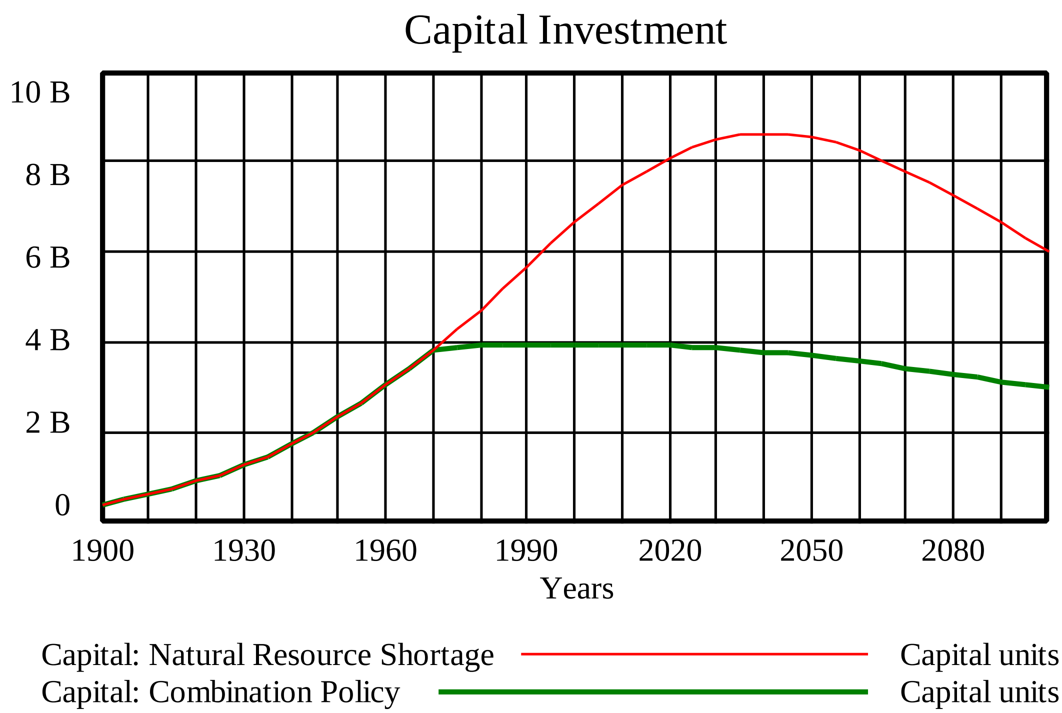
<u>Scenario #7: Combination Policy</u>

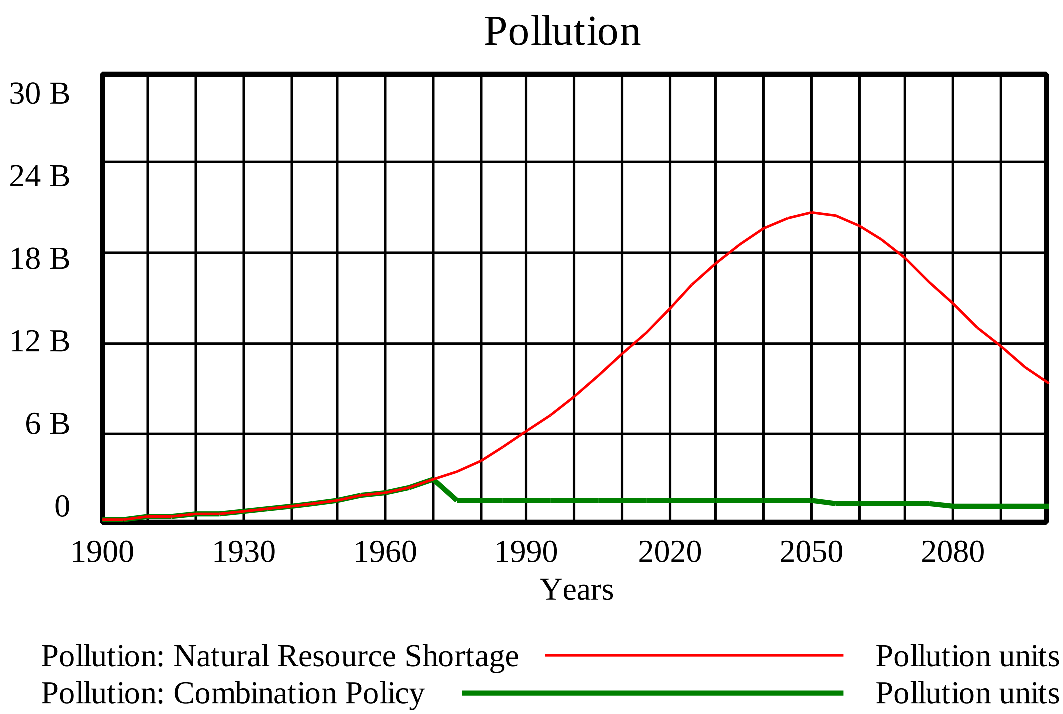
Reduce the "natural resource usage normal" by 75%, reduce the "pollution normal" by 50%, reduce the "capital investment rate normal" by 40%, reduce the "food coefficient" by 20% and reduce the "birth rate normal" by 30%.

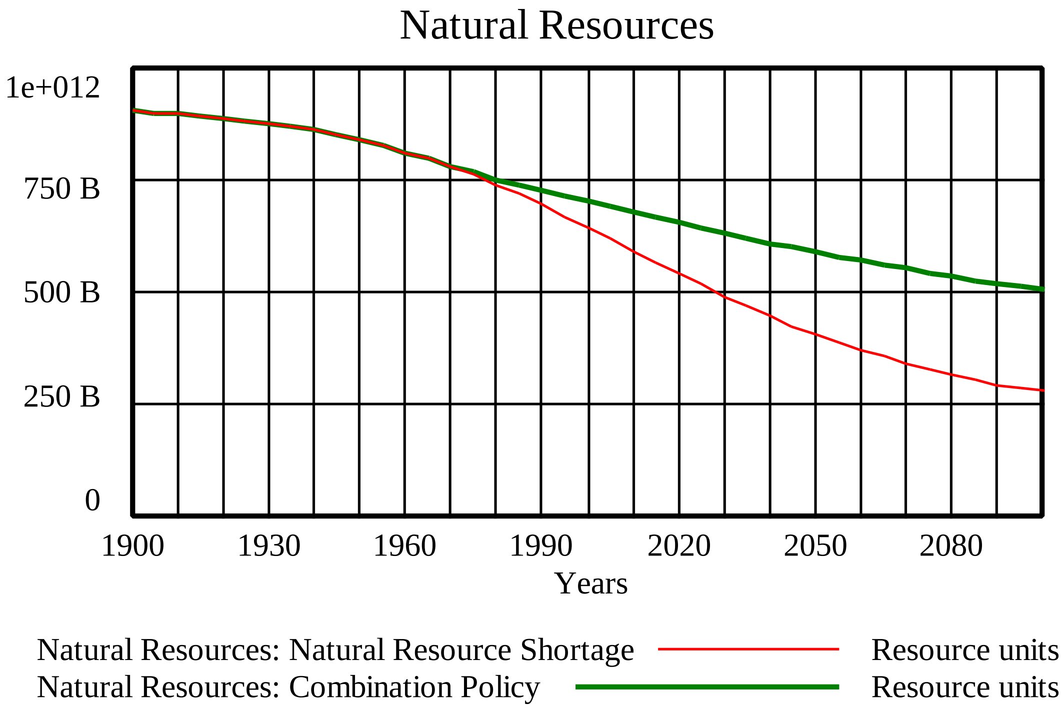
If growth is to be stopped, the major positive feedback loops in the model must be deactivated. Those loops include: high birth rates lead to larger populations which further increase the birth rates; increased capital investment increases the material standard of living which further increases capital investment; and increased birth rates lead to larger populations which consume more natural resources and create more pollution, thereby decreasing the material standard of living. The combination policy in this scenario weakens the different positive feedback loops in the model, limiting growth before any of the crises appear.

The output graphs are as follows:




Capital Investment
10 B
8 B
6 B
4 B
2 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Capital: Natural Resource Shortage
Capital units
Capital: Combination Policy
Capital units


Pollution
30 B
24 B
18 B
12 B
6 B
0
1900
1930
1960
1990
2020
2050
2080
Years
Pollution: Natural Resource Shortage
Pollution units
Pollution: Combination Policy
Pollution units



Thus, we see that any single policy can help delay the inevitable for a period of time, but not forever. Other factors in the system will eventually overpower the delaying effect of that policy and create undesirable effects. A comprehensive policy is needed to ensure satisfactory and desirable behavior in the long term. This lesson is also seen in smaller, less complex systems that we deal with in everyday life such as corporations, our social communities and even within families. It is important to remember that there are multiple causes for any observed effect, and if we wish to change the effect, changes have to be made to most, if not all those underlying causes. The effect of each change on the other factors in the system has to also be considered.