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Up the creek without a paddle?

Does Peak Phosphorus pose a problem to humanity?

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To Rebecca

Contents

Introduction

Today's subject is the climate change. This however is also just part of a more complex system. It shows us that we must stop burning oil, coal and gas, but the debate does not really cope with whether an alternative is possible.

One of the solutions that has been mentioned is biofuels. This closes the carbon cycle, and in theory should not lead to more CO_2 being led into the atmosphere. However, it is well known that biofuels also cause a need for agricultural land to grow biomass, and we do not have a lot of unused agricultural land left.

The agricultural land areas on Earth are also used by humanity to produce food and livestock feed. In the recent years a growing part of the production has been converted into plant oil production and sugar production for biofuels.

This reduces the amount of land available for food production. Before agriculture humans got their nutrients from hunting and gathering, and even though the subject is still debated, the planet seems to have been able to sustain life for roughly 1-4 million humans that way.

Roughly 12,000 years ago it seems that the planet had reached its carrying capacity for the human population (1), which had spread all over the globe. This combined with human intelligence and a primitive understanding of how nature works led to agriculture.

Agriculture has developed in the period since its introduction and is roughly able to feed today's population of 7.8 billion people. The population has been growing mostly exponential, with a large increase since the industrial revolution. This led to machines like tractors and harvesters replacing horses and human labor, allowing us to raise the carrying capacity of Homo Sapiens.

Combined with an equally exponential increase in fertilizer use this has increased the crop yield on a scale so that hunger, malnutrition and famine has been declining while the population grew, especially after the second world war.

This success story of human achievement was primarily caused by fossil energy, technology, deforestation, irrigation, pesticides and fertilizers. Even though large parts of the World are still living in poverty we have had an understanding that everyone would get better living standards and longer lifetimes in the long run.

However, once you start examining the system which is the Earth, it becomes more and more obvious that what we are actually doing is like driving in a car towards a brick wall, accelerating the speed with our eyes closed, while claiming that we have not hit anything yet.

As this thesis will show we are running out of phosphate rock, which is one of the three ingredients in NPK fertilizers, and there seems to be no realistic solution to that. Since the phosphorus content in soil is roughly proportional to the crop yield, reduction of the fertilizer production will, everything else equal, lead to lower food production while the population is expected to increase well above 10 billion.

That in itself is alarming, since we cannot easily compensate a future lack of phosphorus. On top of that we are also running out of fresh water for irrigation, and the mechanization of the agriculture is currently using a large part of the energy we spend by burning fossil fuels. We have almost no unused land that can be turned into fields, and therefore the amount of agricultural land will, at best, remain relatively constant if we are lucky and climate change does not turn too much of it into desserts or drown it in rising sea water.

The main problem we face is the energy. There is no realistic replacement for fossil fuels, and even if we had a plan, it would take a long time to implement. Furthermore, it would demand huge amounts of energy to implement. On top of that some of the ideas we believe in are hopelessly unrealistic, and it does not take a lot of math to realize that.

The more I searched for a plan for a global solution, the more obvious it became, that many of the problems we are aware of is dealt with on a somewhat isolated basis. Often other problems are mentioned, but not included in the models. When IPBES recently released the most comprehensive report on Biodiversity and Ecosystem Services ever, the summary for policymakers does not mention the word phosphorus [1]. When engineers try to develop solutions like electric vehicles, the car manufacturers rarely mention the lack of elements needed for the batteries, and when we hear talk about wind turbines, we rarely hear anyone mentioning the amount of fossil fuels it will take to manufacture and install those.

When we talk about the need to live in a sustainable manner, we do not have any good idea of what that actually means. Buying organic meat in the supermarket or an electric car is not a truly sustainable lifestyle, and if you try to find estimates of what a truly sustainable lifestyle is, the literature is extremely limited. Apart from carbon footprint calculators and Earth Overshoot Day, I have not been able to find any contemporary calculations of what an average human on the planet should do to live in a way that is truly sustainable, and neither have I found large scale proposals for the total population.

Thesis scope and problem formulation

The scope of this thesis is to try to answer the following question:

Does depletion of the phosphate rock resource pose a threat to Homo Sapiens, and if that is the case, what are the time scale?

References

The references are divided into two reference lists. One is called “References (Mendeley)” and uses square brackets. The other is called “References (Books, WWW, etc.)” and uses normal brackets.

Theory

Overview

Earth is a closed system, meaning that the amount of elements in the system is constant and that Earth receives energy from the Sun, and that Earth radiates heat back into space.

Since the beginning of the industrial revolution, the human population has doubled several times, growing exponentially. The use of fossil energy, fertilizers and mechanization of the agriculture has allowed humans to raise its carrying capacity, but there is an upper limit to how much the carrying capacity can be raised in a closed system.

Simultaneously we have changed the biosphere considerably and caused changes to the climate at an unprecedented rate.

In our current situation we are dealing with several interconnected problems: Climate change, resource depletion, increasing energy demand, loss of biodiversity, pollution, rapid population growth, lack of freshwater and arable land to name a few.

Humans, like any living organism, need nutrients to survive. Nowadays we get those through our food. The food is mainly produced in the agriculture and from there distributed to humans.

Food production and distribution use large proportions of our current energy consumption. It also uses large amounts of fertilizer. One of the main ingredients in fertilizers is phosphorus. The crop yield is roughly proportional to the amount of phosphorus in the soil, if phosphorus is the limiting factor of the plant growth.

Phosphorus is a limited resource. Current estimates of the remaining reserve vary. Because phosphorus is a limiting factor of plant growth, and because humans get their vital nutrients through the food chain, soil phosphorus content is also a limiting factor of the human carrying capacity.

Other limiting factors of the food production include water for irrigation, climate change and available energy.

Bartlett and exponential growth

The physicist Albert A. Bartlett is known for his statement, that:

"The greatest shortcoming of the human race is our inability to understand the exponential function." (2)

According to Bartlett we do not understand the consequences of exponential growth, and in his famous lecture "Arithmetic, Population, and Energy", he gives the following example:

Take a single bacterial cell and put it in a bottle. For the sake of the example Bartlett then assumes that the cell divides every minute. After two minutes there are two cells in the glass, after three minutes four cells, after four minutes eight cells, etc. We start the experiment at 11 o'clock, and at 12 o'clock the glass is filled with bacteria.

Bartlett then rhetorically asks the following questions:

"At what time will the bottle be half-filled?"

The answer is 11:59, one minute before 12. Bartlett then continues:

"If you were an average bacterium in the bottle, at what time would you first realize that you were running out of space?"

The concept, that exponential growth cannot continue forever in a finite environment is well known, and have been stated by the economist Kenneth Boulding as follows:

"Anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist."

According to Bartlett politicians and economists do not realize that a harmlessly sounding growth rate like 3.5% per year results in a doubling time of 20 years. Even a steady growth of 7% per year does not sound alarming, Bartlett argues, and he therefore offers a simple approximated method to calculate the doubling time:

$$Doubling\ time = \frac{70}{anual\ growth\ rate\ in\ \%} = \frac{70}{7} = 10\ years$$

Bartlett is right about the serious consequences of not understanding that linear and exponential growth are very different. It is obvious according to physics, that anything growing inside a closed system will reach a limit at a certain point, sooner or later.

Systems

Generally, any system can be defined as one of three types of systems (3):

Isolated system: An isolated system does not exchange neither matter nor energy with its surroundings.

Closed system: A closed system does not exchange matter with its surrounding, but it can receive and release energy from and to its surroundings.

Open system: An open system exchanges both matter and energy with its surroundings.

Earth is a closed system.

Correlation, causation and assumptions.

In 2000-2009, there was a remarkably good correlation (r=0.993) between the Divorce Rate in Maine and the Per Capita Consumption of Margarine. We also lack a good scientific hypothesis supporting that humans get divorced because of their margarine consumption, or that margarine consumption leads to divorces. Therefore, the correlation is considered coincidental.

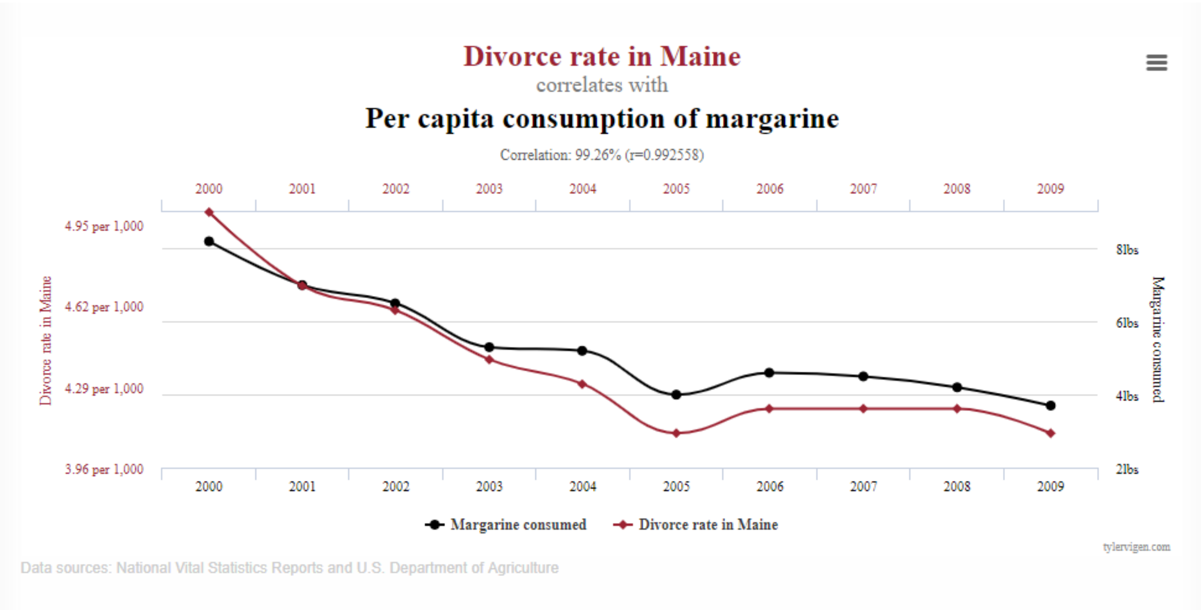


Figure 1 The remarkable correlation between the Divorce rate in The State of Maine and the Per capita consumption of margarine (27).

This dilemma is also a part of creating a global model. However, another example of correlation that is not directly linked to causation is the number of sunglasses sold at a given hemisphere and the amount of ice cream sold in the same hemisphere, both over time. In this example humans do not eat ice cream because they wear sunglasses or vice versa. Instead the causal link is obviously found via the rotational axis of the Earth shifting over time changing the hemisphere both more sunlight and higher temperatures during the summer. We consider it relatively safe to assume that humans like the cooling effect of ice cream better in the summer than in the winter. We also have a physical explanation for why humans prefer wearing sunglasses in the summer, when their eyes have physiological difficulty coping with among other the amount of ultraviolet light.

Likewise, when building a world model, we have to make assumptions based on correlation. If we see a correlation between the population size and the global energy consumption, we can assume that more humans using the same amount of energy per capita, will use more energy in total. The causation could also be linked to other parameters, such as energy consumption per capita. Even though a human living in Afghanistan or in Denmark have very different lives, visually evaluating some of the plotted data can give us a more trustworthy understanding of development in the total system.

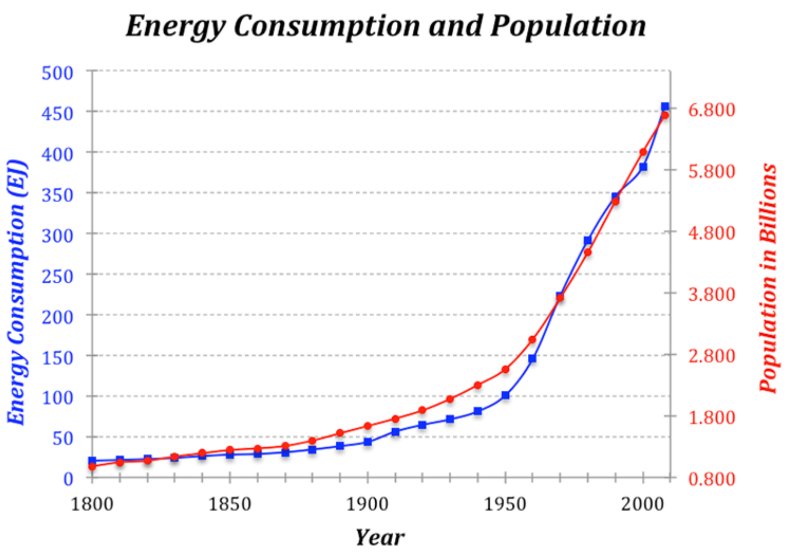


Figure 2 The correlation between Energy consumption and Population size (28)

We also see an increase of the global energy consumption per capita due to increasing living standards:

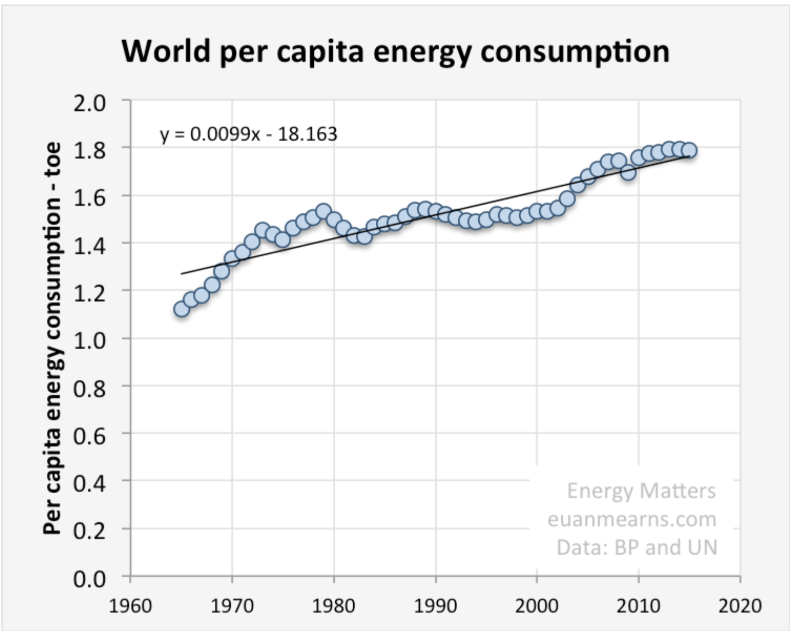


Figure 3 Global energy consumption per capita vs Time (29)

However, if we look at the graphs for 1970 to 2010, the Per capita energy consumption has increased by roughly +30%. The amount of global Energy consumption has more than doubled in the same timeframe by +130%. Therefore, the main driving force on the global energy consumption seems to be the population size growth, being more than 4 times larger than the energy consumption per capita. Also note that if we consider the data being a signal, then the most dominant factor, in this case the population size will typically cause less noise in the signal.

Beneath the energy consumption per capita, there are other parameters, driving the main parameter's development. One parameter is invention of new technology, which cause new demands on the global market, like aircrafts resulting in more people flying around the world. Technology sometimes also result in reduction of energy consumption, like cars with lower fuel consumption.

It is also safe to assume that there is a causal link between the population size and the global food production. However, this is not as simple as both being directly proportional. Due to inequality in the population's access to resources, some people starve as a result of poverty, while others eat more than they need, and the global rise of living standard has caused more people to eat meat. This rising demand is mainly facilitated by more income per capita, making it possible for more people to afford meat.

Still when we look at the development of the overall parameters of the total system, variations in subsystems, even those showing chaotic development seems to get evened out by the mechanism of average.

Human Population

Since the beginning of human history, the human population has increased exponentially:

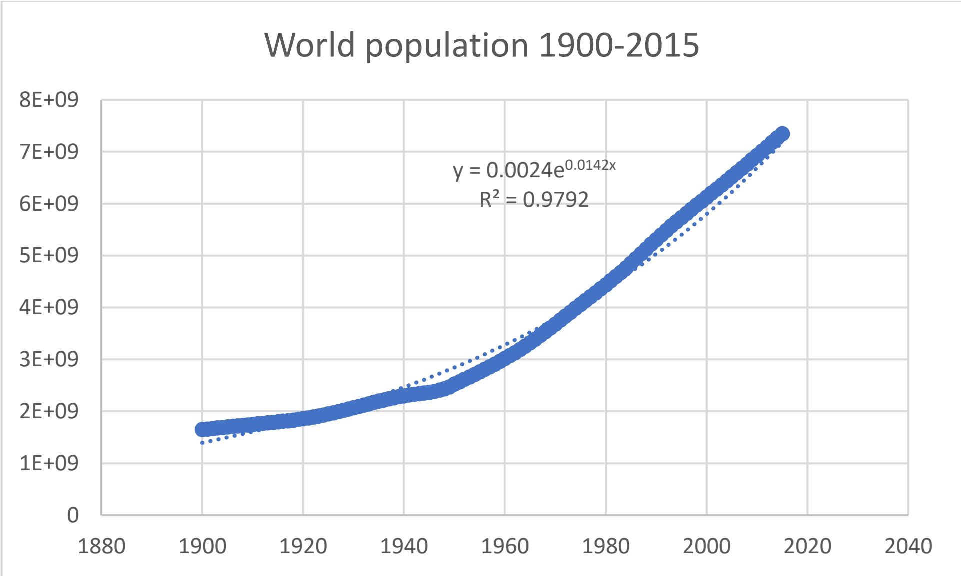


Figure 4 Global human population correlation to an exponential growth function (4)

The annual growth rate has been declining since 1961, where it peaked at 2.2% per year:

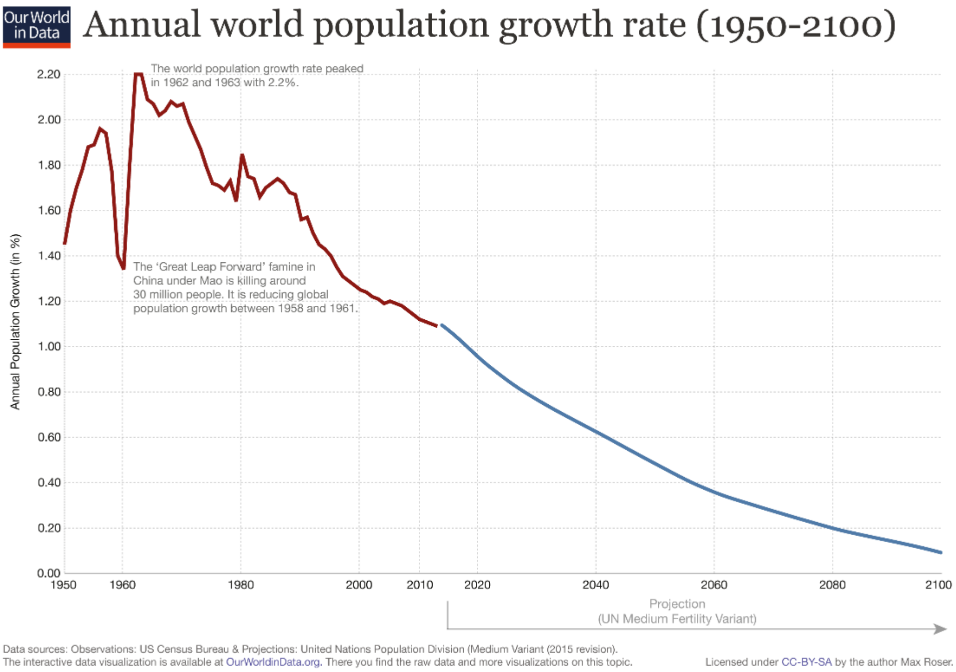


Figure 5 Anual population growth rate (5)

Primarily based on that decline, the UN extrapolates the curve until 2100, where they expect a growth rate approaching zero. This extrapolation of the curve seems somewhat optimistic.

The exponential population growth dates back to at least the introduction of agriculture:

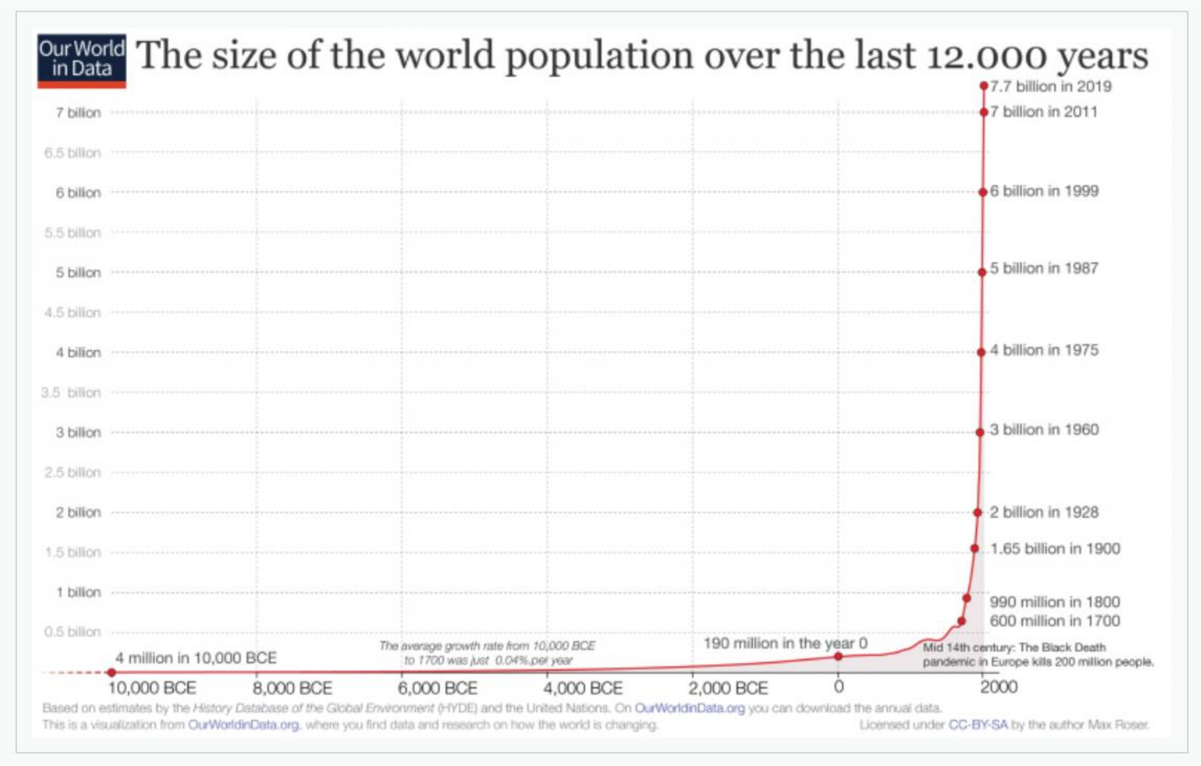


Figure 6 Population since the introduction of agriculture (https://ourworldindata.org/world-population-growth) (5)

The current UN medium estimate for the future population size shows a population of 10 billion in 2050 and 11.2 billion around 2100, with a still growing population by the end of the century:

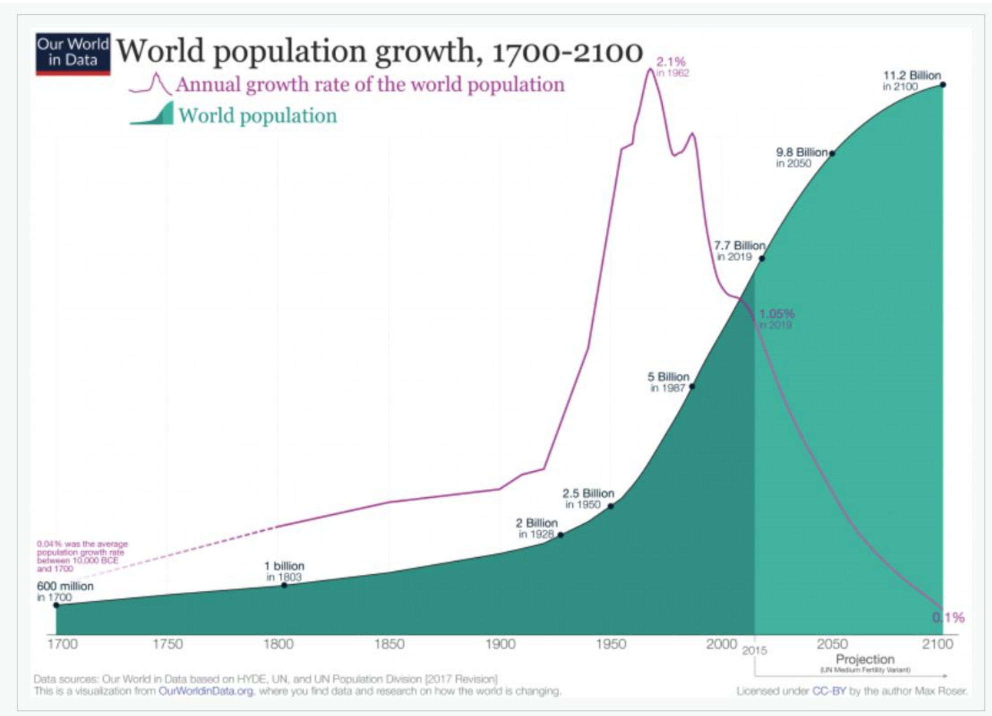


Figure 7 UN medium population estimate (https://ourworldindata.org/world-population-growth) (5)

Sustainability

Sustainability is a word used in many contexts, often with little or no relation to the original meaning of the word. Going back to its origin, first being mentioned in the 1987 report "Our Common Future: Report of the World Commission on Environment and Development" by the Brundtland Commission, we find the following definition:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Among people working with the subject, a combination of three types of sustainability is often used:

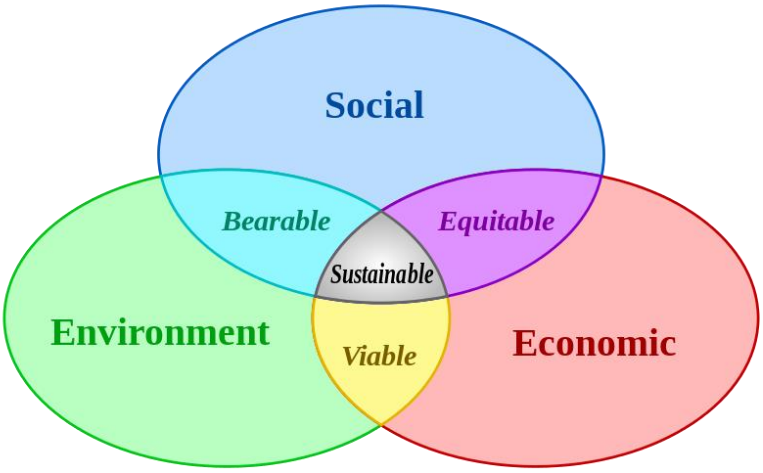


Figure 8 Sustainable development (6)

There is little or no of literature describing the actual consequences of a sustainable lifestyle, but according to the "Earth Overshoot Day" theory, we can calculate the current consumption of resources using the following equation:

$$World\ Biocapacity\ /\ World\ Ecological\ Footprint * 365 = Earth\ Overshoot\ Day$$ (34)

A way of interpreting the result of the calculation is to look at the Earth Overshoot Day, as the day during any given year, when we reach the point, where we have used all the resources available for a sustainable life, and that the consumption of the rest of the year equal spending of the next years resources. As of 2018, Earth Overshoot Day was August 1., meaning that the global overspending amounts to:

$$\frac{12}{7} = 1.7$$

There are large differences in the contribution to global resource spending, if one looks at the spending of the different nations. In the rich countries the resource consumption is several times higher than in the poorer countries. At the same time there are large differences in the size of the population of each country.

Another popular indicator used for estimating humanity's ecological footprint, is the Carbon Footprint. In 2017 the average American had a carbon footprint of 16 tons per year, which is 9 times higher than the average Indian, who has a carbon footprint of 1.8 tons per year (36). The current average world footprint is 4.9 tons per year per capita.

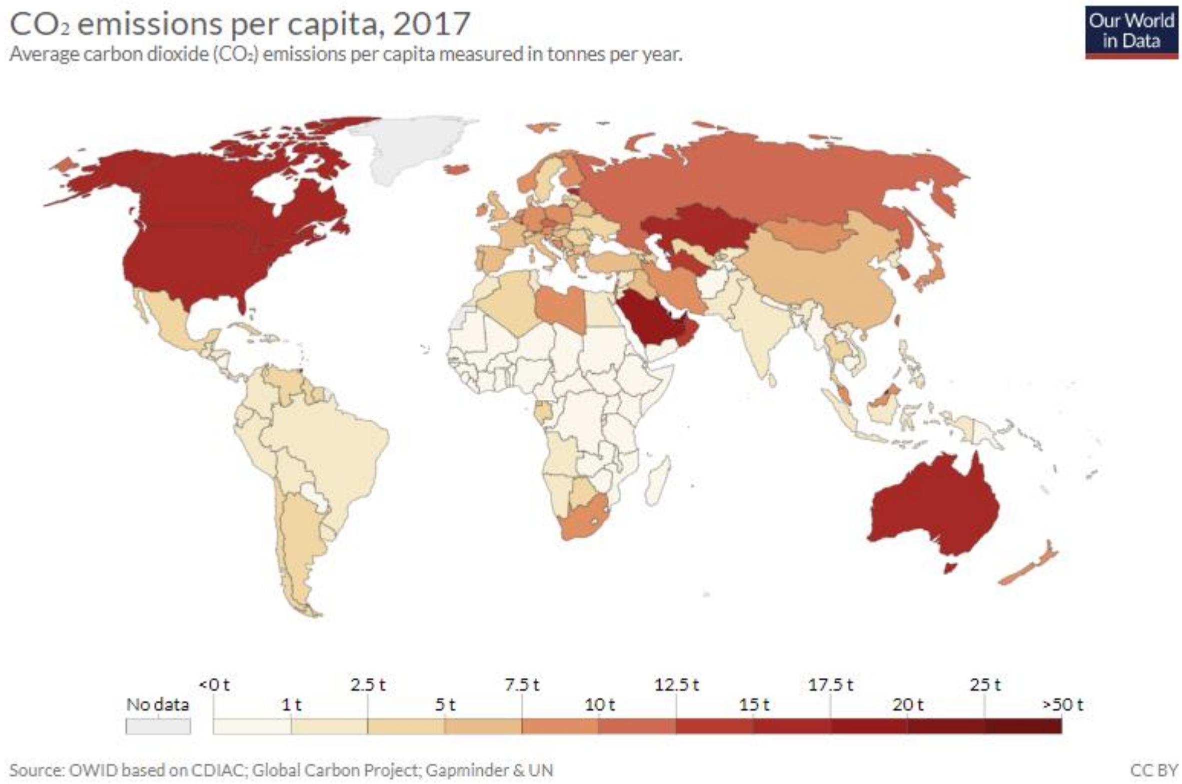


Figure 9 "017 Carbon footprint per capita (36)

A sustainable goal of the carbon footprint per capita is assumed to be 3 tons per year per capita (35).

Dividing the global average carbon footprint with the 3 tons, we get:

$$\frac{4.9}{3} = 1.6$$

A number that correlates well with the 1.7 factor from the Earth Overshoot day.

It is important to notice, that Earth Overshoot Day is based on renewable resources (34). Not all resources are renewable, and we still use those in an increasing amount per year. Some of these resources are essential for sustaining the high carrying capacity we have achieved. Also, any transition towards a more sustainable system will cause an new usage of nonrenewables.

There are several ways to look at these numbers, but one thing is obvious: Globally, we spend more resources than we are allowed to, if we want to meet the constraints given by nature.

This is a problem for future generations and can potentially become a problem even for contemporary generations.

The solution to the problem given by the above calculations originates in an assumption that we either share the resources equally, or that we do not.

If we decide to share the resources equally, the average American will have to reduce their spending of resources by a factor of 1/9, the average Indian must resume current spending, and the average world citizen will have to almost half current spending.

Looking at human history, this proposed equality would be a first time ever, and highly unlikely. Therefore, a more realistic model for the future is the “business as usual” model, saying that the development so far, will continue, until the development reaches physical boundaries given by nature. The counterargument for this hypothesis is that “there is a first time for everything”, but using simple inductive reasoning, this still seems highly optimistic.

Earth and energy

Earth is a planet in orbit around the Sun. Earth is largely isolated from the Universe by empty space, and therefore it can be considered a closed system. A small amount of gas leaks into space from the upper layers of the atmosphere, and a small amount of debris originating from the creation of the solar system falls through the atmosphere.

Earth is built up from elements in the form of atoms. Apart from isotopes decaying, the amount of elements in the system is constant. The atoms are combined into molecules. The molecules are combined into larger structures like rocks and living cells.

Earth is not an isolated system. Earth receives electromagnetic radiation emitted by the Sun. The energy from the sunlight causes the Earth to heat up but the heat is radiated back into space in the form of infrared radiation (IR).

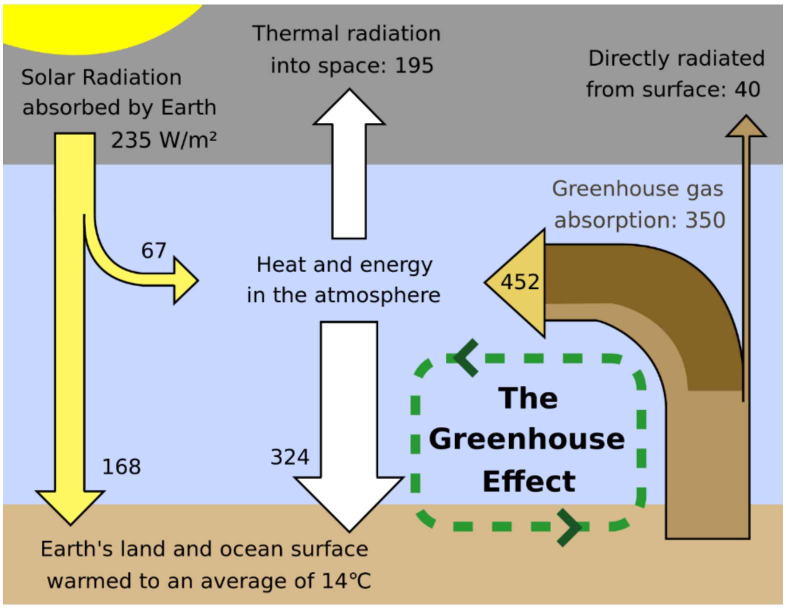


Figure 10 Earth energy balance (7)

Because the energy going into the system and the energy going out of the system balance, no energy is normally built up in the system. The internal energy of the system is normally roughly constant over even longer time periods. The photons entering the system has lower entropy than the photons leaving the system. This is what causes change in the system in the form of work.

In 1824 Carnot came up with a basic understanding that laid the foundation of thermodynamics. He described a model for a theoretical engine that is called the Carnot Engine:

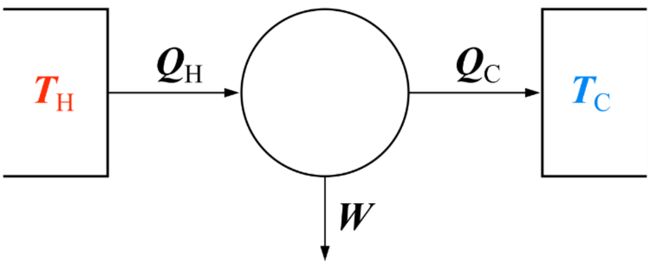


Figure 11 The Carnot engine principle. (8)

The basic knowledge we can pull from what Carnot found is that to generate work you need energy in the form of a high temperature reservoir TH (High temperature) and a heat sink with a lower temperature TC (Temperature Cold). Heat flowing from TH to TC generates the work. If TH=TC then the system cannot generate work.

Earth can be considered as a Carnot engine. TH is the surface temperature of the Sun (5778 K), and TC is the temperature of space (3 K).

These values can be considered relatively constant at least billions of years into the future and has been relatively constant for billions of years. Therefore, a sustainable energy consumption can never exceed the energy received from the Sun. Also, this energy has to be able to escape the system in the form of heat radiation, to avoid an increase of the internal energy of the system, leading to an increase in the global average temperature.

The current global human energy consumption is a combination of the energy we receive through our food and the different energy resources we use, such as fossil energy which corresponds to roughly 90% of the total human energy consumption, if we disregard energy through food. Fossil energy is energy that was chemically stored by plants during the Carboniferous period, 300 to 350 million years ago, which ended up in rock layers over millions of years. Therefore, this energy resource is not renewable.

Alternatives to fossil energy

Wind turbines

According to Vestas a typical wind turbine has an expected lifetime of 20 years [2]. A 2010 article showed an average EROI of a wind turbine to be 20 [3]. If we were to replace all the energy, we currently produce using fossil energy sources covering the next 20 years with wind turbines, this would demand energy roughly corresponding to one year of global energy consumption to manufacture and install the wind turbines. This energy is currently only available from fossil sources. This scenario is not possible in a single year, but could be spread out over a 10 year period. After 20 years we would have to replace the wind turbines.

Global Battery backup

Since solar panels and wind turbines only produce power when the Sun shines or the wind blows, some sort of battery backup will be needed during times with low productivity. This could be solved using large batteries. To manufacture such an amount of battery capacity, you must use elements that are not rare. One of the most promising suggestions is using NaS batteries, since both sodium and sulfur are relatively plentiful. However, NaS batteries are problematic, because large amounts of pure sodium needs to be in liquid phase, meaning that the battery will need to be heated.

One calculation shows that building a NaS battery that would be able to function as a backup for 24 hours of US energy consumption would cost 40 trillion $ and cover an area of 923 square miles (33). Another calculation on a global scale, covering 12 hours of global energy demand based on Li-ion batteries, would need energy corresponding to 18 months of current energy consumption only to manufacture the batteries (33).

Lithium

The current global lithium reserve is 14 million tons [4]. This means:

14e+09 kg / 7.8e+09 capita = 1.79 kg per capita.

In 2016 the number of vehicles were 973 million cars and 349 million trucks and busses:

Historical trend of worldwide vehicle registrations 1960-2016 (thousands)[1][12][13][14][15]									
Type of vehicle	**1960**	**1970**	**1980**	**1990**	**2000**	**2005**	**2010**	**2015**	**2016**
Car registrations(1)	98,305	193,479	320,390	444,900	548,558	617,914	723,567	923,590	973,353
Truck and bus registrations	28,583	52,899	90,592	138,082	203,272	245,798	309,395	337,250	348,919
World total	126,888	246,378	410,982	582,982	751,830	863,712	1,032,962	1,260,840	1,322,272
Note (1) Car registrations do not include U.S. light trucks (SUVs, minivan and pickups) that are used for personal travel. These vehicles are accounted among trucks.									

Figure 12 Number of registered vehicles, global (32)

Estimates of lithium needed for a one kWh battery varies between 113 g to 423 g, depending on the battery type. One article mentions that the battery in a Chevrolet Volt needs 158 grams of lithium per kWh [4]. A typical ELV like the Tesla Model 3 comes with a battery pack of 50, 62 or 75 Kwh.

Optimistically assuming we want to replace 973 million cars with lithium powered ELVs with a 50 kWh battery pack we will need:

50 kWh/car * 158 g/kWh * 9.73e+08 car / 1e+06 g/ton = 7.67e+06 tons litium

Or more than half of the current reserve. Add to that, that there is currently (2019) no commercially available electric powered trucks, and that a truck typically uses 10 times more energy per driven distance than a car. This is equivalent to 3.5 billion extra cars, or more than twice the reserve. A battery pack is typically estimated to last 10 years, and currently we do not recycle lithium because it is dangerous and impractical leading to a high price of recycling. It is cheaper to use the reserve.

Future of energy consumption

These simple calculation shows the magnitude of the energy problem, and it is also a concern in agriculture, where tractors and harvesters run on diesel. There are currently no electric powered tractors, except for prototypes lacking publicly available specifications.

All in all, this makes some of the proposed solutions to the energy problem highly unlikely. Instead a much more probable future scenario is that we continue to use fossil energy until it has been depleted. Currently we have used roughly half the oil reserve, and the oil production can be expected to decline during the rest of the century.

Biosphere and energy

The Earth system develops over time. When Earth was formed it was a large sphere of molten material, and some of the heat was radiated into space. Once Earth had cooled down enough to form a solid crust and some of the water formed lakes and oceans on the surface an equilibrium between energy received and energy radiated was reached an. After that life quickly started.

The early life was primitive, and the conditions was harsh. Slowly evolution developed the biosphere into what we saw roughly 12,000 years ago. This process took roughly 4 billion years.

12,000 years ago, Homo Sapiens had spread all over the surface of the planet and lived as hunter-gatherers. We do not know for sure, but one common explanation for why we started doing agriculture is that the human population had reached the carrying capacity. By using the knowledge humans had learned living in nature, they slowly began growing plants and keeping livestock, thereby increasing the carrying capacity.

Agriculture led to larger and larger societies. Around 1900 we were roughly 1.5 billion people, and since year 0 we had removed almost half of the forests to make room for agriculture.

All the energy that a human need to stay alive comes through the autotrophs, mostly via photosynthesis in the plants. The sugar generated in the plants is an energy storage that is used by all the living biosphere. It is sunlight stored, and once used, it leaves the system as IR dumped into space. Therefore, there is a given flow of energy through the biosphere that starts in the autotrophs and goes through the food chain. For humans today, most of the energy our organisms consume comes from either plants or animals. This food chain is relatively short. If we eat the plants there is one step in the chain, and if we use the plants as feed for livestock, and eat the livestock there are two steps.

To get an understanding of how much we influence this energy flow, 96% of all mammal biomass is either human or livestock [5].

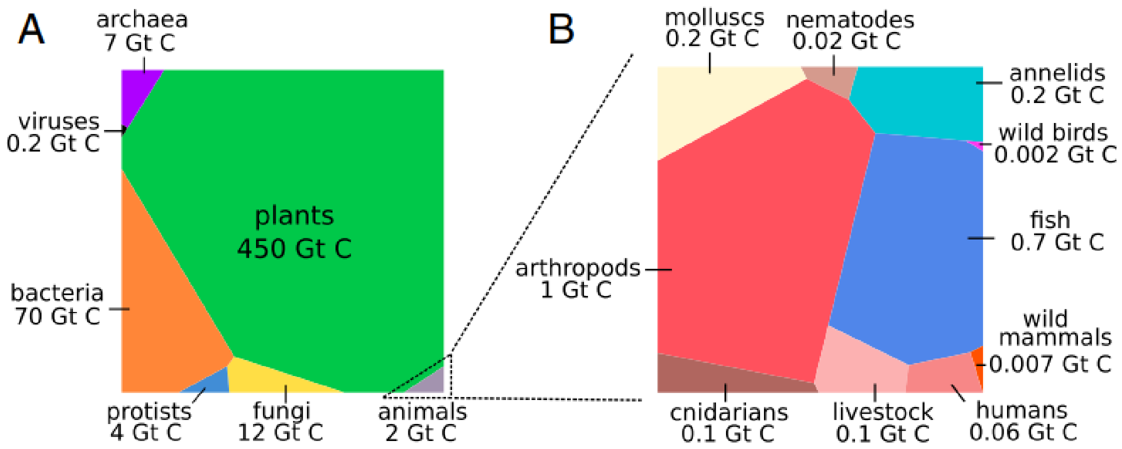


Figure 13 Current biomass on Earth [5]

Likewise we have reduced the total amount of chemical energy in the phytomass (plant biomass) from 35 ZJ around 0 AD to 19 ZJ today[6], roughly halving the phytomass. This is mostly caused by deforestation to create room for agriculture.

The energy humans need comes in the form of chemically stored energy in our food. There is no currently known substitute for that. This means that to keep a certain number of humans alive, there needs to be a certain minimum amount of energy entering the system through the autotrophs.

Each step of the different food chains uses roughly 90% of the energy consumed by the organism to keep the organism alive and the remaining 10% is used to build the cells. Therefore, a plant uses a large part of the energy it stores in sugars to respirate. When an animal eats the plant 90% of the energy from the plant is used to keep the animal alive, and 10% is used for building cells. If a human eats a plant, only 10% of the energy stored through photosynthesis is normally available for the human. If we feed the plant to livestock and eat the meat only 1% of the energy originally stored through photosynthesis is available for humans. If we eat seafood this normally passes even more steps of the food chain, further reducing the available energy for humans.

To sum up: All the energy the human population needs for metabolism and building cells enters the system through the autotrophs, and the amount of available energy is considerably reduced through the food chain.

Net primary production

The total amount of energy stored chemically by the autotrophs is called the Gross Primary Production. Since the plant uses a large part of that stored energy during its life, the energy that is left is called the Net Primary Production (NPP).

Primary production and plant biomass for the Earth [edit]

Ecosystem type	Area (10^6 km²)	Mean NPP (g/m²/yr)	World NPP (10^9 tons/yr)	Mean biomass (kg/m²)	World biomass (10^9 tons)
Tropical rainforest	17.0	2,200	37.4	45	763
Tropical seasonal forest	7.5	1,600	12.0	35	260
Temperate evergreen forest	5.0	1,300	6.5	35	175
Temperate deciduous forest	7.0	1,200	8.4	30	210
Boreal forest	12.0	800	9.6	20	240
Woodlands and shrublands	8.5	700	6.0	6	50
Savanna	15.0	900	13.6	4	60
Temperate grasslands	9.0	600	5.4	1.6	14
Tundra and alpine	8.0	140	1.1	0.6	5
Desert and semi-desert	18.0	90	1.6	0.7	13
Extreme desert and ice	24.0	3	0.07	0.02	0.5
Cultivated land	14.0	650	9.1	1.0	14
Swamp and wetland	2.0	2,000	4.0	12.3	30
Lakes and streams	2.0	250	0.5	0.02	0.05
Total Continental	**149**	**773**	**115**	**12.3**	**1837**
Open ocean	332.0	125	41.5	0.003	1.0
Upwelling zones	0.4	500	0.2	0.02	0.008
Continental shelf	26.6	360	9.6	0.01	0.27
Algal bed and reef	0.6	2,500	1.6	2.0	1.2
Estuaries	1.4	1,500	2.1	1.0	1.4
Total marine	**361**	**152**	**55.0**	**0.01**	**3.9**
Grand total	**510**	**333**	**170**	**3.6**	**1841**

From R.H. Whittaker, quoted in Peter Stiling (1996), "Ecology: Theories and Applications" (Prentice Hall).

Figure 14 Source: (9)

The forests account for 1,6e+12 tons of the total continental biomass of 1.8e+12 tons, or 90%, whereas the cultivated land accounts for less than 1%. At the same time the cultivated land accounts for roughly 10% of the area, whereas the forests accounts for roughly one third of the continental area.

Before agriculture the area covered by cultivated land was 0%. Because the amount of biomass per area of the cultivated land is smaller than the amount of biomass per area for the forests, this has led to a reduction of the global amount of biomass during the evolution of agriculture.

In 2015 Schramski et al made a model where they imagined the Earth as a giant battery[6]. They calculated a variable they called Ω.

$$\Omega = \frac{P}{BN}$$

Where

- P is the chemical energy stored in the phytomass
- BN is the energy needed for the human population's metabolism per year.
- Ω is the amount of years that the phytomass can sustain human metabolism at the current rate of consumption.

They stated in the article that this number was overly optimistic, because humans cannot digest a large part of the biomass. However, their result was alarming:

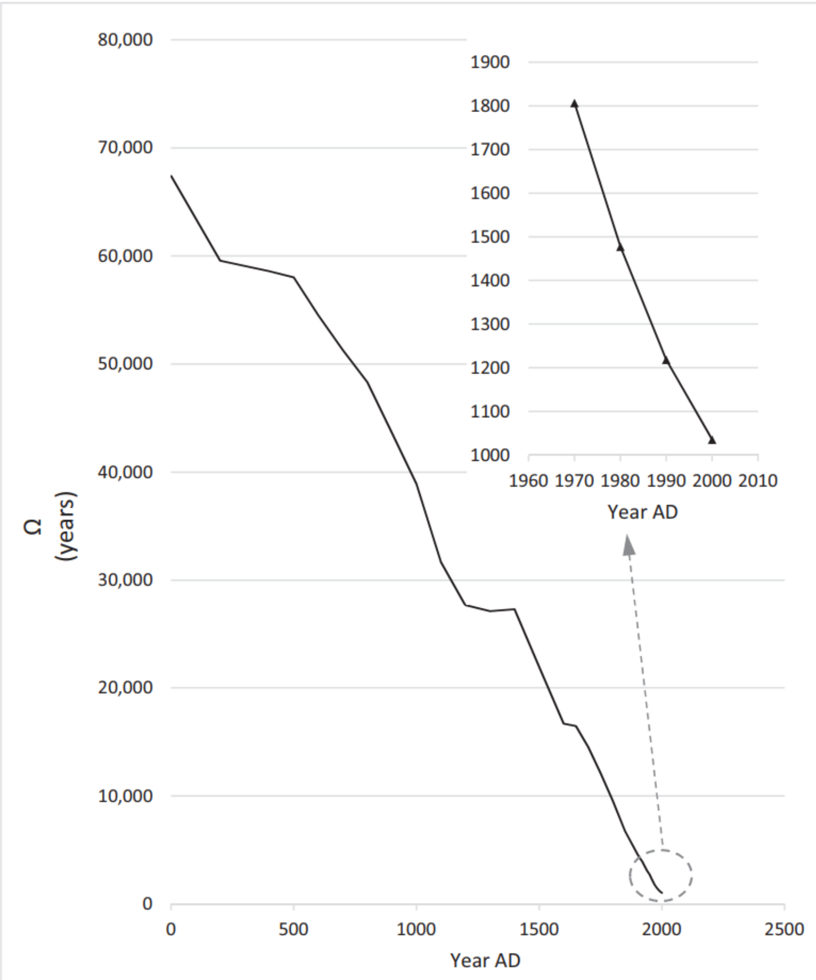


Figure 15 Ω over time [6]

Extrapolating the curve between 1970 and 2000 until Ω reaches a value of 0 shows an estimate of that happening somewhere between 2030 and 2050 depending on the curvature of the graph. After that we will not be able to feed the human population for a single year, even if we could hypothetically eat all the biomass.

Agriculture

Agricultural production can be simplified down to a number of factors determining the crop yield per area. The most important are:

- Cultivated land area
- Plant type
- Irrigation
- Energy used
- Soil nutrient content
- The weather

Since 1900 we have more than doubled the amount of agricultural land area:

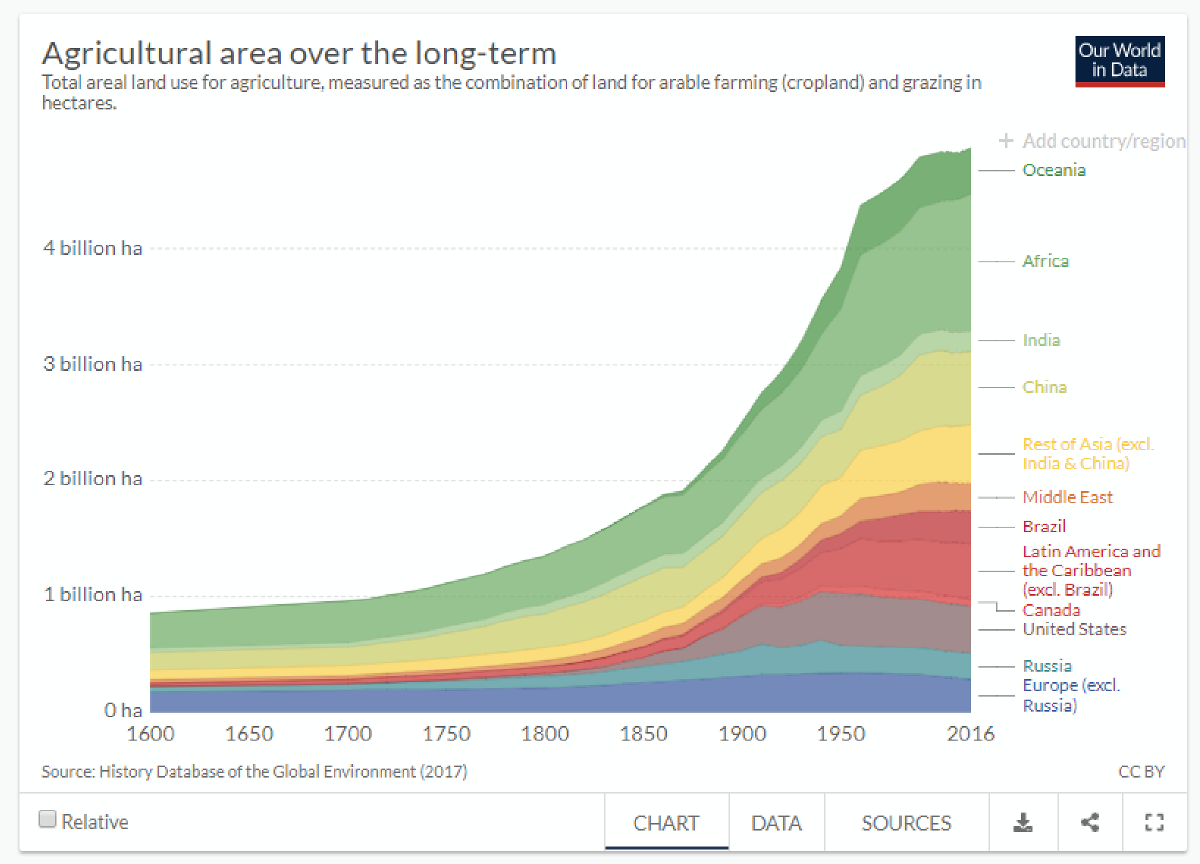


Figure 16 Agricultural land over time (10)

Currently we have very limited amounts of unused arable land. This area is expected to be reduced because of rising sea levels and desertification. Some have suggested that large parts of the tundra could become arable once the temperature rise causes the permafrost to melt, but it would also release huge amounts of methane to the atmosphere. In that case it would cause a temperature rise in the order of 10 deg C, and then arable land would be one of our lesser problems.

1/3 of the agricultural land is used for growing crops and 2/3 is used for pasture.

We currently use roughly 70% of the available freshwater to irrigate, and water is becoming an increasing problem.

Increasing global temperatures causes more extreme weather, due to more energy stored in the atmosphere. This is predicted to cause a decreasing crop yield. As one anecdotal proof of that the Danish harvest in 2018 was 28% lower than the previous year, and 23% lower than normal, due to a very dry summer:

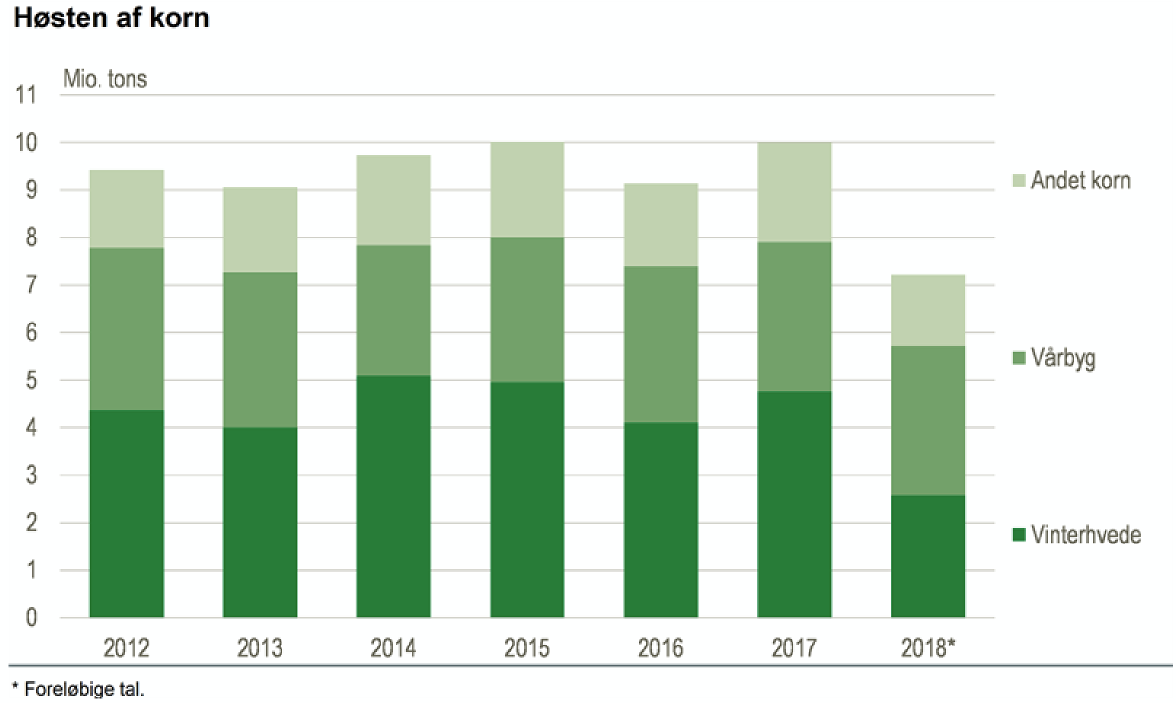


Figure 17 Danish Harvest 2012-2018 (11)

To produce more food for an increasing population, that leaves energy and fertilizers. With a population growing towards 10 billion around 2050 we will have to produce almost 1/3 more food than today to keep everybody alive.

Fossil energy in agriculture is used for machines like tractors and harvesters. Furthermore, distribution of the produced food is done using fossil fuels. Before the introduction of the combustion engine the energy was delivered by animals like horses and human labor. We currently have no realistic alternative to fossil fuels in agriculture, but assuming the good intentions from the Worlds politicians will be transformed into action, that means that we will have to stop burning fossil fuels within the next 20-30 years, or preferably sooner, to avoid reaching too many climate tipping points.

Without an alternative this will mean that we will probably have to go back to manual labor. That will reduce the crop yields considerably.

This leaves us with fertilizers as the only option if we want to increase the food production to follow the population growth.

Phosphorus

Phosphorus is an element. Since naturally occurring phosphorus is a largely stable isotope, and since the Earth can be considered a closed system, the amount of phosphorus on Earth is constant. The Earth's crust contains 0.1% phosphorus, but some rocks has a higher content. When we mine phosphorus without recycling it, the phosphorus goes through the phosphorus cycle. The mined phosphate rock is processed into fertilizer that is added to the soil. The plants absorb phosphorus from the soil and when the plants are harvested, they contain phosphorus that is thereby removed from the soil. The plants are either used for food or feed. The phosphorus in the food is eaten by humans, and the phosphorus in the feed is eaten by animals. Most of the livestock animals end as food that is also eaten by humans. Humans then excrete a large part of it, and the phosphorus ends up in waste water, which is spread into the oceans.

Phosphorus is vital to all known life. It is a part of the phospholipids in cell membranes, and it is part of ATP used in the metabolism. Phosphorus is also part of DNA. There is no known way of replacing phosphorus in a normal living cell. The recommended amount of phosphorus in a human diet is around 1 g per day, or 0.365 kg per year (40).

Before the human population explosion phosphorus was recycled through the phosphorus cycle. When an animal eats a plant, a part of the phosphorus is used for building new cells, and the rest is excreted, mostly in the urine. During pasture the manure and the urine ends up in the soil and in the waters. When a plant or an animal dies and decays, the phosphorus ends up in the soil or in the waters. On larger timescales phosphorus which is not bound is washed from the soil by rain, going into rivers and streams, ending up in the oceans. In the oceans phosphorus is consumed by sea life and ends as sediments on the sea floor. There it sinks and over very large timescales turns into rock sediments. These rock sediments are then spread out over the planet's surface through volcanic activity and rock erosion caused by rain and wind, thereby closing the cycle.

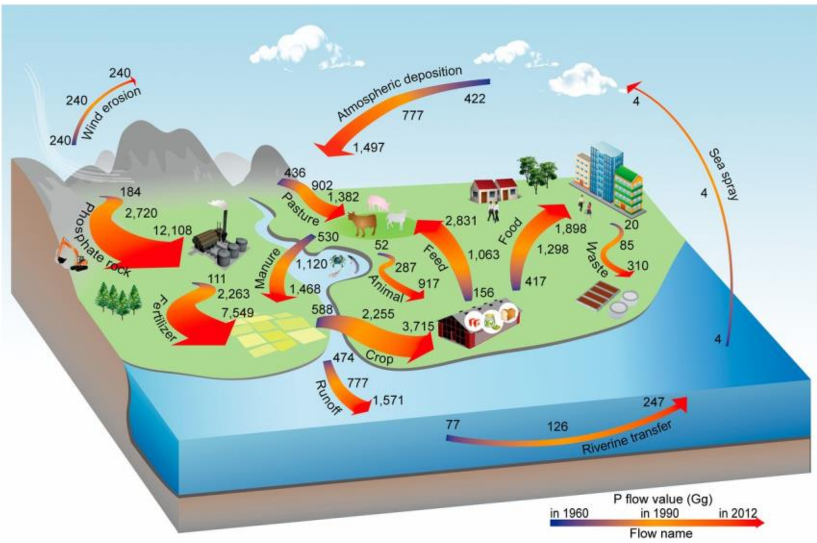


Figure 18 The phosphorus Cycle (12)

The transport of phosphorus through plants and animals is on a timescale of years, but the timescale of the sediments turning into rock is on a timescale of millions of years.

With the introduction of NPK fertilizers this cycle has been disrupted. This spreads the phosphorus from the rather concentrated phosphate rock into the enormous amount of water in the oceans. One way of looking at this process is that we increase the entropy. To retrieve the phosphorus from the oceans, we need to do work, spending energy, thereby reducing the entropy of the phosphorus. When we spread the phosphorus into the oceans, it will take a lot more energy to extract it than we currently use to extract it from the crust, since we must reduce much more entropy, when extracting phosphorus from the ocean.

Currently the recycling being done is mostly done by using manure as fertilizer. Sludge from water treatment plants have been proposed used for fertilizer production, but this is mostly avoided, since the sludge also contains other ingredients than phosphorus, and there are widely spread, more or less rational concerns about using sludge for food production. On top of that, most of the phosphorus is diluted in the wastewater, and therefore needs to be precipitated using chemicals and energy, if we want to have easily distributable fertilizers.

Phosphorus is absorbed well by soil up to a certain degree, where the soil becomes saturated. After that, adding more phosphorus will lead to most of it being eroded by rain and irrigation.

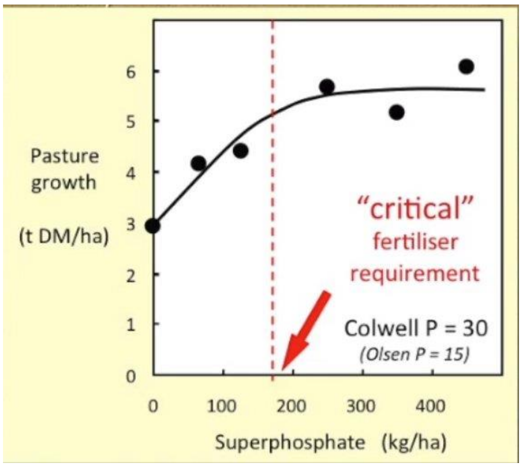


Figure 19 Pasture growth vs amount of fertilizer added (13)

In the US the use of fertilizers and mechanization has resulted in a large increase in the crop yield:

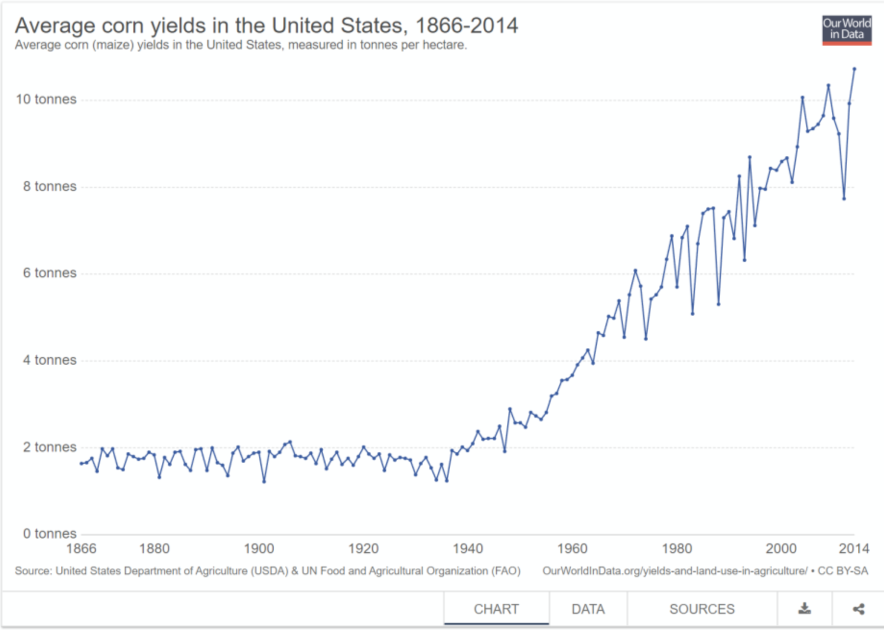


Figure 20 Avareage corn yields (US) (14)

This correlates well with the addition of fertilizer to the soil:

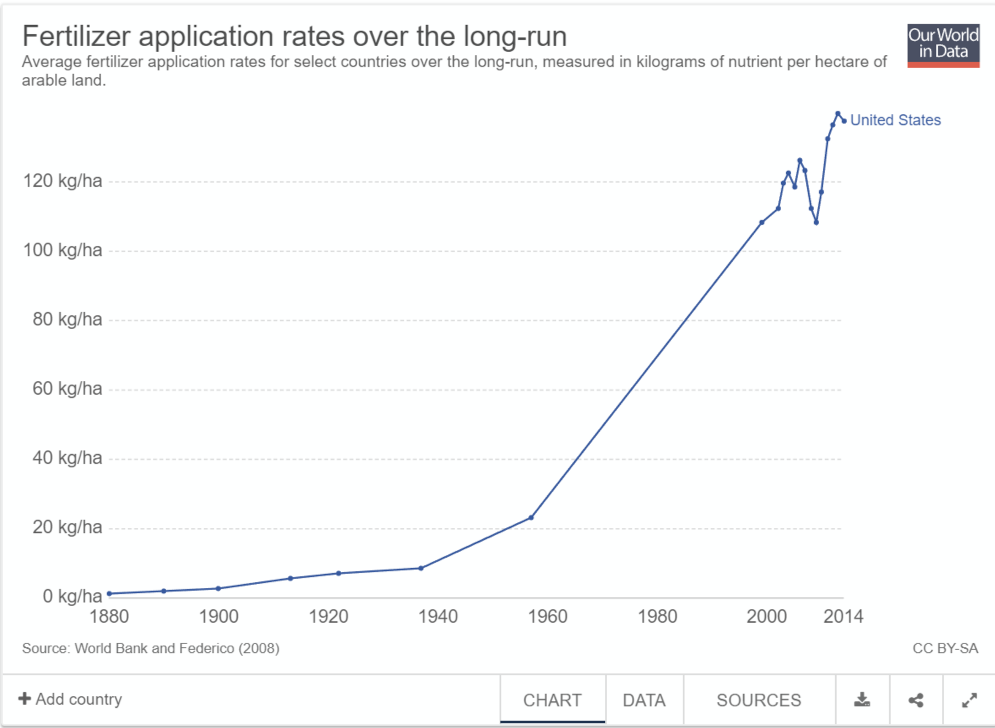


Figure 21 Fertilizer application (US) (14)

On a global scale, there is also a clear correlation between fertilizer usage and crop yield:

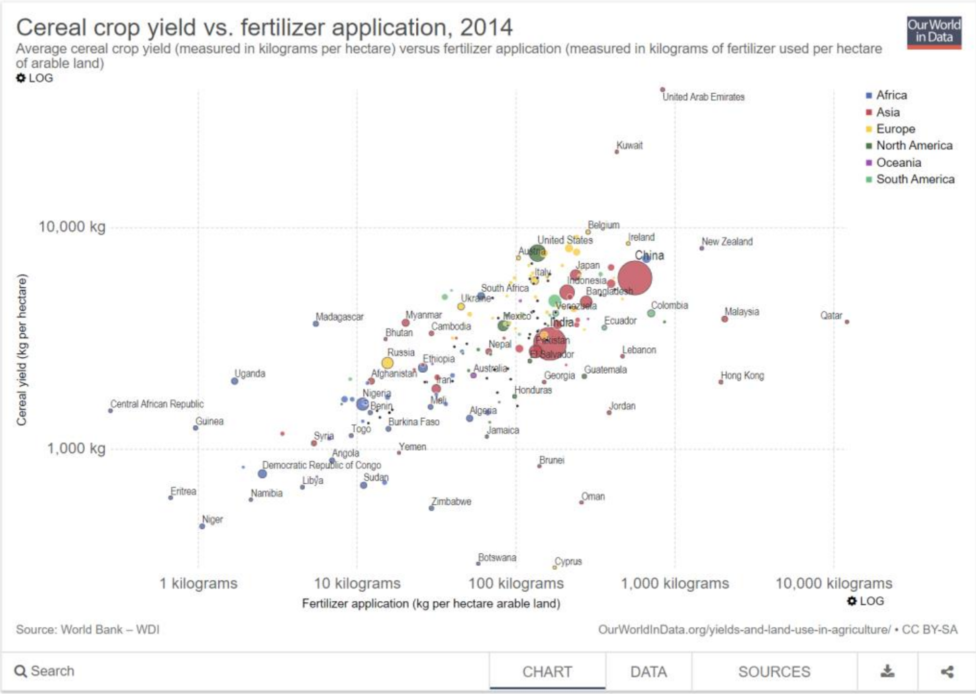


Figure 22 Cereal crop yield vs. fertilizer application, 2014 (14)

Globally the phosphorus content in the soils has increased, mostly in the developed countries. This creates a buffer of phosphorus in the soil, but a simple mass balance shows that once you stop adding phosphorus, the soil's phosphorus content will decrease roughly corresponding to the amount of phosphorus in the harvested plants. The only way to compensate that is either adding more NPK fertilizer or manure.

There are wildly varying estimates of how much organic vs. non-organic farming will reduce the crop yield, but a rough estimate is that going from non-organic farming using NPK to organic farming reduces the crop yield somewhere between 30-50%. This demands that we have enough manure to use. In the case of reducing the global meat consumption to reduce methane led into the atmosphere, where it causes climate change, reducing the amount of livestock, we will have less manure to fertilize the soil. Instead we would eat a larger proportion of the plants, and then more of the phosphorus would end in the wastewaters.

It is obvious that removing NPK and converting to organic farming could be disastrous to the global food security, since we have no way of increasing any of the other limiting factors for the crop yield.

During my work, I have spoken to organic farmers, asking them how they would enrich the soil if they did not have manure. Some had no answer, but others mentioned adding phosphate rock. In organic farming you are not allowed to add NPK, but grinded raw phosphate rock is considered "natural" and thereby acceptable. It is absorbed slowly, since the phosphorus has to be released by erosion, and therefore it is mostly an option if the soil has a pH lower than 7.

When asked if the organic farmers had an alternative to both manure and phosphate rock the answer was an obvious "No".

Phosphate rock

Phosphate rock is rock that has relatively high phosphorus content. This has been found wide spread over the planet, but in concentrated ore in specific places. Much of the known reserve is currently being depleted, with the highest remaining reserve considered to be in Morocco.

The phosphate rock, like most other ore was originally taken from the surface, but as the surface reserve has become depleted, deeper and deeper mining has been introduced. This causes a higher production cost and a higher energy consumption related to the mining.

Most phosphate rock also contains heavy elements, and this causes concerns about using the treated rock as fertilizer. During the life of an animal it will eat and accumulate the heavy elements, and because of roughly 10% of each step of the food chain turning into cells, this means roughly a 10x buildup for each step of the chain.

The global production of phosphate rock has been largely growing exponentially since 1900 with a decade of stagnation probably primarily caused by the collapse of the Soviet Union.

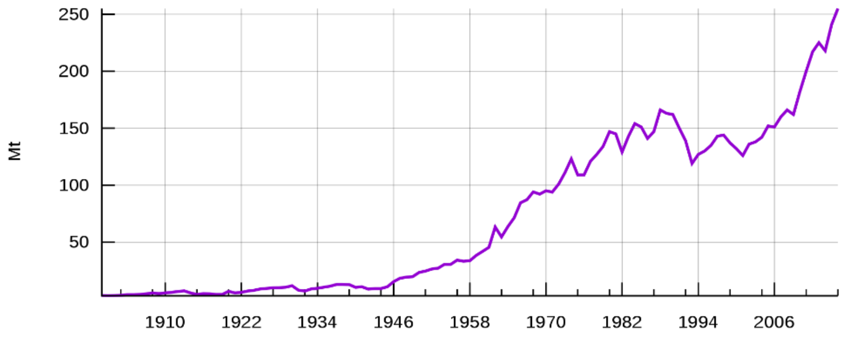


Figure 23 Global phosphate rock production (15)[7]

This development correlates with the population, and with the global food production.

Some of the previous large producers of phosphate rock, like the US and China are currently seeing their reserves running out.

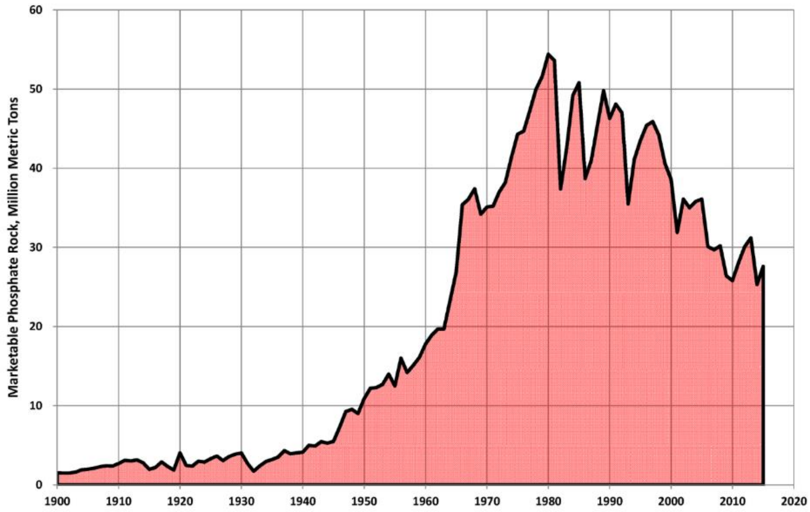


Figure 24 US phosphate rock production (16)

Looking at the remaining reserves, the majority of phosphate rock is expected to be in Morocco:

	Mine production		Reserves[4]
	2016	2017[e]	
United States	27,100	27,700	1,000,000
Algeria	1,270	1,300	2,200,000
Australia	3,000	3,000	[5]1,100,000
Brazil	5,200	5,500	1,700,000
China[6]	135,000	140,000	3,300,000
Egypt	5,000	5,000	1,300,000
Finland	940	950	1,000,000
India	2,000	1,800	65,000
Israel	3,950	4,000	74,000
Jordan	7,990	8,200	1,300,000
Kazakhstan	1,500	1,600	260,000
Mexico	1,700	2,000	30,000
Morocco and Western Sahara	26,900	27,000	50,000,000
Peru	3,850	3,900	400,000
Russia	12,400	12,500	700,000
Saudi Arabia	4,200	4,500	1,400,000
Senegal	2,200	2,200	50,000
South Africa	1,700	1,800	1,500,000
Syria	—	100	1,800,000
Togo	850	1,000	30,000
Tunisia	3,660	3,700	100,000
Vietnam	2,800	3,000	30,000
Other countries	1,950	1,940	900,000
World total (rounded)	255,000	263,000	70,000,000

Figure 25 Current reserves [7]

Resources and reserves

When looking at any finite resource it is important to distinguish between the terms reserve and resource.

The resource is the total amount of theoretically extractable material. This includes every known occurrence.

Reserves is the given amount of a finite resource, that it is economically feasible to extract. This does not include all of the resource, because some of the ore might be of a very low concentration, thereby making refining too expensive, or the ore might be placed deep in the ground resulting in similarly high production costs.

Dispute

In 2009 a group of scientists used data from United States Geological Survey (USGS) to predict the peak of Phosphorus Rock (PR) production, using among other methods, the Hubbert Curve [8]. They concluded that PR production could peak as early as 2030, and then decline.

This has caused a lot of debate [9][10][11][12], resulting in a report from the International Fertilizer Development Center (IFDC) [13], stating that USGS' estimates were wrong, and that resulted in USGS adjusting their numbers in 2011 [14]. As a result, the official reserve went from $16*10^9$ tons (2010) [15] to $65*10^9$ tons (2011) [14].

This caused even further debate, and in 2014, a new group of scientists reviewed the numbers, and found that, first of all the resources that had been upgraded to reserves was almost solely from one single mine in Morocco, more than quadrupling the total global reserve, secondly that the reported reserve was speculative[16].

As a result of the IFDC report, and USGS' regulated numbers, the general consensus today is that we have roughly 70 billion tons P reserve, and 300 billion tons P resource [17].

The typical way of calculating the lifetime of the reserve, is the R/P method:

$$Lifetime = \frac{Reserve}{current\ anual\ production}$$

This assumes zero growth in consumption, which is obviously not true when you look at the empirical data for the production.

Using this wrong method, USGS and IFDC concludes that the world has phosphorus for several centuries:

$$Lifetime = \frac{6.5e + 10}{2.61e + 08} = 249\ years$$

It is also important to notice, that the phosphorus concentration in the remaining resource, often gets lower with time, because you start extracting the ore with the highest concentration. Also, much of the rock that might contain new P resources have already been tested with negative results by other drillings, looking for oil, coal, gas etc. This means that the chances of finding a new prosperous reserve gets lower with time.

One probable explanation

USGS gets its data from the phosphate rock producers. In 2007, increasing demands on the global market led to a large increase in the price of phosphorus rock. I have not been able to verify this, but the higher price in 2007 might have caused the Moroccan producers to estimate their reserve based on the higher price [18].

The logistic function

For any given finite depletable resource the following is considered to be true, according to among others, historical data, simple logic and economics:

- At t_0, being time=0, the cumulative production, Q, is 0.
- Because the resource has a given size at t_0 the resource must have a Q_{max} being the total amount that can be extracted and used from the planet.
- In the beginning of the extraction, the production rate will be slow, due to learning processes, investments and installation of new equipment, etc.
- Then the production rate increases, often exponentially.
- Due to increased demand and production, the easily accessible reserves are being depleted first.
- This results in higher production costs like refinement costs, mining depth, etc.
- As a result of the increased cost, the price increase, and this leads to lower demand and thereby lower production rate.
- When Q reaches Q_{max}, the production stops, because the resource is depleted. In practice a certain amount of the resource will be left, but due to a very high price, the production will be equally low.

These assumptions lead to a Sigmoid function

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}}$$

where

e = the base of the natural logarithm, 2,718…

x_0 = the *x*-value of the Sigmoid function's midpoint

L = the maximum value of the curve

k = the steepness of the curve

[19]

The function plotted, gives a S-shaped curve:

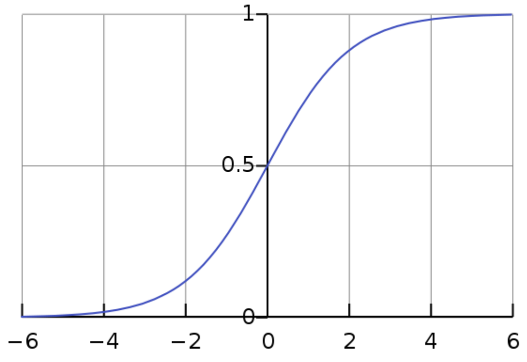


Figure 26 The logistic curve showing cumulative production vs time

Hubbert function

In the mid-1950s, M. King Hubbert, a geophysicist working at Shell, used a derivative of the logistic function to estimate a potential future peak in US oil production [20][21][22](41). He had noticed that the common contemporary way to estimate the lifetime of a finite resource, was to take the known resource size, and divide it by the current yearly consumption, assuming zero growth. The assumption made absolutely no sense, when Hubbert looked at the exponential growth, he saw in the oil production. The derivate of the logistic function plotted over time, gives a bell-shaped curve:

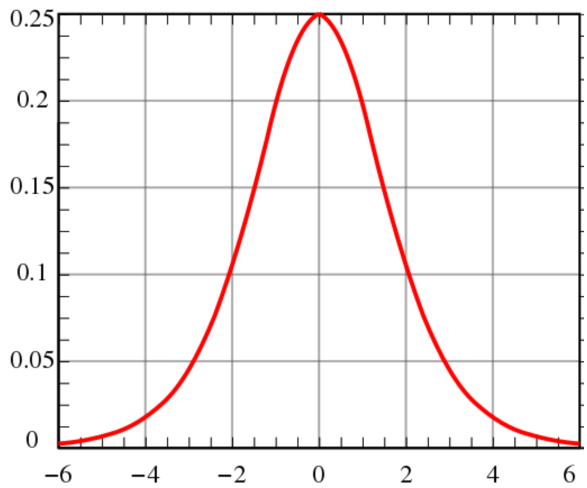


Figure 27 Hubbert Curve (17)

The x-axis represents time, and the y-axis represent annual production. By fitting the function to historical data, Hubbert, in 1956 predicted that the US oil production would peak around 1970, and then decline with the same rate it had inclined up to the peak date. Not many took him seriously in the roaring 50s, but the US oil production peaked in 1970, as Hubbert had predicted (17)(41), and even more startling, the yearly production declined with the rate he had predicted:

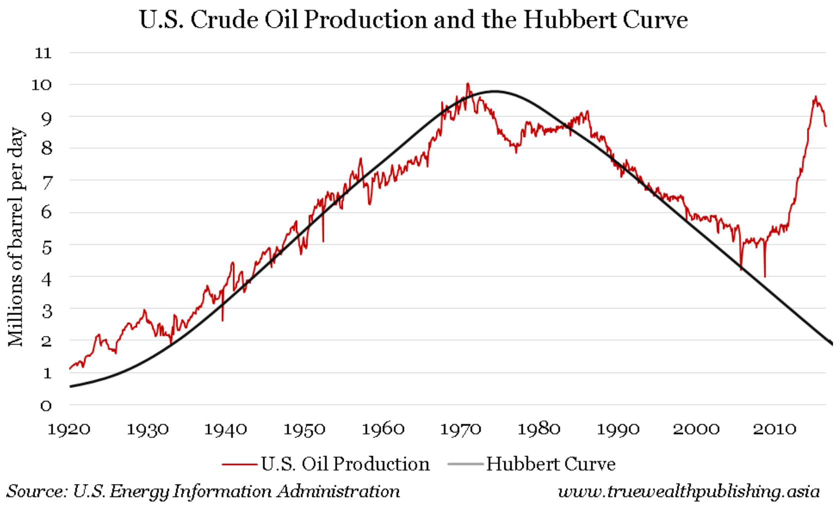


Figure 28 US crude oil production and Hubbert's prediction (17)

Since Hubberts US oil estimate, the model has been proven to work with several other finite resources, including many elements (18).

An important consequence of Hubberts curve is that after the peak, the curve decline with the same slope that it inclined.

Critique of Hubberts Peak Theory

In recent years the US oil production has departed from Hubberts predictions and it has rapidly increased:

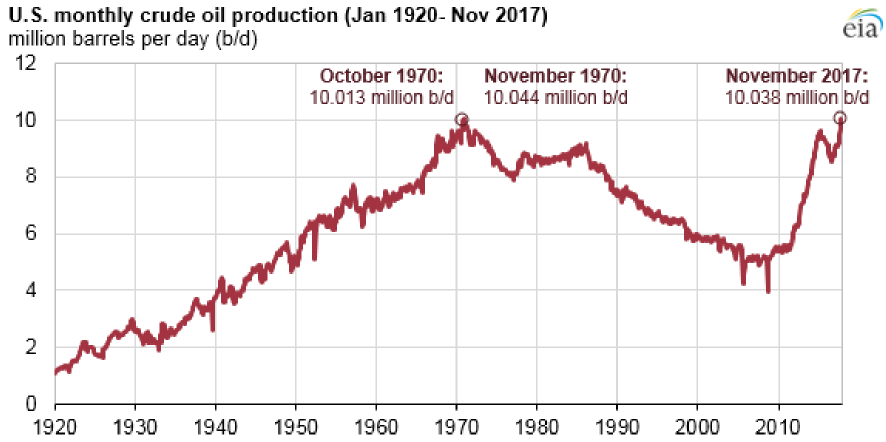


Figure 29 US crude oil prduction has increased since 2010 due to shale oil and tar sands becoming feasible after the 2008 financial crisis, which caused the oil price to reach more than 100$ per barrel. (19)(20)

This new increased production is widely explained by a reaction from the shale oil producers in the US to the oil price increasing to more than 100$ per barrel after the 2008 financial crisis. This shale oil however, in many ways, cannot be compared to the crude oil the US oil producers used to produce before the peak was reached in 1970. In economics it is assumed, that with a given a certain purchasing power, a consumer will look for alternative products once the price of a product gets too high. Furthermore, it is considerably more expensive to extract shale oil, than crude oil, leading to a high price of the end product. Most economist agree that the days of “cheap oil” are over, and that the oil price will increase further in the future.

Another often mentioned critique of Hubbert’s Peak Theory is that increasing prices will lead to more of the resource being upgraded to reserve [23](21)(22). To understand that better we need to look towards economics.

Economics

The Value Paradox

In economics, a well known paradox is called the Value Paradox. One example of the paradox is:

If value equals utility, then why is a diamond much more expensive than a glass of water?

This paradox has puzzled both economists and philosophers. However, a simple thought experiment shows that the assumption of diamonds having higher value than water is simply wrong:

Let us assume that you lock up a human in a room with two buttons called W and D. When button W is pushed, the human receives 2 liters of water, and when pushing button D the human will receive a one carat diamond. The human can push only one button every day.

The first day, the human might choose the diamond, hoping to be released before dying from thirst. The second day the human will be more thirsty than the first day, and therefore the probability of choosing water instead of diamond will increase. After 3-7 days the human will become dehydrated to a degree that threatens survival. It would be safe to assume that in that case, almost any human would value water higher than diamonds.

Value might depend on current needs and irrational priorities, but over a timespan these abnormalities will be overruled by vital needs.

Demand

The demand function describes the amount being asked of a given commodity, as a function of the price asked for the commodity.

Often the demand curve is plotted as a straight downwards sloping line, with quantity on the X-axis, and price on the Y-axis. This is done for practical reasons, since the linear function makes it easier to work with, and the approximation often works satisfactory, in a market where the changes in price, demand or supply are small. However, this is not the true demand function.

Instead, let us consider that you want to buy apples, and you have 10 dollars you want to spend. We could call the 10$ the Purchasing power, PP. If the price of one apple is 1$, you can afford and will buy 10 apples. If however the price of one apple is 2$ you can only afford 5 apples. If the price is 10$ you can afford one apple. The Demand Quantity, or Demand is the number of apples you will and can buy at any given price, and therefore we get:

$$Demand = Quantity\ Demanded = \frac{PP}{Price}$$

Or

$$Price = \frac{PP}{Quantity\ Demanded}$$

Plotting the quantity demand as a function of price we get:

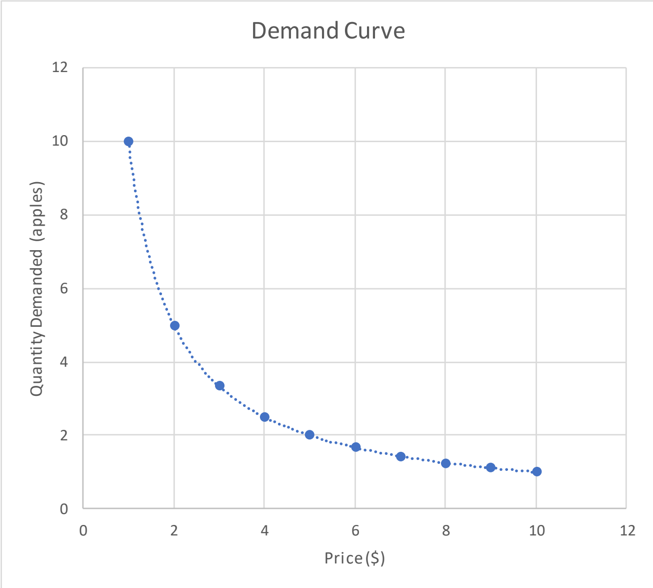


Figure 30 Nonlinear demand curve

Looking at our example with the apples, lets consider, that there was another buyer who also wanted to spend 10$ on apples. This would change the demand:

$$Quantity\ Demanded = \frac{2 * 10\$}{Price}$$

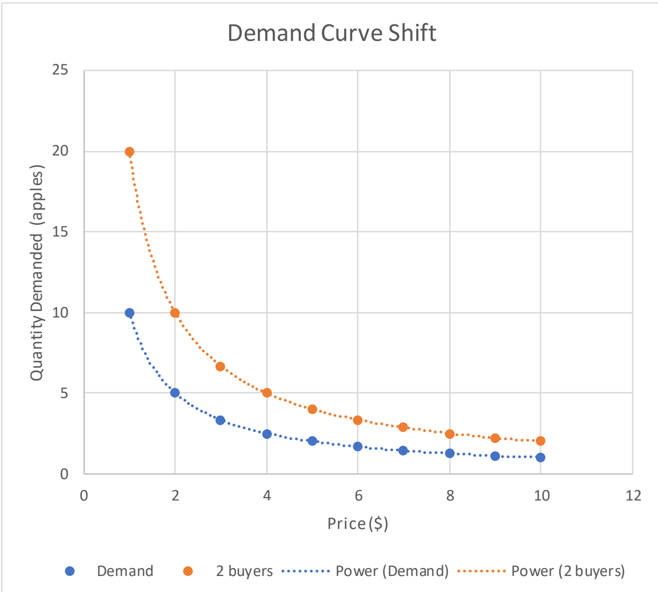


Figure 31 Shifting of demand (blue) by doubling the number of buyers (red)

The different buyers on the market have different amounts of PP, but the Total PP, is the sum of all the individual buyers PP, and we can average this to PP per capita, by dividing by the number of people. Assuming that all buyers in the market follow the Law of Demand:

$$PP\ per\ capita = \frac{\sum PP}{Population}$$

Supply

The Supply function describes how many units of a good or commodity the seller is willing to produce, at any given price.

The Supply Curve can have different shapes, but often the Supply curve is depicted as a straight line with a positive slope.

$$Supply = a * Price + b$$

Or

$$Price = \frac{Supply - b}{a}$$

Where a is the slope of the curve and b is an offset. The slope is the rising interest in producing, and the offset is due to the input cost.

Assuming that a price of 0 would result in an incentive to produce 0 units, in it's simplest version, the Supply Function looks like this:

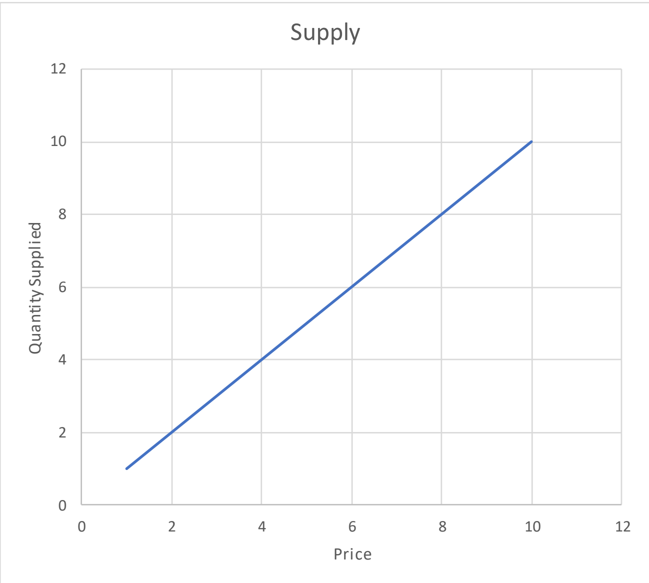


Figure 32 Simple Supply Curve

Because we know that the extraction of a resource follows the logistic function, we also know that the production towards the end will slow down, due to increased production costs, or input price, resulting in higher product price.

If we reduce the resource, it will result in a steeper supply curve.

Equilibrium price

By combining the Supply Curve with the Demand Curve we can calculate the equilibrium price. This is where the two curves intersect:

Figure 33 Equilibrium Price is where the Demand Curve (red) intersects the Supply Curve (blue). The intersection of the blue line and the grey line shows the effect on the Equilibrium Price, when the demand doubles.

Likewise, lowering the supply will also cause the Equilibrium Price to change:

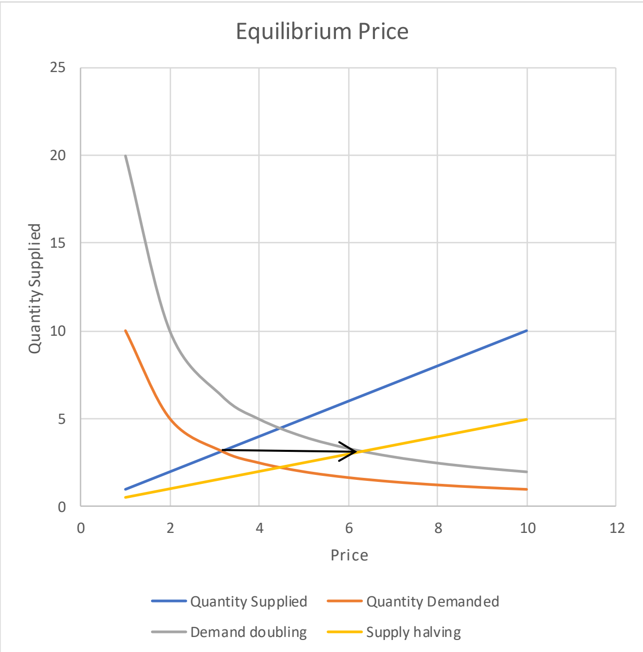


Figure 34 This plot shows the combination of Demand Shift, doubling (red to grey) and Supply Shift, halving (blue to yellow), resulting in a doubling of the Equilibrium Price.

Because the demand curve is not linear, once the ratio between demand and supply increases, the equilibrium price begins to increase rapidly. This causes a negative feedback loop in the market, so even though a higher price will cause more of a resource to be upgraded to reserve, there is an upper limit to what the consumers can afford. Therefore, the upgrade will be limited by the purchasing power, which is limited.

The price of phosphorus

In 2007-2008 the price of phosphate rock increased almost by a factor of 10x (25), jumping from 45 $/t to 430 $/t. This was caused by a number of different factors (26), which combined increased the demand. The fertilizer demand in India and China was increasing, increasing livestock production caused further demands, and the production of biofuels in US and Brazil also caused increasing demands. Because the supply could not follow the demand, this led to an increasing equilibrium price. In 2009 the price dropped back to 90 $/t, twice the price before 2007. Since then the price has been unstable varying between 203 $/t in 2010, to a current (2019) price of roughly 100 $/t.

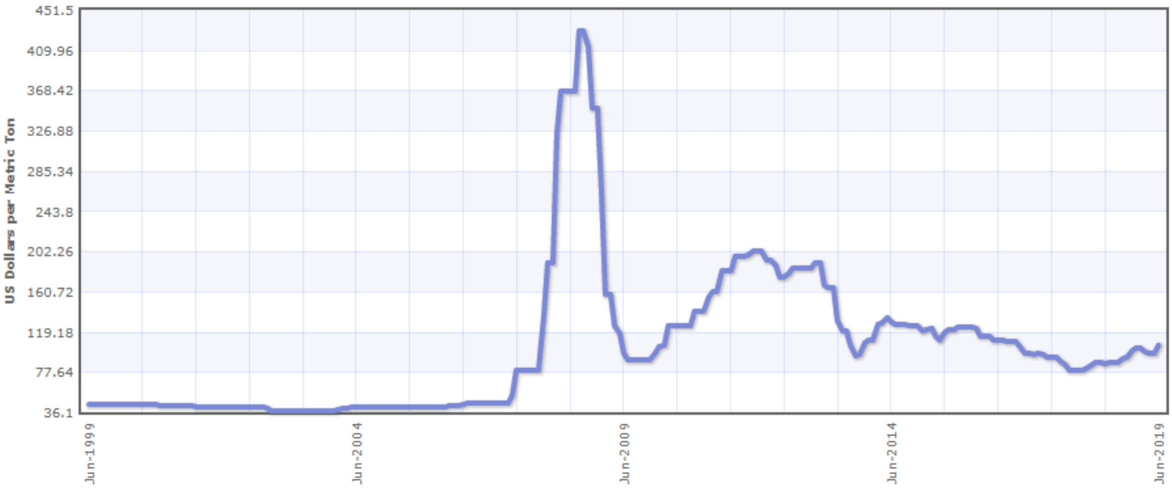


Figure 35 Phosphate rock price (Morocco), 70% BPL, contract, f.a.s. Casablanca (25)

The increase in the price of phosphate rock resulted in increasing food prices:

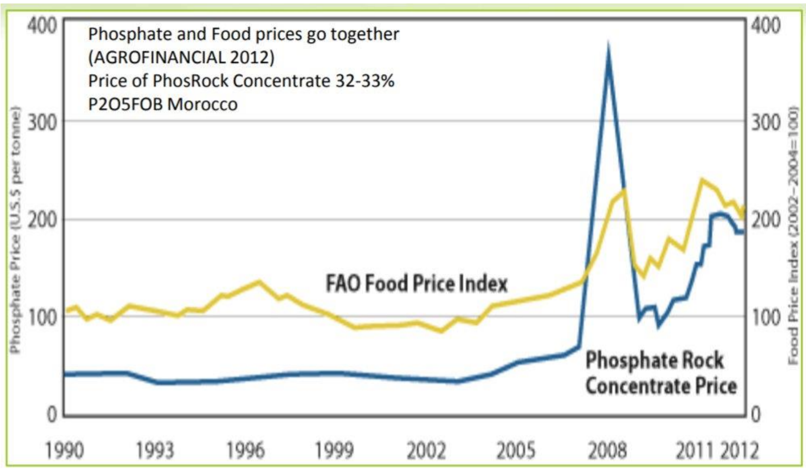


Figure 36 The correlation between prices on phosphate rock and the FAO food price index (24)

As mentioned earlier, the 10x price increase led to a great concern about a potential peak phosphorus scenario, leading to the revision of the estimated reserve from 15 Gt to 65-70 Gt. This increase in the reserve was mainly due to Morocco's reserve being raised from 5.7 Gt in 2010 to 50 Gt in 2011. However, since then, even though the global production has increased, the Moroccan production has not increased in a similar way. Instead China has seen a large increase in production, which might explain a lower global demand after the 2008 price spike:

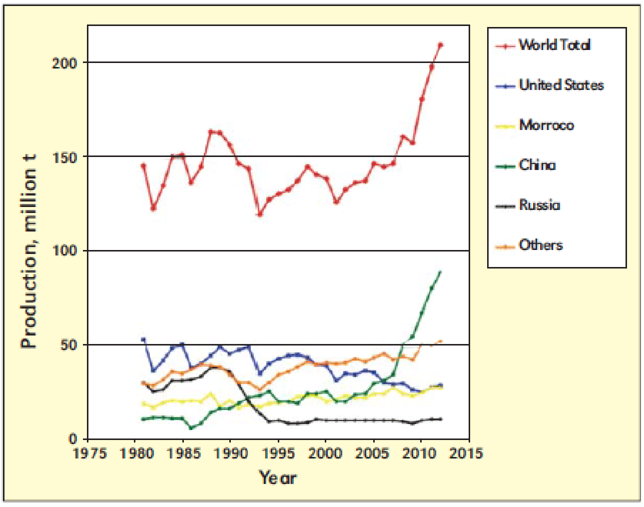


Figure 37 Phosphate Rock production of the five largest producing nations. (23)

Oil is a finite resource

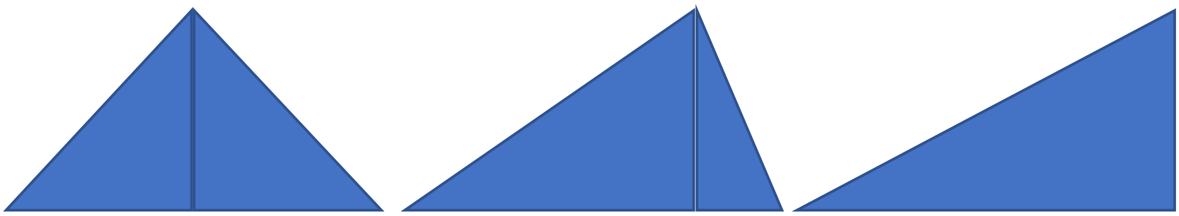
Any limited reserve we use is bound to become depleted some time in the future. If you, at that time in the future, calculate the total cumulated production you will get a number. Current events in the system will cause the final cumulated production to change, viewed from our current reference frame, but the final number cannot change once the resource is depleted, because that would take backwards causation. This also means that the current available data is part of the final curve. These are both not changeable and they also describe part of the final curve. Therefore, there will be a true size of the total reserve at one point in the future. In the following this is what is called the reserve.

Disregarding climate change etc., we could use all of the reserve. Depending on many factors like demand and price, this final cumulated production could either follow the Hubbert Curve (simple logistic function), or demand could cause the production peak to shift towards the end of production:

Figure 38 Seneca Shift (30)

It is important to notice the the integral of the Hubbert function is equal to the area under the graph, which simultaneously represent the cumulated production. Therefore shifting the peak will not change the area under the curve and therefore not change the cumulated production for any given finite resource. As a consequence of that, a delayed peak will cause a steeper slope of the curve after the peak than after a Hubbert peak, called the Seneca Trap (31).

We could make an even simpler model:



…all have the same area and the same length and height.

Because the true size of the reserve is given, we can change the slope of the curve at any given time, but we cannot change the true size of the reserve, the area under the curve.

Looking at Hubbert's prediction of the US oil production peak in 1970, the decline was better approximated by Hubbert's function than by the Seneca effect.

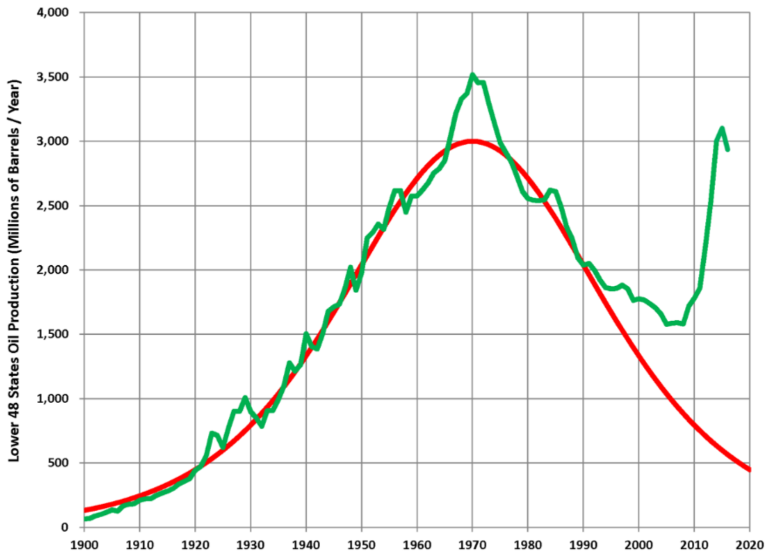


Figure 39 Hubbert curve and US oil production does not show the Seneca effect

Even though the peak production in 1970 was higher than the Hubbert curve predicted, the symmetry of both empirical data and the prediction corelate well, with a decline mirroring the growth before the peak. The lack of correlation after 1990 is due to shale oil, tar sands etc. which is not the same type of oil that Hubbert used for his method. Tar sands and shale oil have a considerably lower EROI. Furthermore, even though the resource, if you include the new reserves, is large compared to the reserve Hubbert was working with, because EROI is so low, and because normal production cannot satisfy needs, driving up the price and production, the new resources run out much quicker than the oil Hubbert used in his prediction. Therefore the curve can be seen as two curves with two peaks, the second due to the new reserves.

Considering Hubbert's data, the curve he predicted with such accuracy looked different:

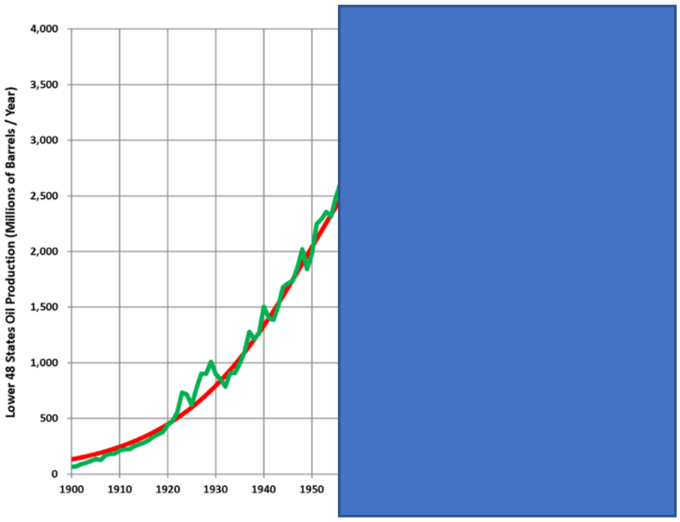


Figure 40 The data Hubbert had available in 1955 when he predicted the 1970 peak.

Method

To create a prediction of the future phosphorus situation and thereby the food availability, a global model was constructed using Stella 9.0. Because the scope of the model primarily was to look at the role of phosphorus, whenever assumptions was made due to either unavailable or uncertain data, the assumptions was made towards the optimistic.

The model looks at the timespan from 1950 to 2100.

Model

The model was built as simple as possible, using inductive logical arguments and abductive logical arguments, meaning that whenever data was not available, abductive reasoning was used.

The model was built around the soil phosphorus available to the plants, using a simple mass balance based on the beforementioned theory.

Three possible scenarios were run:

Scenario A: The reserve is 15 GT.

Scenario B: The reserve is 70 GT.

Scenario C: The reserve is 15 GT, and we immediately stop having livestock in the agriculture.

Iteration of Hubbert Curve to empirical data

An iteration of the Hubbert Curve against empirical USGS data was made in Excel, using Solver running an Evolutionary method. First, the reserve was calculated as a sum of the current cumulated production and the two different estimates of the current reserve, 15 Gt and 70 Gt. Then the Exponential Rate and the Peak Time was iterated with the objective set to maximize the correlation factor R^2. These numbers were used in the Stella model.

Sensitivity analysis

Normally, when making similar models, a sensitivity analysis is also made to get an estimate of the accuracy and precision of the model. This was deliberately not done in this case. First of all the reserve data are highly questionable, and secondly the intention with the model is not to come up with an precise estimate, only to show the development of the system.

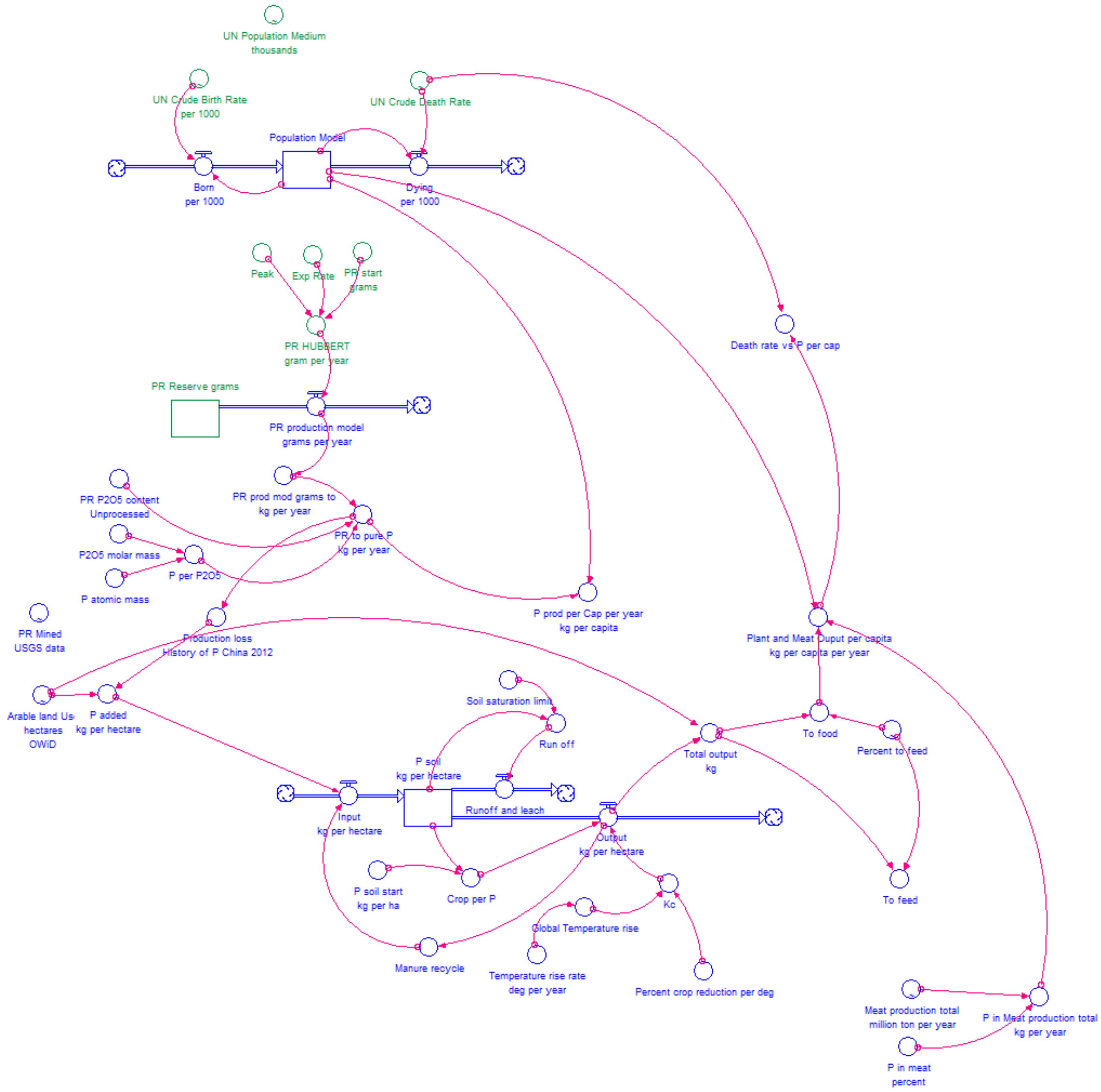


Figure 41 The model used

Model assumptions

The future agricultural land area was assumed to be constant. This does not include deforestation, or climate change caused reduction of the area due to desertification or rising sea levels.

The average global phosphorus content of the soils were estimated to 50 kg per hectare.

The population was assumed to follow the UN medium prognosis. Increasing death rate caused by starvation was not included in the model. Instead the model output is the amount of phosphorus available per capita in plant food and meat.

The meat production was assumed to continue its current growth, due to increasing living standards.

It was assumed that the crop yield was proportional to the phosphorus content of the soil, meaning that phosphorus was considered the primary limiting factor of the plant growth.

A global average soil saturation limit of 700 kg per hectare was assumed.

The amount of phosphorus in the harvest was assumed to be 0.2% in meat.

The meat production was assumed to be by pasture and forage. The amount of plant harvest was assumed to be 2% in 1950, 30% in 2025 and 50% in 2100.

The production loss of phosphorus due to fertilizer production was assumed to be constant, equal to the numbers of the current Chinese fertilizer production.

It was assumed that we continue to use fossil energy because we have no alternatives that works on a global scale. This will cause the global temperature to rise and the crop yield to drop. The current temperature rate of 0.02 deg K per year was used. Also an optimistic linear reduction of the crop yield of 5% per deg K was assumed.

The amount of phosphorus recycled via manure was set to 30%, and a 1/10 ratio of feed+forage vs meat was assumed.

Results

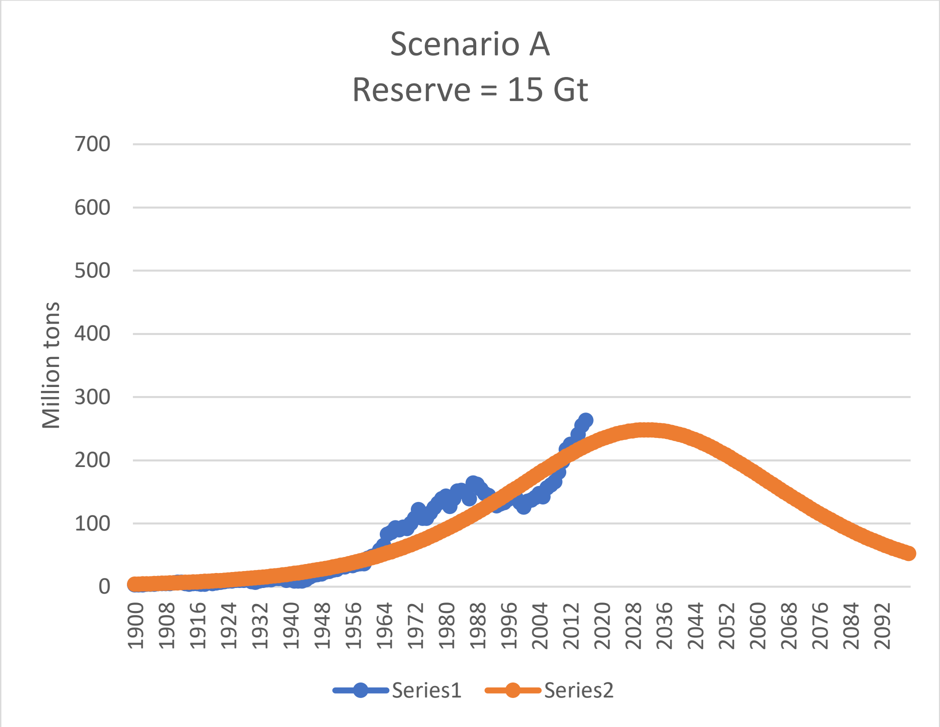


Figure 42 showing a 15 Gt scenario. Series 1 is empirical data. Series 2 is a fitted Hubbert curve. Correlation factor = 0.903.

Qmax	2.36E+10
exp rate	0.042055231
peak	132.7929223

R^2= 0.903841557

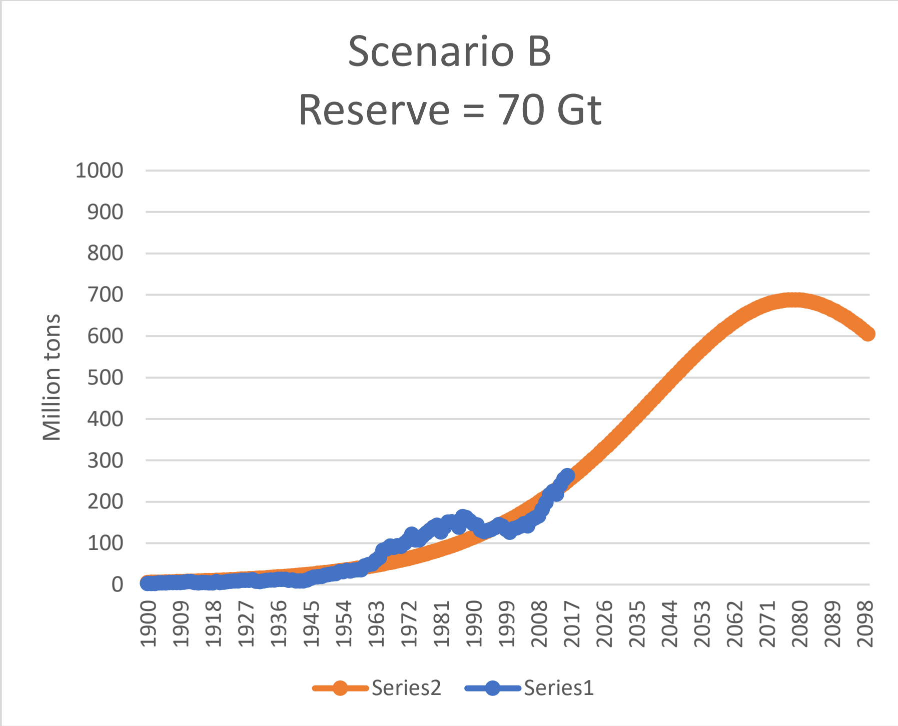


Figure 43 showing a 70 Gt scenario. Series 1 is empirical data. Series 2 is a fitted Hubbert curve. Correlation factor = 0.885.

Qmax	7.86E+10
exp rate	0.03501328
peak	179.3673358

R^2 = 0.884882239

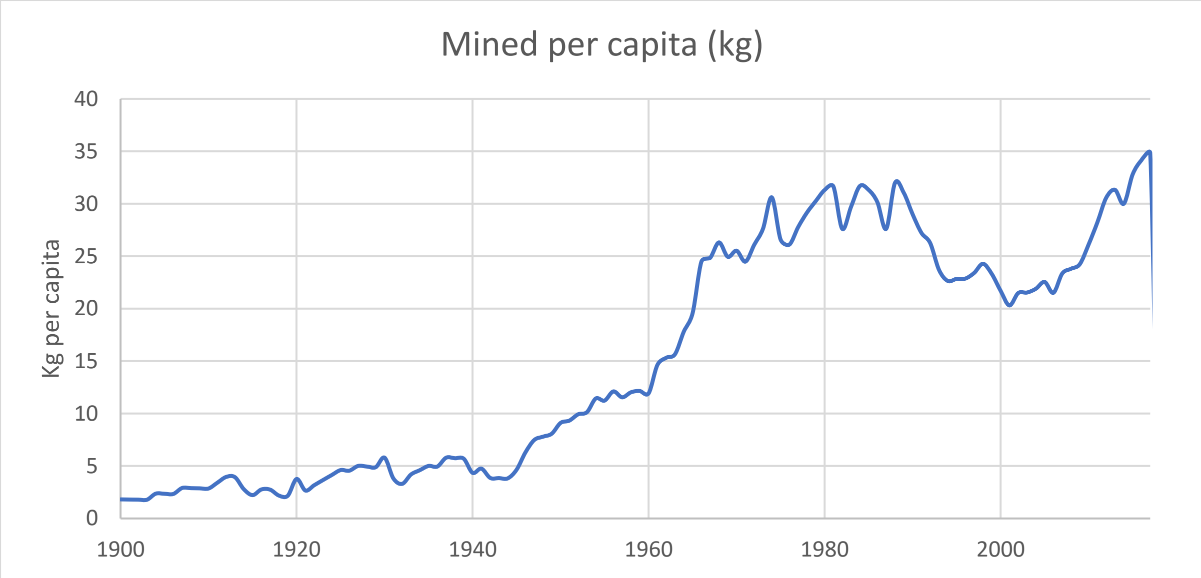


Figure 44 Phosphorus mined per capita

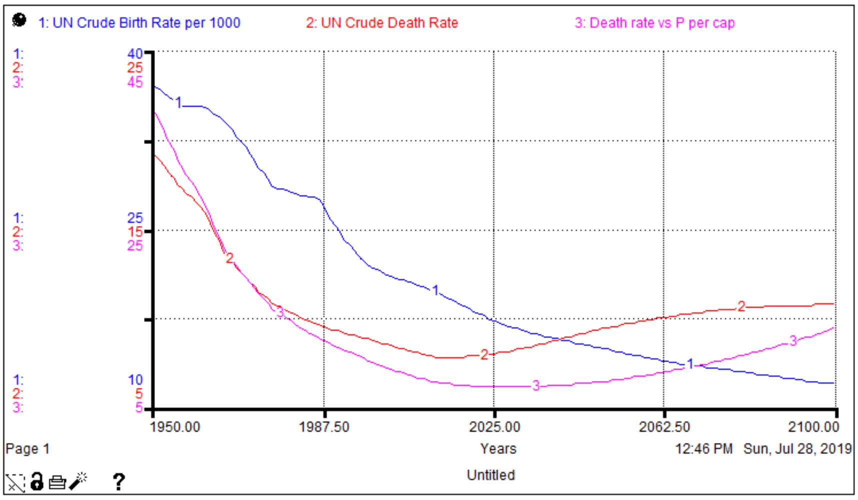


Figure 45 Correlation between reath rate and Phosphorus per capita

Scenario A 15 Gt

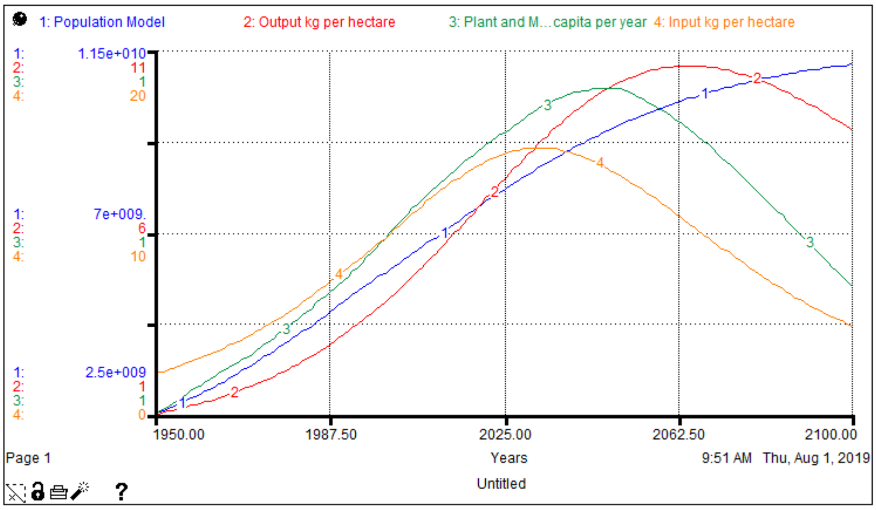


Figure 46 15 Gt scenario showing a peak in Phosphorus available to humans in 2046. (1: Population, 2: Phosphorus output per hectare, 3: Plant and Meat phosphorus per capita per year, 4: Phosphorus input per hectare)

Years	Population Model	Input kg per hectare	Output kg per hectare	Plant and Meat Ouput per capita kg per capita per year
1950	2536274721	2.258847	1	0.502942
1960	3035889613	3.149988	1.302053	0.568006
1970	3697152458	4.353146	1.737615	0.631096
1980	4437743335	5.911685	2.343577	0.708257
1990	5282923856	7.810343	3.153766	0.79255
2000	6078982740	9.920284	4.184202	0.900038
2010	6877836213	12.094994	5.422552	1.000472
2020	7699720252	13.812362	6.800312	1.086063
2030	8451609850	14.638513	8.169668	1.159299
2040	9113488928	14.35612	9.345772	1.208686
2050	9683626391	13.092627	10.166863	1.217139
2060	10149935874	11.428214	10.566746	1.163932
2070	10519372408	9.521064	10.562346	1.08433
2080	10809239918	7.693632	10.21293	0.987578
2090	11027853238	6.116961	9.613034	0.884204
2100	11181762331	4.839121	8.859913	0.782607

Scenario B 70 Gt

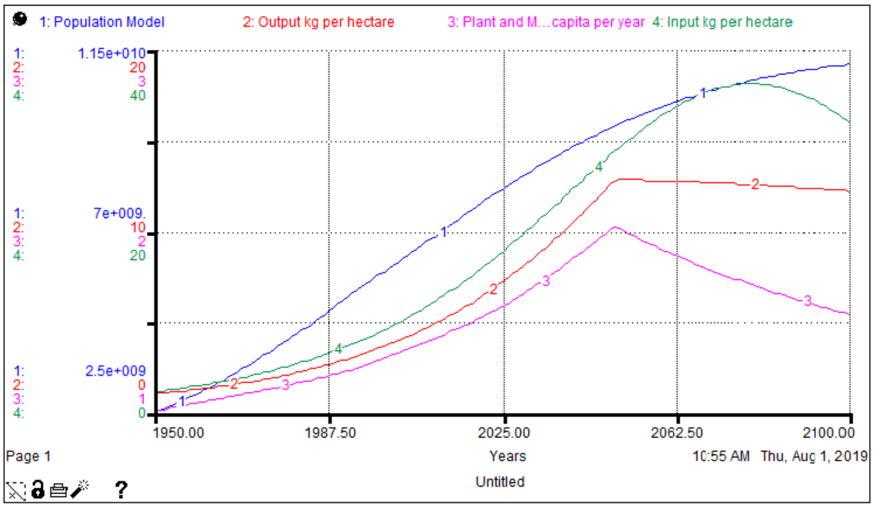


Figure 47 70 Gt scenario showing a peak in Phosphorus available to humans in 2050. (1: Population, 2: Phosphorus output per hectare, 3: Plant and Meat phosphorus per capita per year, 4: Phosphorus input per hectare)

Years	Population Model	Input kg per hectare	Output kg per hectare	Plant and Meat Ouput per capita kg per capita per year
1950	2536274721	2.238349	1	0.502942
1960	3035889613	2.987107	1.275218	0.557357
1970	3697152458	3.988037	1.650273	0.602522
1980	4437743335	5.314527	2.155178	0.656888
1990	5282923856	7.051169	2.827309	0.718018
2000	6078982740	9.285746	3.711121	0.806812
2010	6877836213	12.233351	4.866231	0.905812
2020	7699720252	15.854492	6.358243	1.020623
2030	8451609850	20.092848	8.230819	1.167368
2040	9113488928	24.729059	10.496782	1.347224
2050	9683626391	29.274259	12.88896	1.519794
2060	10149935874	33.092626	12.814805	1.392357
2070	10519372408	35.66167	12.720366	1.286605
2080	10809239918	36.424271	12.594632	1.194844
2090	11027853238	35.195872	12.434768	1.113296
2100	11181762331	32.248975	12.245773	1.039989

Scenario C 15 Gt, no livestock from 2020

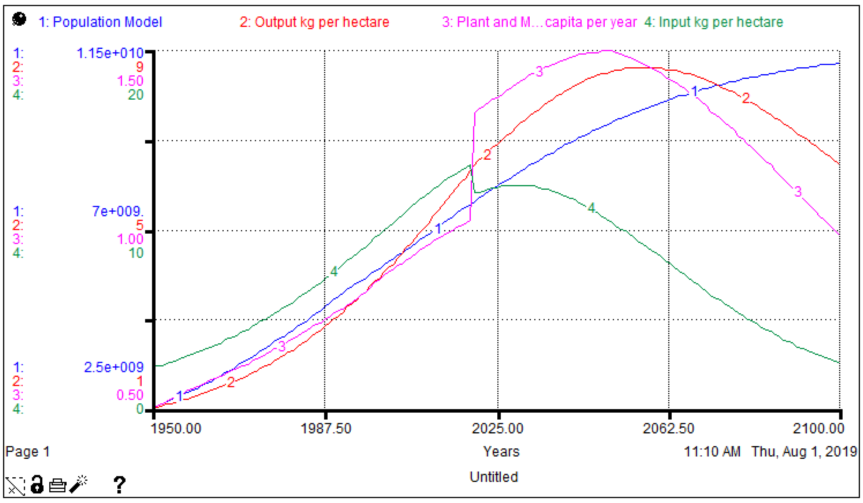


Figure 48 15 Gt scenario, without livestock from 2020, showing a peak in Phosphorus available to humans in 2048. (1: Population, 2: Phosphorus output per hectare, 3: Plant and Meat phosphorus per capita per year, 4: Phosphorus input per hectare)

Years	Population Model	Input kg per hectare	Output kg per hectare	Plant and Meat Ouput per capita kg per capita per year
1950	2536274721	2.258847	1	0.502942
1960	3035889613	3.146673	1.289773	0.563133
1970	3697152458	4.344736	1.706468	0.620906
1980	4437743335	5.895322	2.282976	0.691733
1990	5282923856	7.781877	3.048336	0.76848
2000	6078982740	9.874307	4.013917	0.866481
2010	6877836213	12.025252	5.164249	0.956521
2020	7699720252	11.976278	6.432201	1.324914
2030	8451609850	12.432703	7.358398	1.413936
2040	9113488928	11.832762	8.103406	1.477794
2050	9683626391	10.347575	8.535505	1.498443
2060	10149935874	8.575193	8.614846	1.44289
2070	10519372408	6.669231	8.374178	1.353322
2080	10809239918	4.936141	7.878499	1.239074
2090	11027853238	3.521442	7.216932	1.112527
2100	11181762331	2.446945	6.474215	0.984296

Discussion

All three scenarios show a peak in the amount of phosphorus available per capita. In all scenarios, the peak occurs around 2050. In Scenario A, (Reserve=15 Gt), the peak reaches a maximum of 1.2 kg P/cap, and then drops to 0.78 kg P/cap at the end of the century. In Scenario B (reserve=70Gt), the peak reaches a maximum of 1.51 kg P/cap, and 1.03 kg P/cap in2100.

In Scenario A, P/cap reaches 0.78 kg, or roughly the same level as 1990, where the undernourishment in developing countries were around 20% (37). This might not sound alarming, but the model does not predict the effect of lack of energy. If this follows Hubbert's predictions, we will se the oil production decline in the rest of the century, leading to a further reduction of the global production. If the oil production follows the Seneca Effect, this will delay the influence of energy on the food production, but it will also result in a steeper decline, once the oil production drops. Decreasing food production will cause the global death rate to rise, which will decrease the demand.

Scenario B shows a different development, where the food production levels out after 2050, due to phosphorus saturation of the available agricultural land, but the population is still rising, causing the P/cap to decrease. Combined with the energy problem, this still poses a serious threat to the food security. Another parameter that the model does not include is the effects of overfertilizing leading to runoff and leaching of phosphorus into rivers, lakes and oceans. This will rapidly increase once the soil gets saturated. Overfertilizing is still highly probable, because it might raise the crop yield slightly.

In all three scenarios irrigation was not included in the model. Global freshwater usage has increased from 1.23 trillion m^3 in 1950 to 3.99 trillion m^3 in 2014(38). However the curve has been leveling out in recent years. This might cause the actual production per capita to decrease drastically when the population grows.

All in all, the food security seems to be seriously challenged after 2050, and phosphorus is a major limiting factor on that. Therefore, much depends on the true size of the reserve. It is highly recommendable to verify the Moroccan reserve, and it is also important to ensure that production can be increased to follow the demand.

Food prices will increase as food production cannot follow the increasing demand caused by the increasing population.

The model also shows that there will not be much room left for biofuel production.

The Romanian economist Nicholas Georgescu-Roegen, who's theories is seen as a foundation of ecological economics, in his book "The Entropy Law and the Economic Process", proposed a world view, where resources are degraded by human activity, primarily based on the 2. Law of Thermodynamics (39).

Georgescu-Roegen was not a physicist, and he overinterpreted entropy somewhat, but the fact that Earth can be seen as a giant Carnot engine, and that human activity increases the entropy in the system, by reorganizing atoms using nonrenewable energy, seems to be a foundation of how the global system currently works. Combined with the declining NPP this should be at least as large a concern as global warming.

Conclusion

Does depletion of the phosphate rock resource pose a threat to Homo Sapiens, and if that is the case, what are the time scale?

It is highly likely that humanity will see a peak in phosphate rock production in this century. This is a problem considering that the population is expected to increase towards 2100 and even further.

When the peak will happen depends first and foremost on the true size of the Moroccan reserve. If the estimate has been too optimistic, then we will see a peak in the phosphate rock production around 2050, with a relatively steep decline after the peak. What consequences that will have highly depends on our behavior. The most likely scenario seems to be that hunger and starvation will rise, leading to an increased death rate. This in many cases leads to an increase in the birth rate. This is a positive feedback loop that will lead to an even higher death rate.

The World seen as a system is basically a large ball of rock in outer space covered with a biosphere going through evolution. The evolution has given us the ability to raise our carrying capacity, but it has not given us an understanding of how the system works.

The intensive farming we have developed to feed the population and the population growth that this has allowed, has painted us into a corner. If we give up intensive farming, we will not be able to feed everybody. If we want to continue the intensive farming, we will need to use fossil energy caused global warming leading to decreasing food production.

On top of that the inevitable peak in phosphorus production will become a major limiting factor together with the limited amount of land. Phosphorus has been used to turbo charge the production, and similarly removing that boost will be a serious problem with regards to the food security.

We cannot continue deforestation to gain more arable land. This will further increase the CO_2 level in the atmosphere. We cannot replace rising the fossil fuel driven transportation demand using energy from the Sun with the given technology and the limited amount of elementary resources we need for a transition towards electric cars.

It is very unpopular to state so, but it certainly seems like we are too many people, and that we have already reached a population size high above our real carrying capacity. Combined with a growth economy which is connected to using energy, this locks us in the development towards the future.

If there is one important number that everyone should focus on, it is the NPP. Primarily the one from the agriculture, but also globally, since the total biomass is dropping dangerously fast. We also need a global plan for how we use and distribute that NPP without fossil fuels, even though that will mean a harsh reduction of the average living standard.

The soil used for pasture could be used for vegetables, but it is used for pasture because it has low levels of nutrients. This includes phosphorus, which is currently being added to pasture soil. Also, a removal of the livestock would mean that no phosphorus was recycled through manure.

The IFDC report from 2010 states some obvious wrong numbers in their summary[13]. Among others they state that:

"Based on the data reviewed, and assuming current rates of production, phosphate rock concentrate reserves to produce fertilizer will be available for the next 300-400 years"

This assumes that future production will be constant. The important part of that being that the production has increased exponentially the last 100 years, following the population growth. Therefore, it is not correct to consider that the future consumption will be constant. Instead it will follow the logistic function and the derivate, the Hubbert Curve. IFDC nowhere states how they explain that.

Also the USGS does not have a proper reason for the increase in 2011. More research should be put into whether it was caused by the price spike in 2008 leading to the Moroccans building a new estimate on a higher price. It is important to understand that both geopolitical and economic interests are involved in these numbers.

Recycling is important. However, a 100% recycling is impossible. Therefore, we will lose phosphorus from runoff etc. every year.

I do not trust my model enough to come with certain predictions of a timescale, but that does not change the systems development. This is based on simple mass balances, and numbers everyone largely agree upon.

The development of the Earth system the last 200 years compared to the 4 billion years the biosphere has existed is like the blink of an eye (200 ms) compared to 46 days. In that small amount of time we have used roughly half the energy stored in crude oil, coal and natural gas.

Running out of any crucial element like phosphorus can influence the utility of other elements or parts of the total system. Without phosphorus we cannot currently make efficient solar cells. That means less access to solar energy.

Since phosphorus is a limiting parameter for plant growth and no phosphorus makes plant life as we know it impossible, and we can assume that anything above zero will facilitate an amount of life in the system, it is logical that close to zero availability would reduce the yield to close to zero, not matter how much you irrigate. This would also reduce the amount of energy spent and reduce the amount of energy spendable with utility.

With phosphorus we know that adding phosphorus to the soil, everything else equal, increase the yield roughly proportional up to a maximum level where erosion removes the phosphorus that is not absorbed by the soil. The is a maximum of theoretical yield set by the plant's ability to develop biomass. Summing up all the plants on earth there is a maximum theoretical yield with a given area and optimal growth conditions. We are somewhat able to manipulate that maximum yield using GMO's.

Perspectivation

Pasture land conversion to arable land

Conversion of pastureland into arable land seems like an obvious solution, since this removes a link in the food chain. However, most pastureland has a low soil phosphorus content, and therefore it needs to have phosphorus added before it can be used for growing crops. With phosphorus becoming sparse this is therefore not possible on a global scale.

Soil microbiology

In recent years, research has been done into the soil microbiology. It might be possible to use GMOs to enhance the conversion of organic phosphorus stored in the soil into inorganic phosphorus that can be used by the plants. Also it could be possible to enhance the fungi living in the vicinity of the plant roots, so that they will make more phosphorus accessible to the plants. However, this cannot solve the basic mass balance. If we increase the crop yield per hectare, we also remove more phosphorus from the soil, and we will have to add equal amounts of phosphorus in the form of fertilizer to avoid the soil phosphorus content to drop.

Toilets

It has been suggested to sperate human urine, with a high phosphorus content from the wastewater [8], using special toilets:

Figure 49 Different examples of urine diverting toilets [8]

Urine diversion is perhaps the most reasonable suggestion I have seen during my work with this thesis, as recycling is the only sustainable solution. There are however one major challenge involved with this. To keep the urine separated we will need an extra global sewer system. Considering all the other problems we face and have to deal with, and the fact that the current global sewer system is limited in many poor countries, it is not impossible to implement this solution globally, but it seems highly unlikely that this will be done. Also, even if we implemented such a solution, 100% recycling is almost never possible in real life applications.

Food vs Fuel

The idea about using agricultural land to produce biofuels conflict with the need to increase the food production needed for a growing population. Biofuels might be used efficiently for tractors and harvesters, if no other solution will be possible, but with the current energy demand biofuels is not a potential global energy source for transportation, heating etc.

Hydrogen

Hydrogen used as a fuel might be a way to store energy from the Sun, but we do not currently have a global hydrogen production that could satisfy the demand. Furthermore, it is uncertain whether we have the resources needed. Fuel cells use very limited elements. Finally, with regards to hydrogen, we need to consider that handling such large amounts of hydrogen will cause hydrogen leaking into the atmosphere, which could cause considerable problems with the ozone layer.

Insects as food

The idea about human food demand being covered by insects as food, does not work if the insects would be grown in farm like plants. An insect is not a primary producer, meaning that it will need energy from the primary producers to live. Instead a better solution is to eat the plants ourselves. Some insects are able to digest plants that humans cannot, such as termites, but it still does not solve the problem, because the NPP is decreasing at alarming rates.

Buy locally produced food

Distribution of food uses large amounts of energy. This should be minimized, by producing the food as close to the consumers as possible.

Ecological economy

The proper solution involves a global transition to a sustainable society with an ecological economy. This would first need a welly thought through total plan of how such a transition could be done, and we currently do not have anything ressembling that. The plan would have to be a combination of the current solutions we have, and it has to account for the system interconnections of the problems and sollutions. Otherwise we risk ending up with a not so great leap forward. Also everyone would have to agree and adapt to the plan. Humans have a history showing that something like that might be possible. We removed lead from gasoline and we stopped using CFC gasses. However the magnitude of the current problems is far larger than those previous problems.

References (Mendeley)

[1] L. Dziba, G. Erpul, A. Fazel, M. Fischer, and A. M. Hernández, “Summary for policymakers of the global assessment report on biodiversity and ecosystem services – unedited advance version Key messages,” *Ipbes Onu*, 2019.

[2] L. Sokka *et al.*, “A Life Cycle Assessment of Electricity Production from Hard Coal,” *Int. Min. Forum 2005, New Technol. Undergr. Mining, Saf. Sustain. Dev.*, pp. 13–24, 2010.

[3] I. Kubiszewski, C. J. Cleveland, and P. K. Endres, “Meta-analysis of net energy return for wind power systems,” *Renew. Energy*, vol. 35, no. 1, pp. 218–225, 2010.

[4] D. Production, B. Columbia, and N. T. Relations, “U.S. Geological Survey, Mineral Commodity Summaries, February 2019,” no. 703, pp. 2018–2019, 2018.

[5] Y. M. Bar-On, R. Phillips, and R. Milo, “The biomass distribution on Earth,” *Proc. Natl. Acad. Sci.*, vol. 115, no. 25, pp. 6506–6511, 2018.

[6] J. R. Schramski, D. K. Gattie, and J. H. Brown, “Human domination of the biosphere : Rapid discharge of the earth-space battery foretells the future of humankind,” vol. 112, no. 31, pp. 9511–9517, 2015.

[7] D. Production and N. T. Relations, “Phosphate rock,” no. 703, pp. 122–123, 2018.

[8] D. Cordell, J. O. Drangert, and S. White, “The story of phosphorus: Global food security and food for thought,” *Glob. Environ. Chang.*, vol. 19, no. 2, pp. 292–305, 2009.

[9] I. Opportunities and S. White, “Doomsday : Will Peak Phosphate Get us Before Global Warming ?,” pp. 1–6, 2014.

[10] D. P. Van Vuuren, A. F. Bouwman, and A. H. W. Beusen, “Phosphorus demand for the 1970-2100 period: A scenario analysis of resource depletion,” *Glob. Environ. Chang.*, vol. 20, no. 3, pp. 428–439, 2010.

[11] M. De Ridder, S. De Jong, J. Polchar, and S. Lingemann, *Risks and Opportunities in the Global Phosphate Rock Market: Robust Strategies in Times of Uncertainty*. 2012.

[12] L. Lodge, “A rock and a hard place - peak phosphorus and the threat to our food security,” *Br. J. Gen. Pract.*, vol. 63, no. 606, p. 11, 2013.

[13] S. J. Van Kauwenbergh, “World Phosphate Rock Reserves and Resources Technical Bulletin IFDC-T-75,” *Ifdc-T-75*, p. 48, 2010.

[14] D. Production, N. Carolina, and N. T. Relations, “Phosphate rock,” no. 703, pp. 2011–2012, 2011.

[15] D. Production, N. Carolina, and N. T. Relations, “Phosphate rock,” no. 703, pp. 2002–2003, 2010.

[16] J. D. Edixhoven, J. Gupta, and H. H. G. Savenije, “Recent revisions of phosphate rock reserves and resources: A critique,” *Earth Syst. Dyn.*, vol. 5, no. 2, pp. 491–507, 2014.

[17] D. Production and N. T. Relations, “Phosphate rock,” no. 703, pp. 2016–2017, 2018.

[18] B. Reuter, J. Riedl, A. M. Bradshaw, T. Hamacher, and M. Lienkamp, “Future Resource Availability for the Production of Lithium-Ion Vehicle Batteries,” *Proc. Conf. Futur. Automot. Technol. Munich, Ger.*, no. March, 2014.

[19] P.-F. Verhulst, “Notice sur la loi que la population poursuit dans son accroissement,” *Corresp.*

mathématique Phys., vol. 10, pp. 113–121, 1838.

[20] M. Schumack, "2006-657 : THE HUBBERT CURVE : ENABLING STUDENTS TO MEANINGFULLY MODEL ENERGY RESOURCE DEPLETION The Hubbert Curve : Enabling Students to," 2006.

[21] S. Daneshgar, A. Callegari, A. Capodaglio, and D. Vaccari, "The Potential Phosphorus Crisis: Resource Conservation and Possible Escape Technologies: A Review," *Resources*, vol. 7, no. 2, p. 37, 2018.

[22] J. Claerbout and F. Muir, "Hubbert math," *2008*, vol. 136, pp. 205–208, 2008.

[23] Lynch Michael C and L. M. C, "The new pessimism about petroleum resources," 2002.

References (Books, WWW, etc.)

(1) Harari, Yuval N. author. (2015). Sapiens : a brief history of humankind. New York :Harper,
(2) https://www.youtube.com/watch?v=e_VpyoAXpA8, Wednesday, August 7, 2019
(3) https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Thermodynamics/Fundamentals_of_Thermodynamics/A_System_and_Its_Surroundings, Wednesday, August 7, 2019
(4) http://data.un.org/Data.aspx?d=PopDiv&f=variableID%3A12, Wednesday, August 7, 2019
(5) https://ourworldindata.org/world-population-growth, Wednesday, August 7, 2019
(6) https://en.wikipedia.org/wiki/Sustainable_development, Wednesday, August 7, 2019
(7) https://en.wikipedia.org/wiki/Carnot_heat_engine#/media/File:Carnot_heat_engine_2.svg, Wednesday, August 7, 2019
(8) https://en.wikipedia.org/wiki/Carnot_heat_engine#/media/File:Carnot_heat_engine_2.svg, Wednesday, August 7, 2019
(9) https://en.wikipedia.org/wiki/Primary_production, Wednesday, August 7, 2019
(10) https://ourworldindata.org/yields-and-land-use-in-agriculture, Wednesday, August 7, 2019
(11) https://www.dst.dk/da/Statistik/nyt/NytHtml?cid=28083, Wednesday, August 7, 2019
(12) https://phys.org/news/2016-03-history-china-told-phosphorus.html, Wednesday, August 7, 2019
(13) https://www.youtube.com/watch?v=F4C3t4PuQqM, Wednesday, August 7, 2019
(14) https://ourworldindata.org/yields-and-land-use-in-agriculture, Wednesday, August 7, 2019
(15) https://en.wikipedia.org/wiki/Peak_phosphorus#/media/File:Phosphateproductionworldwide.svg, Wednesday, August 7, 2019
(16) https://en.wikipedia.org/wiki/Peak_phosphorus#/media/File:US_Mined_Phosphate_Rock_1900-2015.png, Wednesday, August 7, 2019
(17) https://en.wikipedia.org/wiki/Hubbert_curve#/media/File:Hubbert_curve.svg, Wednesday, August 7, 2019
(18) https://en.wikipedia.org/wiki/Hubbert_peak_theory, Wednesday, August 7, 2019
(19) https://inflationdata.com/articles/inflation-adjusted-prices/historical-crude-oil-prices-table/, Wednesday, August 7, 2019
(20) http://climateerinvest.blogspot.com/2018/02/us-monthly-crude-oil-production-exceeds.html, Wednesday, August 7, 2019
(21) https://www.agchemigroup.eu/es/blog/entrada/why-does-myth-global-phosphate-shortage-still-exist, Wednesday, August 7, 2019
(22) https://reflectionsofarationalrepublican.com/2011/03/08/debunking-peak-phosphorus/, Wednesday, August 7, 2019
(23) http://www.thecropsite.com/articles/1621/world-reserves-of-phosphate-rock-dynamic-unfolding-story/, Wednesday, August 7, 2019
(24) https://collapseofindustrialcivilization.com/tag/peak-phosphorus/, Wednesday, August 7, 2019
(25)https://www.indexmundi.com/commodities/?commodity=rock-phosphate&months=240, Wednesday, August 7, 2019
(26) https://www.eurekalert.org/pub_releases/2008-12/i-wfp121608.php, Wednesday, August 7, 2019
(27) https://www.tylervigen.com/spurious-correlations, Thursday, July 11, 2019

(28) https://www.e-education.psu.edu/earth104/node/1347, Thursday, July 11, 2019
(29) http://euanmearns.com/global-energy-forecast-to-2100/, Thursday, July 11, 2019
(30) https://www.resilience.org/stories/2018-03-12/the-world-oil-supply-is-infinite-i-know-that-because-i-believe-it/, Wednesday, August 7, 2019
(31) https://en.wikipedia.org/wiki/Seneca_effect, Wednesday, August 7, 2019
(32) https://en.wikipedia.org/wiki/Motor_vehicle, Wednesday, August 7, 2019
(33) http://energyskeptic.com/2019/utility-scale-energy-storage-has-a-long-way-to-go-to-make-renewables-possible/, Wednesday, August 7, 2019
(34) https://www.footprintnetwork.org/resources/data/, Wednesday, August 7, 2019
(35) http://www.ecocivilization.info/three-tons-carbon-dioxide-per-person-per-year.html, Wednesday, August 7, 2019
(36) https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions, Wednesday, August 7, 2019
(37) https://ourworldindata.org/hunger-and-undernourishment, Wednesday, August 7, 2019
(38) https://ourworldindata.org/grapher/global-freshwater-use-over-the-long-run, Wednesday, August 7, 2019
(39) https://en.wikipedia.org/wiki/Nicholas_Georgescu-Roegen, Wednesday, August 7, 2019
(40) https://www.nrv.gov.au/nutrients/phosphorus, Wednesday, August 7, 2019
(41) https://en.wikipedia.org/wiki/Hubbert_peak_theory, Wednesday, August 7, 2019
(42) https://www.youtube.com/watch?v=ImV1voi41YY, Wednesday, August 7, 2019

Appendix

Scenario A, 15 Gt, model equation

```
P_soil_kg_per_hectare(t) = P_soil_kg_per_hectare(t - dt) + (Input_kg_per_hectare -
Output_kg_per_hectare - Runoff_and_leach) * dt
INIT P_soil_kg_per_hectare = P_soil_start_kg_per_ha
 INFLOWS:
   Input_kg_per_hectare = P_added_kg_per_hectare+Manure_recycle
 OUTFLOWS:
   Output_kg_per_hectare = Crop_per_P*Kc
   Runoff_and_leach = Run_off
Population_Model(t) = Population_Model(t - dt) + (Born_per_1000 - Dying_per_1000) * dt
INIT Population_Model = init(UN_Population_Medium_thousands)*1000
 INFLOWS:
   Born_per_1000 = Population_Model*UN_Crude_Birth_Rate_per_1000/1000
 OUTFLOWS:
   Dying_per_1000 = Population_Model*(UN_Crude_Death_Rate/1000)
PR_Reserve_grams(t) = PR_Reserve_grams(t - dt) + (- PR_production_model_grams_per_year) * dt
INIT PR_Reserve_grams = PR_start_grams
 OUTFLOWS:
   PR_production_model_grams_per_year = PR_HUBBERT_gram_per_year
Crop_per_P = (P_soil_kg_per_hectare/P_soil_start_kg_per_ha)
Death_rate_vs_P_per_cap =
UN_Crude_Death_Rate/Plant_and_Meat_Ouput_per_capita_kg_per_capita_per_year
Exp_Rate = 0.042
Global_Temperature_rise = (TIME-1950)*Temperature_rise_rate_deg_per_year
Kc = (100-Global_Temperature_rise*Percent_crop_reduction_per_deg)/100
Manure_recycle = 0.3*0.9*Output_kg_per_hectare
P_added_kg_per_hectare =
Production_loss_History_of_P_China_2012/Arable_land_Use_hectares_OWiD
P_atomic_mass = 30.973
P_in_meat_percent = 0.2
P_in_Meat_production_total_kg_per_year =
Meat_production_total_million_ton_per_year*1e+06*1000*P_in_meat_percent/100
P_per_P2O5 = P_atomic_mass/P2O5_molar_mass*2
P_prod_per_Cap_per_year_kg_per_capita = PR_to_pure_P_kg_per_year/Population_Model
P_soil_start_kg_per_ha = 50
P2O5_molar_mass = 283.9/2
Peak = 2032
Percent_crop_reduction_per_deg = 5
Plant_and_Meat_Ouput_per_capita_kg_per_capita_per_year =
(To_food+P_in_Meat_production_total_kg_per_year)/Population_Model
PR_HUBBERT_gram_per_year = PR_start_grams * Exp_Rate  / (EXP( -Exp_Rate/2 * (Peak-TIME) ) +
EXP( Exp_Rate/2 * (Peak-TIME) ))^2
PR_P2O5_content_Unprocessed = 0.3
PR_prod_mod_grams_to_kg_per_year = PR_production_model_grams_per_year/1000
PR_start_grams = 2.36e+16
PR_to_pure_P_kg_per_year =
PR_prod_mod_grams_to_kg_per_year*PR_P2O5_content_Unprocessed*P_per_P2O5
Production_loss_History_of_P_China_2012 = PR_to_pure_P_kg_per_year*(7549/12108)
Run_off = if P_soil_kg_per_hectare>Soil_saturation_limit then

P_soil_kg_per_hectare-Soil_saturation_limit

else

0
Soil_saturation_limit = 700
Temperature_rise_rate_deg_per_year = 0.02
To_feed = Total_output_kg*Percent_to_feed/100
To_food = Total_output_kg*(1-Percent_to_feed/100)
Total_output_kg = Output_kg_per_hectare*Arable_land_Use_hectares_OWiD
Arable_land_Use_hectares_OWiD = GRAPH(TIME)
(1950, 1.2e+009), (2000, 1.5e+009), (2050, 1.7e+009), (2100, 1.7e+009)

Meat_production_total_million_ton_per_year = GRAPH(TIME)
(1950, 40.0), (2000, 229), (2050, 420), (2100, 610)

Percent_to_feed = GRAPH(TIME)
(1950, 2.00), (2025, 30.0), (2100, 50.0)

PR_Mined_USGS_data = GRAPH(TIME)
(1950, 23.0), (1951, 24.0), (1952, 26.0), (1953, 27.0), (1954, 31.0), (1955, 31.0), (1956, 34.0), (1957,
33.0), (1958, 35.0), (1959, 36.0), (1960, 36.0), (1961, 45.0), (1962, 48.0), (1963, 50.0), (1964, 58.0),
(1965, 65.0), (1966, 83.0), (1967, 86.0), (1968, 93.0), (1969, 90.0), (1970, 94.0), (1971, 92.0), (1972,
100), (1973, 108), (1974, 122), (1975, 108), (1976, 108), (1977, 117), (1978, 125), (1979, 132), (1980,
139), (1981, 143), (1982, 127), (1983, 139), (1984, 151), (1985, 152), (1986, 149), (1987, 139), (1988,
164), (1989, 162), (1990, 154), (1991, 147), (1992, 144), (1993, 132), (1994, 128), (1995, 131), (1996,
133), (1997, 138), (1998, 145), (1999, 141), (2000, 133), (2001, 126), (2002, 135)...
UN_Crude_Birth_Rate_per_1000 = GRAPH(TIME)
(1950, 36.9), (1955, 35.4), (1960, 35.4), (1966, 34.0), (1971, 31.4), (1976, 28.5), (1981, 27.9), (1986,
27.4), (1991, 24.3), (1997, 22.0), (2002, 20.9), (2007, 20.3), (2012, 19.6), (2017, 18.6), (2022, 17.6),
(2028, 16.7), (2033, 16.1), (2038, 15.6), (2043, 15.2), (2048, 14.8), (2053, 14.4), (2059, 14.0), (2064,
13.6), (2069, 13.3), (2074, 13.1), (2079, 12.8), (2084, 12.5), (2090, 12.3), (2095, 12.0), (2100, 11.8)
UN_Crude_Death_Rate = GRAPH(TIME)
(1950, 19.1), (1955, 17.4), (1960, 16.1), (1966, 13.5), (1971, 12.0), (1976, 10.8), (1981, 10.1), (1986,
9.50), (1991, 9.10), (1997, 8.73), (2002, 8.37), (2007, 7.99), (2012, 7.71), (2017, 7.70), (2022, 7.79),
(2028, 7.99), (2033, 8.27), (2038, 8.62), (2043, 8.96), (2048, 9.28), (2053, 9.55), (2059, 9.79), (2064,
9.99), (2069, 10.2), (2074, 10.3), (2079, 10.5), (2084, 10.6), (2090, 10.6), (2095, 10.6), (2100, 10.7)
UN_Population_Medium_thousands = GRAPH(TIME)
(1950, 2.5e+006), (1951, 2.6e+006), (1952, 2.6e+006), (1953, 2.7e+006), (1954, 2.7e+006), (1955,
2.8e+006), (1956, 2.8e+006), (1957, 2.9e+006), (1958, 2.9e+006), (1959, 3e+006), (1960, 3e+006),
(1961, 3.1e+006), (1962, 3.1e+006), (1963, 3.2e+006), (1964, 3.3e+006), (1965, 3.3e+006), (1966,
3.4e+006), (1967, 3.5e+006), (1968, 3.6e+006), (1969, 3.6e+006), (1970, 3.7e+006), (1971, 3.8e+006),
(1972, 3.9e+006), (1973, 3.9e+006), (1974, 4e+006), (1975, 4.1e+006), (1976, 4.2e+006), (1977,
4.2e+006), (1978, 4.3e+006), (1979, 4.4e+006), (1980, 4.5e+006), (1981, 4.5e+006), (1982, 4.6e+006),
(1983, 4.7e+006), (1984, 4.8e+006), (1985, 4.9e+006), (1986, 5e+006), (1987, 5.1e+006), (1988,
5.1e+006), (1989, 5.2e+006), (1990, 5.3e+006), (1991, 5.4e+006), (1992, 5.5e+006), (1993, 5.6e+006),
(1994, 5.7e+006), (1995, 5.8e+006), (1996, 5.8e+006), (1997, 5.9e+006), (1998, 6e+006), (1999,
6.1e+006), (2000, 6.1e+006), (2001, 6.2e+006), (2002, 6.3e+006)...
```

Scenario B, 70 Gt, model equation

```
P_soil_kg_per_hectare(t) = P_soil_kg_per_hectare(t - dt) + (Input_kg_per_hectare -
Output_kg_per_hectare - Runoff_and_leach) * dt
INIT P_soil_kg_per_hectare = P_soil_start_kg_per_ha
 INFLOWS:
   Input_kg_per_hectare = P_added_kg_per_hectare+Manure_recycle
 OUTFLOWS:
   Output_kg_per_hectare = Crop_per_P*Kc
   Runoff_and_leach = Run_off
Population_Model(t) = Population_Model(t - dt) + (Born_per_1000 - Dying_per_1000) * dt
INIT Population_Model = init(UN_Population_Medium_thousands)*1000
 INFLOWS:
   Born_per_1000 = Population_Model*UN_Crude_Birth_Rate_per_1000/1000
 OUTFLOWS:
   Dying_per_1000 = Population_Model*(UN_Crude_Death_Rate/1000)
PR_Reserve_grams(t) = PR_Reserve_grams(t - dt) + (- PR_production_model_grams_per_year) * dt
INIT PR_Reserve_grams = PR_start_grams
 OUTFLOWS:
   PR_production_model_grams_per_year = PR_HUBBERT_gram_per_year
Crop_per_P = (P_soil_kg_per_hectare/P_soil_start_kg_per_ha)
Death_rate_vs_P_per_cap =
UN_Crude_Death_Rate/Plant_and_Meat_Ouput_per_capita_kg_per_capita_per_year
Exp_Rate = 0.035013
Global_Temperature_rise = (TIME-1950)*Temperature_rise_rate_deg_per_year
Kc = (100-Global_Temperature_rise*Percent_crop_reduction_per_deg)/100
Manure_recycle = 0.3*0.9*Output_kg_per_hectare
P_added_kg_per_hectare =
Production_loss_History_of_P_China_2012/Arable_land_Use_hectares_OWiD
P_atomic_mass = 30.973
P_in_meat_percent = 0.2
P_in_Meat_production_total_kg_per_year =
Meat_production_total_million_ton_per_year*1e+06*1000*P_in_meat_percent/100
P_per_P2O5 = P_atomic_mass/P2O5_molar_mass*2
P_prod_per_Cap_per_year_kg_per_capita = PR_to_pure_P_kg_per_year/Population_Model
P_soil_start_kg_per_ha = 50
P2O5_molar_mass = 283.9/2
Peak = 2079
Percent_crop_reduction_per_deg = 5
Plant_and_Meat_Ouput_per_capita_kg_per_capita_per_year =
(To_food+P_in_Meat_production_total_kg_per_year)/Population_Model
PR_HUBBERT_gram_per_year = PR_start_grams * Exp_Rate  / (EXP( -Exp_Rate/2 * (Peak-TIME) ) +
EXP( Exp_Rate/2 * (Peak-TIME) ))^2
PR_P2O5_content_Unprocessed = 0.3
PR_prod_mod_grams_to_kg_per_year = PR_production_model_grams_per_year/1000
PR_start_grams = 7.86e+16
PR_to_pure_P_kg_per_year =
PR_prod_mod_grams_to_kg_per_year*PR_P2O5_content_Unprocessed*P_per_P2O5
Production_loss_History_of_P_China_2012 = PR_to_pure_P_kg_per_year*(7549/12108)
Run_off = if P_soil_kg_per_hectare>Soil_saturation_limit then

P_soil_kg_per_hectare-Soil_saturation_limit

else

0
Soil_saturation_limit = 700
Temperature_rise_rate_deg_per_year = 0.02
To_feed = Total_output_kg*Percent_to_feed/100
To_food = Total_output_kg*(1-Percent_to_feed/100)
Total_output_kg = Output_kg_per_hectare*Arable_land_Use_hectares_OWiD
Arable_land_Use_hectares_OWiD = GRAPH(TIME)
(1950, 1.2e+009), (2000, 1.5e+009), (2050, 1.7e+009), (2100, 1.7e+009)

Meat_production_total_million_ton_per_year = GRAPH(TIME)
(1950, 40.0), (2000, 229), (2050, 420), (2100, 610)

Percent_to_feed = GRAPH(TIME)
(1950, 2.00), (2025, 30.0), (2100, 50.0)

PR_Mined_USGS_data = GRAPH(TIME)
(1950, 23.0), (1951, 24.0), (1952, 26.0), (1953, 27.0), (1954, 31.0), (1955, 31.0), (1956, 34.0), (1957,
33.0), (1958, 35.0), (1959, 36.0), (1960, 36.0), (1961, 45.0), (1962, 48.0), (1963, 50.0), (1964, 58.0),
(1965, 65.0), (1966, 83.0), (1967, 86.0), (1968, 93.0), (1969, 90.0), (1970, 94.0), (1971, 92.0), (1972,
100), (1973, 108), (1974, 122), (1975, 108), (1976, 108), (1977, 117), (1978, 125), (1979, 132), (1980,
139), (1981, 143), (1982, 127), (1983, 139), (1984, 151), (1985, 152), (1986, 149), (1987, 139), (1988,
164), (1989, 162), (1990, 154), (1991, 147), (1992, 144), (1993, 132), (1994, 128), (1995, 131), (1996,
133), (1997, 138), (1998, 145), (1999, 141), (2000, 133), (2001, 126), (2002, 135)...
UN_Crude_Birth_Rate_per_1000 = GRAPH(TIME)
(1950, 36.9), (1955, 35.4), (1960, 35.4), (1966, 34.0), (1971, 31.4), (1976, 28.5), (1981, 27.9), (1986,
27.4), (1991, 24.3), (1997, 22.0), (2002, 20.9), (2007, 20.3), (2012, 19.6), (2017, 18.6), (2022, 17.6),
(2028, 16.7), (2033, 16.1), (2038, 15.6), (2043, 15.2), (2048, 14.8), (2053, 14.4), (2059, 14.0), (2064,
13.6), (2069, 13.3), (2074, 13.1), (2079, 12.8), (2084, 12.5), (2090, 12.3), (2095, 12.0), (2100, 11.8)
UN_Crude_Death_Rate = GRAPH(TIME)
(1950, 19.1), (1955, 17.4), (1960, 16.1), (1966, 13.5), (1971, 12.0), (1976, 10.8), (1981, 10.1), (1986,
9.50), (1991, 9.10), (1997, 8.73), (2002, 8.37), (2007, 7.99), (2012, 7.71), (2017, 7.70), (2022, 7.79),
(2028, 7.99), (2033, 8.27), (2038, 8.62), (2043, 8.96), (2048, 9.28), (2053, 9.55), (2059, 9.79), (2064,
9.99), (2069, 10.2), (2074, 10.3), (2079, 10.5), (2084, 10.6), (2090, 10.6), (2095, 10.6), (2100, 10.7)
UN_Population_Medium_thousands = GRAPH(TIME)
(1950, 2.5e+006), (1951, 2.6e+006), (1952, 2.6e+006), (1953, 2.7e+006), (1954, 2.7e+006), (1955,
2.8e+006), (1956, 2.8e+006), (1957, 2.9e+006), (1958, 2.9e+006), (1959, 3e+006), (1960, 3e+006),
(1961, 3.1e+006), (1962, 3.1e+006), (1963, 3.2e+006), (1964, 3.3e+006), (1965, 3.3e+006), (1966,
3.4e+006), (1967, 3.5e+006), (1968, 3.6e+006), (1969, 3.6e+006), (1970, 3.7e+006), (1971, 3.8e+006),
(1972, 3.9e+006), (1973, 3.9e+006), (1974, 4e+006), (1975, 4.1e+006), (1976, 4.2e+006), (1977,
4.2e+006), (1978, 4.3e+006), (1979, 4.4e+006), (1980, 4.5e+006), (1981, 4.5e+006), (1982, 4.6e+006),
(1983, 4.7e+006), (1984, 4.8e+006), (1985, 4.9e+006), (1986, 5e+006), (1987, 5.1e+006), (1988,
5.1e+006), (1989, 5.2e+006), (1990, 5.3e+006), (1991, 5.4e+006), (1992, 5.5e+006), (1993, 5.6e+006),
(1994, 5.7e+006), (1995, 5.8e+006), (1996, 5.8e+006), (1997, 5.9e+006), (1998, 6e+006), (1999,
6.1e+006), (2000, 6.1e+006), (2001, 6.2e+006), (2002, 6.3e+006)...
```

Scenario C 15 Gt, no livestock from 2020

```
P_soil_kg_per_hectare(t) = P_soil_kg_per_hectare(t - dt) + (Input_kg_per_hectare -
Output_kg_per_hectare - Runoff_and_leach) * dt
INIT P_soil_kg_per_hectare = P_soil_start_kg_per_ha
 INFLOWS:
   Input_kg_per_hectare = P_added_kg_per_hectare+Manure_recycle
 OUTFLOWS:
   Output_kg_per_hectare = Crop_per_P*Kc
   Runoff_and_leach = Run_off
Population_Model(t) = Population_Model(t - dt) + (Born_per_1000 - Dying_per_1000) * dt
INIT Population_Model = init(UN_Population_Medium_thousands)*1000
 INFLOWS:
   Born_per_1000 = Population_Model*UN_Crude_Birth_Rate_per_1000/1000
 OUTFLOWS:
   Dying_per_1000 = Population_Model*(UN_Crude_Death_Rate/1000)
PR_Reserve_grams(t) = PR_Reserve_grams(t - dt) + (- PR_production_model_grams_per_year) * dt
INIT PR_Reserve_grams = PR_start_grams
 OUTFLOWS:
   PR_production_model_grams_per_year = PR_HUBBERT_gram_per_year
Crop_per_P = (P_soil_kg_per_hectare/P_soil_start_kg_per_ha)
Death_rate_vs_P_per_cap =
UN_Crude_Death_Rate/Plant_and_Meat_Ouput_per_capita_kg_per_capita_per_year
Exp_Rate = 0.042
Global_Temperature_rise = (TIME-1950)*Temperature_rise_rate_deg_per_year
Kc = (100-Global_Temperature_rise*Percent_crop_reduction_per_deg)/100
Manure_recycle = if time<2020 then
0.3*0.9*Output_kg_per_hectare
else
0.3*0.9*Output_kg_per_hectare*0
P_added_kg_per_hectare =
Production_loss_History_of_P_China_2012/Arable_land_Use_hectares_OWiD
P_atomic_mass = 30.973
P_in_meat_percent = 0.2
P_in_Meat_production_total_kg_per_year = if time <2020 then
Meat_production_total_million_ton_per_year*1e+06*1000*P_in_meat_percent/100
else
Meat_production_total_million_ton_per_year*1e+06*1000*P_in_meat_percent/100*0
P_per_P2O5 = P_atomic_mass/P2O5_molar_mass*2
P_prod_per_Cap_per_year_kg_per_capita = PR_to_pure_P_kg_per_year/Population_Model
P_soil_start_kg_per_ha = 50
P2O5_molar_mass = 283.9/2
Peak = 2032
Percent_crop_reduction_per_deg = 5
Plant_and_Meat_Ouput_per_capita_kg_per_capita_per_year =
(To_food+P_in_Meat_production_total_kg_per_year)/Population_Model
PR_HUBBERT_gram_per_year = PR_start_grams * Exp_Rate  / (EXP( -Exp_Rate/2 * (Peak-TIME) ) +
EXP( Exp_Rate/2 * (Peak-TIME) ))^2
PR_P2O5_content_Unprocessed = 0.3
PR_prod_mod_grams_to_kg_per_year = PR_production_model_grams_per_year/1000
PR_start_grams = 2.36e+16
PR_to_pure_P_kg_per_year =
PR_prod_mod_grams_to_kg_per_year*PR_P2O5_content_Unprocessed*P_per_P2O5
Production_loss_History_of_P_China_2012 = PR_to_pure_P_kg_per_year*(7549/12108)
Run_off = if P_soil_kg_per_hectare>Soil_saturation_limit then

P_soil_kg_per_hectare-Soil_saturation_limit

else

0
Soil_saturation_limit = 700
Temperature_rise_rate_deg_per_year = 0.02
To_feed = Total_output_kg*Percent_to_feed/100
To_food = If time<2020 then
Total_output_kg*(1-Percent_to_feed/100)
else
Total_output_kg
Total_output_kg = Output_kg_per_hectare*Arable_land_Use_hectares_OWiD
Arable_land_Use_hectares_OWiD = GRAPH(TIME)
(1950, 1.2e+009), (2000, 1.5e+009), (2050, 1.7e+009), (2100, 1.7e+009)

Meat_production_total_million_ton_per_year = GRAPH(TIME)
(1950, 40.0), (2000, 229), (2050, 420), (2100, 610)

Percent_to_feed = GRAPH(TIME)
(1950, 2.00), (2025, 30.0), (2100, 50.0)

PR_Mined_USGS_data = GRAPH(TIME)
(1950, 23.0), (1951, 24.0), (1952, 26.0), (1953, 27.0), (1954, 31.0), (1955, 31.0), (1956, 34.0), (1957,
33.0), (1958, 35.0), (1959, 36.0), (1960, 36.0), (1961, 45.0), (1962, 48.0), (1963, 50.0), (1964, 58.0),
(1965, 65.0), (1966, 83.0), (1967, 86.0), (1968, 93.0), (1969, 90.0), (1970, 94.0), (1971, 92.0), (1972,
100), (1973, 108), (1974, 122), (1975, 108), (1976, 108), (1977, 117), (1978, 125), (1979, 132), (1980,
139), (1981, 143), (1982, 127), (1983, 139), (1984, 151), (1985, 152), (1986, 149), (1987, 139), (1988,
164), (1989, 162), (1990, 154), (1991, 147), (1992, 144), (1993, 132), (1994, 128), (1995, 131), (1996,
133), (1997, 138), (1998, 145), (1999, 141), (2000, 133), (2001, 126), (2002, 135)...
UN_Crude_Birth_Rate_per_1000 = GRAPH(TIME)
(1950, 36.9), (1955, 35.4), (1960, 35.4), (1966, 34.0), (1971, 31.4), (1976, 28.5), (1981, 27.9), (1986,
27.4), (1991, 24.3), (1997, 22.0), (2002, 20.9), (2007, 20.3), (2012, 19.6), (2017, 18.6), (2022, 17.6),
(2028, 16.7), (2033, 16.1), (2038, 15.6), (2043, 15.2), (2048, 14.8), (2053, 14.4), (2059, 14.0), (2064,
13.6), (2069, 13.3), (2074, 13.1), (2079, 12.8), (2084, 12.5), (2090, 12.3), (2095, 12.0), (2100, 11.8)
UN_Crude_Death_Rate = GRAPH(TIME)
(1950, 19.1), (1955, 17.4), (1960, 16.1), (1966, 13.5), (1971, 12.0), (1976, 10.8), (1981, 10.1), (1986,
9.50), (1991, 9.10), (1997, 8.73), (2002, 8.37), (2007, 7.99), (2012, 7.71), (2017, 7.70), (2022, 7.79),
(2028, 7.99), (2033, 8.27), (2038, 8.62), (2043, 8.96), (2048, 9.28), (2053, 9.55), (2059, 9.79), (2064,
9.99), (2069, 10.2), (2074, 10.3), (2079, 10.5), (2084, 10.6), (2090, 10.6), (2095, 10.6), (2100, 10.7)
UN_Population_Medium_thousands = GRAPH(TIME)
(1950, 2.5e+006), (1951, 2.6e+006), (1952, 2.6e+006), (1953, 2.7e+006), (1954, 2.7e+006), (1955,
2.8e+006), (1956, 2.8e+006), (1957, 2.9e+006), (1958, 2.9e+006), (1959, 3e+006), (1960, 3e+006),
(1961, 3.1e+006), (1962, 3.1e+006), (1963, 3.2e+006), (1964, 3.3e+006), (1965, 3.3e+006), (1966,
3.4e+006), (1967, 3.5e+006), (1968, 3.6e+006), (1969, 3.6e+006), (1970, 3.7e+006), (1971, 3.8e+006),
(1972, 3.9e+006), (1973, 3.9e+006), (1974, 4e+006), (1975, 4.1e+006), (1976, 4.2e+006), (1977,
4.2e+006), (1978, 4.3e+006), (1979, 4.4e+006), (1980, 4.5e+006), (1981, 4.5e+006), (1982, 4.6e+006),
(1983, 4.7e+006), (1984, 4.8e+006), (1985, 4.9e+006), (1986, 5e+006), (1987, 5.1e+006), (1988,
5.1e+006), (1989, 5.2e+006), (1990, 5.3e+006), (1991, 5.4e+006), (1992, 5.5e+006), (1993, 5.6e+006),
(1994, 5.7e+006), (1995, 5.8e+006), (1996, 5.8e+006), (1997, 5.9e+006), (1998, 6e+006), (1999,
6.1e+006), (2000, 6.1e+006), (2001, 6.2e+006), (2002, 6.3e+006)...
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