Limits to Consumption

By Bradley Jarvis

This paper presents an analysis of global consumption trends to determine what if any limits constrain consumption in the future.

The analysis indicates that, if current trends continue, in less than 10 years we will be forced to stop our annual increases in conversion of natural resources (primarily fossil fuels) into products and waste. Over the course of the next 20 years, we could face a drastic reduction in population. This corresponds closely to predictions of "peak oil."

Reducing our consumption rate would buy us some time. If in 2008 we decreased our annual consumption by 99% (effectively doing away with waste), the population would reach a maximum is less than 400 years and drop to zero less than 1,600 years after that.

Even if we go into space our rate of consumption will be limited, by how fast we can travel. For example, with a maximum speed of half the speed of light, an annual consumption increase of 2.5% could be sustained for less than 1,400 years and only a few tens of light years of distance. After the maximum speed is reached, the rate of increase will drop dramatically. If our maximum speed never gets higher than it is now, the rate will be forced to drop before we can even leave the Solar System.

This paper is divided into the following sections:

Assumptions

The analysis is based on several basic assumptions:

- "Consumption" is the total mass converted by humans from its natural state into another form. All such mass is interchangeable.
- In 1999, the average world citizen consumed over 100 tons per year, most of which was waste.
- In 1986, consumption exceeded the maximum amount that natural systems can reprocess.
- Population and consumption are interdependent, and the average person weighs 135 pounds.
- The average population of non-human species varies with consumption.
- The Gross World Product varies with consumption.
- Mass in interstellar space (out to the disk of the Galaxy) is distributed evenly.
- The amount of consumable mass in an average star system is the same as that for our Solar System.
- The maximum speed that can be attained is half the speed of light.

Humans convert raw material into various forms; this is the process of consumption. It includes mass discarded as waste as well as that which is converted into durable products. As an approximation, the material currently consumed is from the Earth's crust, and may be liquid, gas, or solid. Biomass (other than human) is considered as part of this. If we choose to bypass our current dependence on other biomass, such as for food and paper, we will presumably have the technology to utilize other materials, both here on Earth and on other planets, as well as asteroids and comets.

In 1999, Paul Hawken, Amory Lovins, and L. Hunter Lovins conservatively estimated that "Americans waste or cause to be wasted nearly 1 million pounds of materials per person per year." They further asserted that "Less than 2 percent of the total waste stream is actually recycled." [1] They gave multiple examples of how the mass wasted was a hundred or more times the amount actually used as end products.

How much did the average global citizen consume? One way to estimate this is to compare the ecological footprint of the U.S. to that of the world. The ecological footprint is a measure of the "human demand on nature" and "includes only those aspects of resource consumption and waste production that are potentially sustainable."[2] Based on data for 2001, the ratio of the World Ecological Footprint to the U.S. ecological footprint was about 0.2.[3] This fraction is consistent with comparisons of specific commodities.[4] An average world citizen therefore consumed about 100 tons per year.

According to the WWF, the Global Ecological Footprint exceeded the amount available in 1986.[5] For our purposes, this means that mass may have begun to accumulate at that time, rather than being processed into other usable forms by natural systems.

Since some part of consumption is necessary for survival, and since some of that consumption (such as pollution) may adversely impact the population, we expect consumption and population size to be interdependent.

Consumption is intimately tied to the economy. A key measure of the world economy is the total of the gross national products of every country, called the Gross World Product (GWP). We can therefore assume that the GWP varies with consumption.

To estimate the impact of consumption on other species, we can use the Living Planet Index (LPI). The LPI represents the size of a typical non-human population, and is periodically calculated by the WWF.[6] Since the mass we consume is typically not usable by other species, it tends to crowd out (and often actually poison) resources they need for their survival. We can therefore expect some correlation between the LPI and consumption.

The only sure way to continue growth of our species into the far future is to settle space, since Earth and the Sun have a fixed lifetime. The human presence in space may likely resemble a sphere whose radius increases over time, especially once we leave the Solar System. Stars in the disk of the Galaxy (out to several hundred light years) are distributed roughly uniformly. Locally, each star, its planets, asteroids, comets, and dust (collectively called a star system) occupies over 300 cubic light years. The mass of our Solar System, excluding the Sun, is less than one percent the mass of the Sun (*solar mass*); and of this mass, an unknown amount may be consumable.[7] For simplicity, our star system is considered average in terms of mass.

The speed of expansion of the sphere of human influence is a key to determining our overall consumption. Nature imposes a strict speed limit on everything in the Universe: the speed of light. The most anyone could hope to achieve is half this, both out of energy considerations and because it will take some time to locate and consume resources. Our fastest present speed is about 40 millionths of this.

Methodology

To identify consumption trends and their effects, the following steps are followed.

1. Annual consumption per person is set at the value in 1999.
2. An indicator with known time variation is selected that is believed to be proportional to annual consumption.
3. The indicator is scaled to the value of consumption in 1999. The result is a set of points that are considered to be the annual variation in consumption over time.
4. Values of annual variation are summed over time. The result is treated as the consumption curve (consumption as a function of time).
5. A least-mean-squares curve fit is used to derive an equation for the consumption curve.
6. The entire mass of the population is estimated for each point in time on the consumption curve. The result is the population mass curve.
7. The consumption curve is plotted against the population mass curve, and a least-mean-squares curve fit is used to derive an equation for population mass as a function of consumption.
8. The population mass is converted into human mass (alive and dead) and the result is added to the consumption mass that isn't being recycled by natural systems. The result is the total mass curve.
9. The consumption curve is plotted against values of the LPI, and a least-mean-squares curve fit is used to derive an equation for LPI as a function of consumption.
10. The consumption curve is plotted against values of the GWP, and a least-mean-squares curve fit is used to derive an equation for GWP as a function of consumption.

To explore the consumption of the Earth and of matter in space, the following additional steps are followed.

11. The density of the Earth as a function of depth is used to calculate the average depth associated with the total mass (consumption plus human mass).[8]
12. The average density (consumable mass per unit volume) of space is estimated and used to derive a distance associated with the total mass that is the radius of a sphere that would enclose that mass.
13. The speed of expansion is calculated as the change in radius per unit time as the sphere grows to encompass more mass.
14. The distance and time are calculated at the point the maximum speed is reached.
15. For time intervals after the maximum speed is reached, the increase in mass per unit time is used to determine the total mass.

Results

Following is a description of the results obtained with each step of the process.

Step 1: Setting Initial Consumption

The daily per capita world consumption was estimated to be 550 pounds in 1999, when the population was 6.00 billion people. Therefore the consumption for that year was $1.20 \cdot 10^{15}$ pounds.[9]

Step 2: Choosing an Indicator

Two potential indicators were considered: the Global Ecological Footprint ("footprint"), and the sum of non-fuel mineral production and fossil fuel consumption ("minerals plus fuel").[10] Of the two, the footprint was considered the most reliable, since it included a large number of consumable items, while the other indicator was used as a reality check. Indeed, both indicators tracked each other closely over time (see **Figure 1**). By all appearances, fossil fuel is driving everything else.

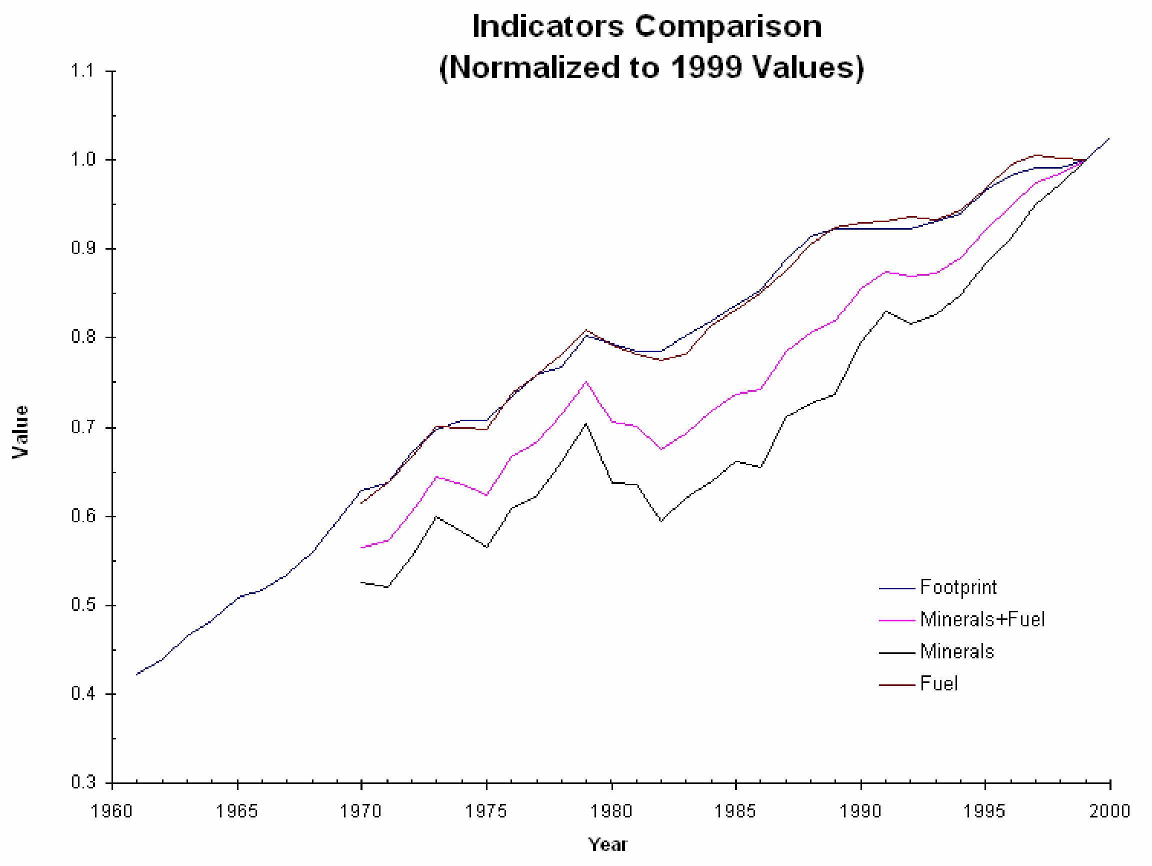

Figure 1: Indicators of consumption trends considered in the analysis, normalized to their values in 1999 (value in 1999 = 1.0). Actual values for 1999 are 0.62 (Footprint) and $3.46 \cdot 10^{13}$ lb

(Minerals+Fuel). Minerals+Fuel consists of (also plotted) $1.92 \cdot 10^{13}$ lb (Minerals) and $1.54 \cdot 10^{13}$ lb (Fuel).

Steps 3-5: Creating the Consumption Curve

The consumption curves for both indicators are shown in **Figure 2**. Since the earliest data for constructing the curve is for 1961, the zero value for the curve corresponds to the consumption in 1960.

For consumption based on the footprint, here are the curve fit coefficients:

X^6	X^5	X^4	X^3	X^2	X	X_0	Comment
					9.45E+14	-1.86E+18	**High Case**
				8.67E+12	-3.34E+16	3.22E+19	Not Valid
			-8.71E+10	5.26E+14	-1.06E+18	7.09E+20	Not Valid
		2.54E+09	-2.02E+13	6.03E+16	-8.00E+19	3.98E+22	Not Valid
	-6.41E+07	6.37E+11	-2.53E+15	5.04E+18	-5.01E+21	1.99E+24	Not Valid
-1.08E+07	1.28E+11	-6.33E+14	1.67E+18	-2.48E+21	1.96E+24	-6.48E+26	**Low Case**

To interpret these coefficients, note that the full 14-digit (to the right of the decimal) expression in blue found in **Figure 2** is the expression corresponding to the set of coefficients in the last row; this example is the "sixth-order curve fit" (named after highest exponent of the variable X found in the expression). The numbers in the row above it are the fifth order curve fit, and so on. Note that in this and other curve fits, the full 14-digit coefficients are used for projections.

Only the first-order and sixth-order curve fits are valid because for past years they tend to increase over time, as we would expect real consumption to have done. The first-order curve fit always increases, making it a "high case" approximation for consumption; that is, it has the highest future values. The sixth-order curve fit decreases in the future, which qualifies it as the "low case" approximation.

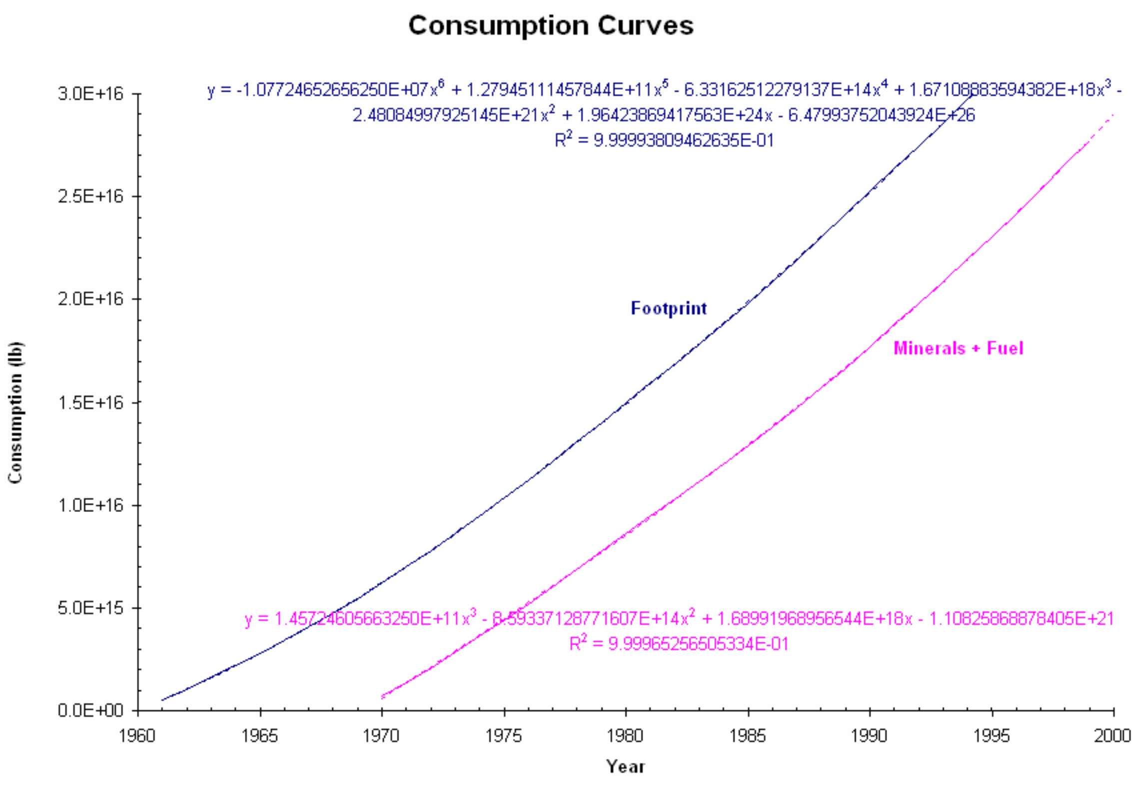

Figure 2: Consumption curves, based on the footprint and minerals plus fuel, plotted over time. Solid lines are values and dotted lines are curve fits.

Steps 6-7: Consumption vs. Population Mass

The amount of mass used by humans includes both what we consume and the total mass of our population. To estimate the mass of humanity, we can multiply an average weight per person by the number of people.[11] Averaging standard weights (by height) gives a weight of 135 pounds.[12] The result is shown in **Figure 3**.

Plotting the consumption against human weight (**Figure 4**), several solutions emerge for the function describing the relationship between them. For consumption based on the footprint, here are the curve fit coefficients:

X^6	X^5	X^4	X^3	X^2	X	X_0	Comment
					1.10E-05	4.29E+11	**High Case**
				-7.36E-23	1.37E-05	4.15E+11	Increasing
			1.77E-39	-1.70E-22	1.51E-05	4.11E+11	Increasing
		-1.87E-55	1.55E-38	-4.94E-22	1.77E-05	4.06E+11	**Low Case**
	4.93E-72	-6.43E-55	3.05E-38	-6.99E-22	1.87E-05	4.05E+11	Increasing
5.38E-88	-5.49E-71	1.87E-54	-1.91E-38	-2.41E-22	1.70E-05	4.06E+11	Not Valid

To be a valid a curve fit, the projected values in the past should tend to increase. For the footprint, all but the sixth-order curve fit meet his criteria, and of these only one decreases in the future (see Low Case in the table above). Of the curve fits that increase into the future ("Increasing"), all except the first-order curve fit lead to an unrealistic ratio of population mass to consumption (see **Figure 5**).

For consumption based on minerals plus fuel, all curve fits except the third-order curve fit are valid. Unlike consumption based on the footprint, the majority of valid curve fits *decrease* in the future (second, fourth, and sixth order). This suggests that for the footprint, the decreasing curve fit is as valid as the increasing curve fits.

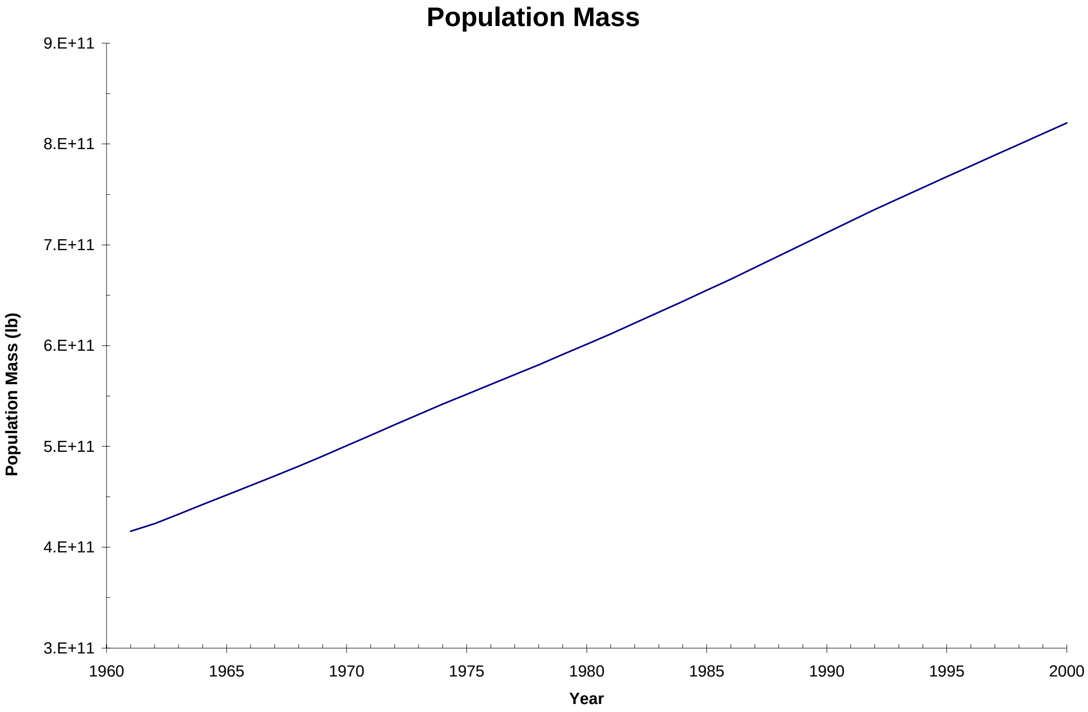

Figure 3: Population mass curve.

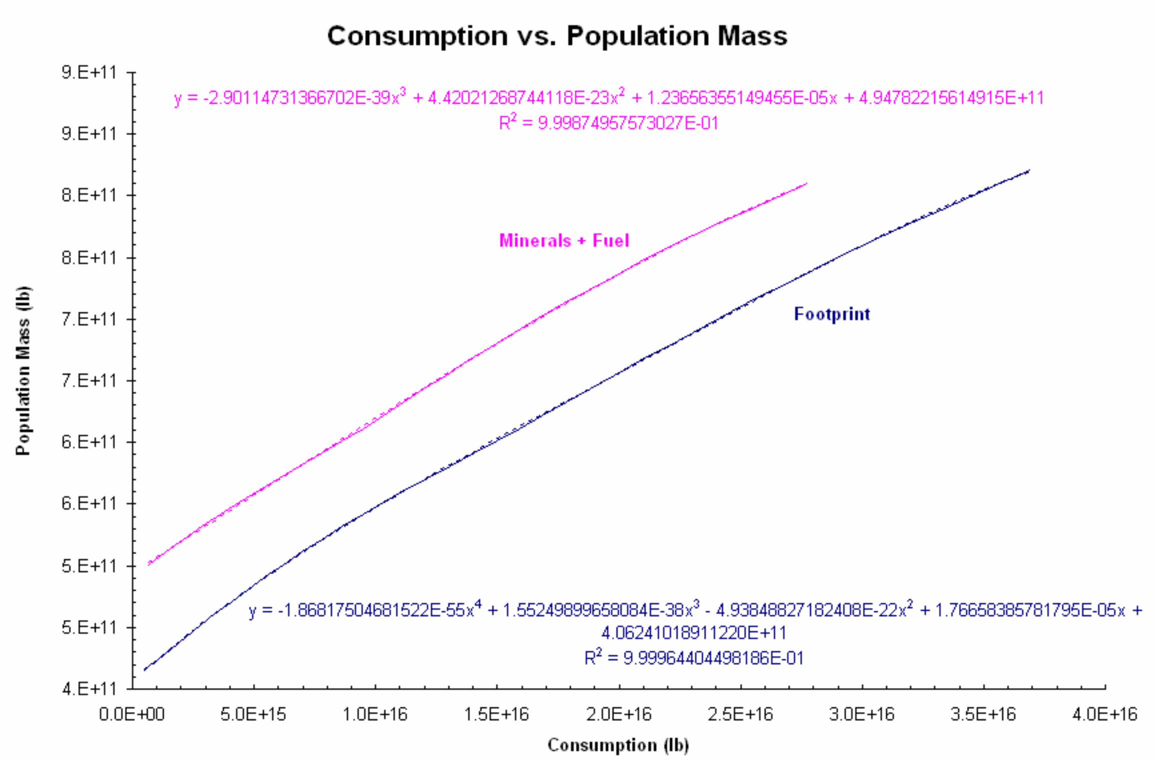

Figure 4: Curves (solid lines) and curve fits (dotted lines) for consumption vs. population mass.

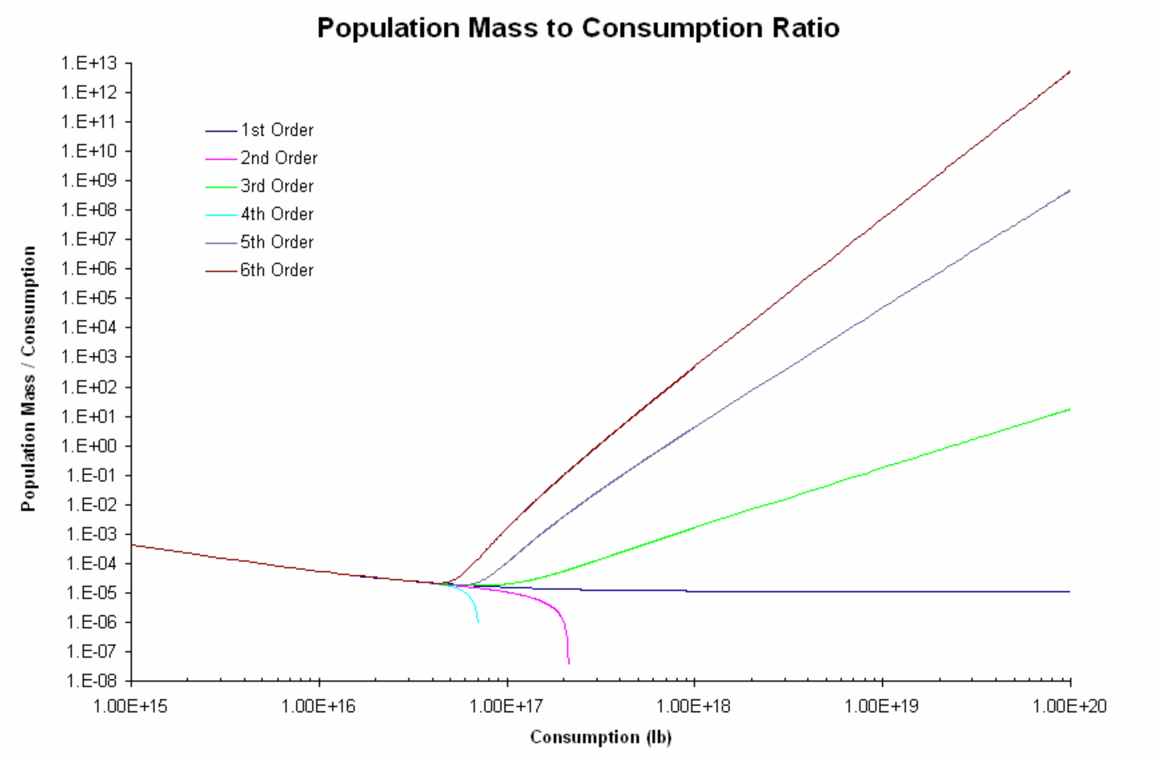

Figure 5: Ratio of population mass to consumption (based on the footprint) for each curve fit. Note that only the first-order, second-order, and fourth-order curve fits do not increase with consumption.

Step 8: Total Mass

Total mass consists of both the mass of material consumed and the mass of all humans, alive and dead.

Over the period 1965-2000, the ratio of deaths to the difference between births and deaths averaged about 0.6, fluctuating as shown in the table below.[13] To estimate the total human mass for a given year, the change in population mass from the previous year is multiplied by 1 + 0.6 = 1.6 and added to the previous year's total mass.

Year Range	Death Rate / (Birth Rate – Death Rate)
1965-1970	0.65
1970-1975	0.59
1975-1980	0.62
1980-1985	0.60
1985-1990	0.56
1990-1995	0.63
1995-2000	0.68

Because in 1986 the amount of consumed mass exceeded the annual amount that Earth's natural systems reprocess, mass began accumulating. This "unabsorbed mass" is the remaining part of the total mass. From the consumption curve (for the footprint), $1.03 \cdot 10^{15}$ pounds were consumed in 1986; this amount is assumed to be the amount of mass that Nature is annually reprocessing. Unabsorbed mass for any given interval is therefore:

Unabsorbed Mass = Consumption during the period – Processed Mass

Where:

Processed Mass = Number of years · ($1.03 \cdot 10^{15}$ pounds)

If the result of these calculations is below zero, unabsorbed mass is assumed to be zero. If the population is zero, then the total mass is assumed to be zero in the following year.

The total mass for 1961-2000 is shown in **Figure 6**.

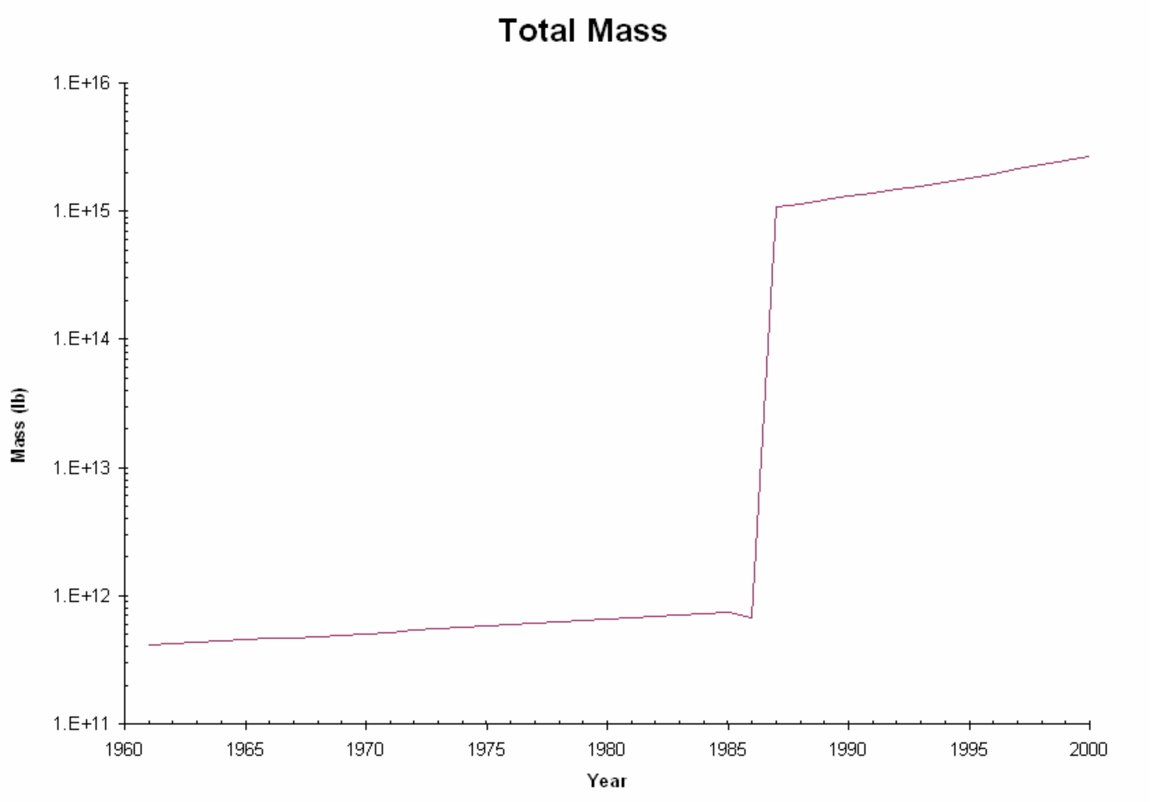

Figure 6: Total mass based on the footprint. The human mass is the only mass until the consumed mass exceeds Nature's ability to reprocess it, then the total mass includes the excess (less reprocessed mass) plus the human mass.

Step 9: Consumption vs. Living Planet Index

Consumption was plotted against the Living Planet Index, as shown in **Figure 7**. Curve fits were chosen based whether projections for times prior to the data range were decreasing or constant over time.

For consumption based on the footprint, here are the curve fit coefficients:

X^6	**X^5**	**X^4**	**X^3**	**X^2**	**X**	**X_0**	**Comment**
					-1.35E-17	1.16	**Low**
				-4.91E-34	7.32E-18	9.78E-01	Not Valid
			1.92E-51	- 6.14E-34	9.65E-18	9.66E-01	Not Valid
		1.06E-66	-8.93E-50	2.09E-33	-2.24E-17	1.09	**High**
	2.44E-82	-2.51E-65	9.68E-49	-1.77E-32	1.47E-16	5.69E-01	Not Valid
3.59E-99	-2.18E-82	-1.52E-66	3.61E-49	-9.48E-33	9.20E-17	7.08E-01	Not Valid

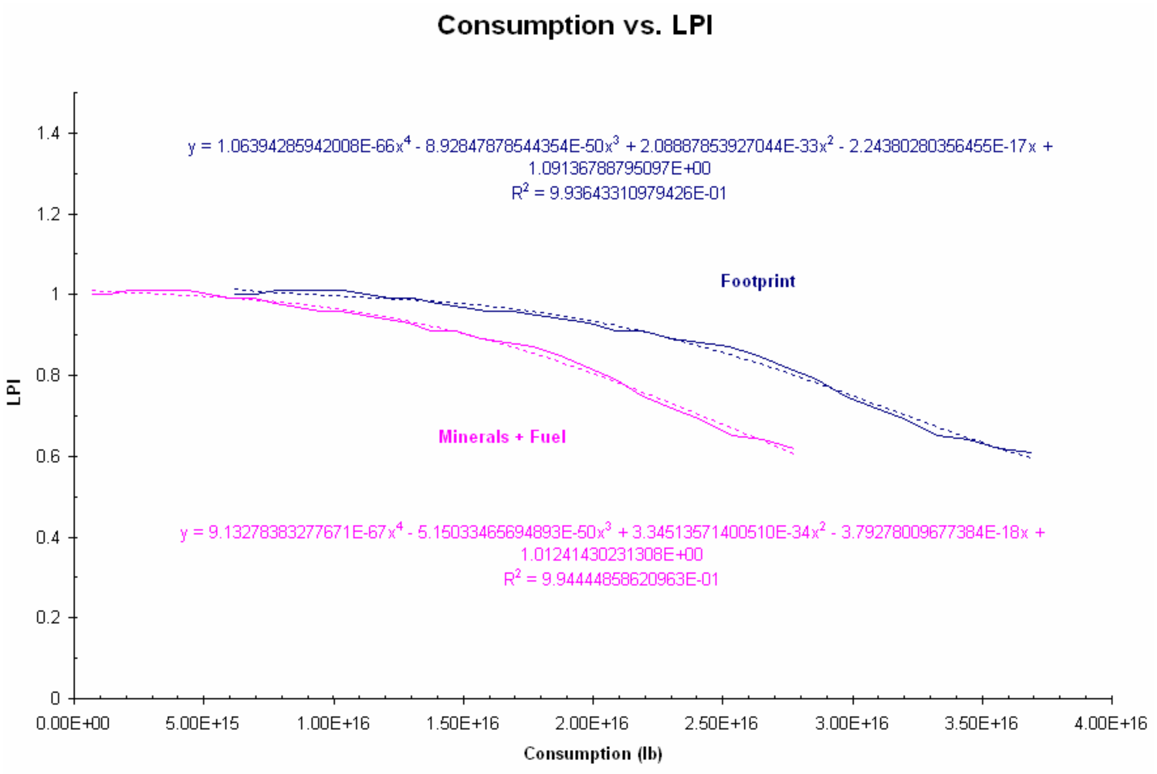

Figure 7: Consumption plotted against the Living Planet Index. Curves are solid lines and curve fits are dotted lines.

Step 10: Gross World Product

The curves are shown in **Figure 8**. Curve fits were chosen based on whether they increased in past years.

For minerals plus fuel, two curve fits meet the criterion: the third order and fifth order curve fits. For footprint, all but the fourth and sixth order curve fits meet the criterion.

For consumption based on the footprint, here are the curve fit coefficients:

X^6	X^5	X^4	X^3	X^2	X	X_0	Comment
					9.16E-16	1.15E+01	Valid
				-5.75E-34	9.36E-16	1.14E+01	**Low Case**
			4.96E-49	-2.77E-32	1.33E-15	1.03E+01	Valid
		3.61E-66	2.30E-49	-2.14E-32	1.27E-15	1.04E+01	Not Valid
	8.98E-82	-7.94E-65	2.95E-48	-5.89E-32	1.47E-15	1.01E+01	**High Case**
1.17E-97	-1.21E-80	4.66E-64	-7.80E-48	4.05E-32	1.10E-15	1.05E+01	Not Valid

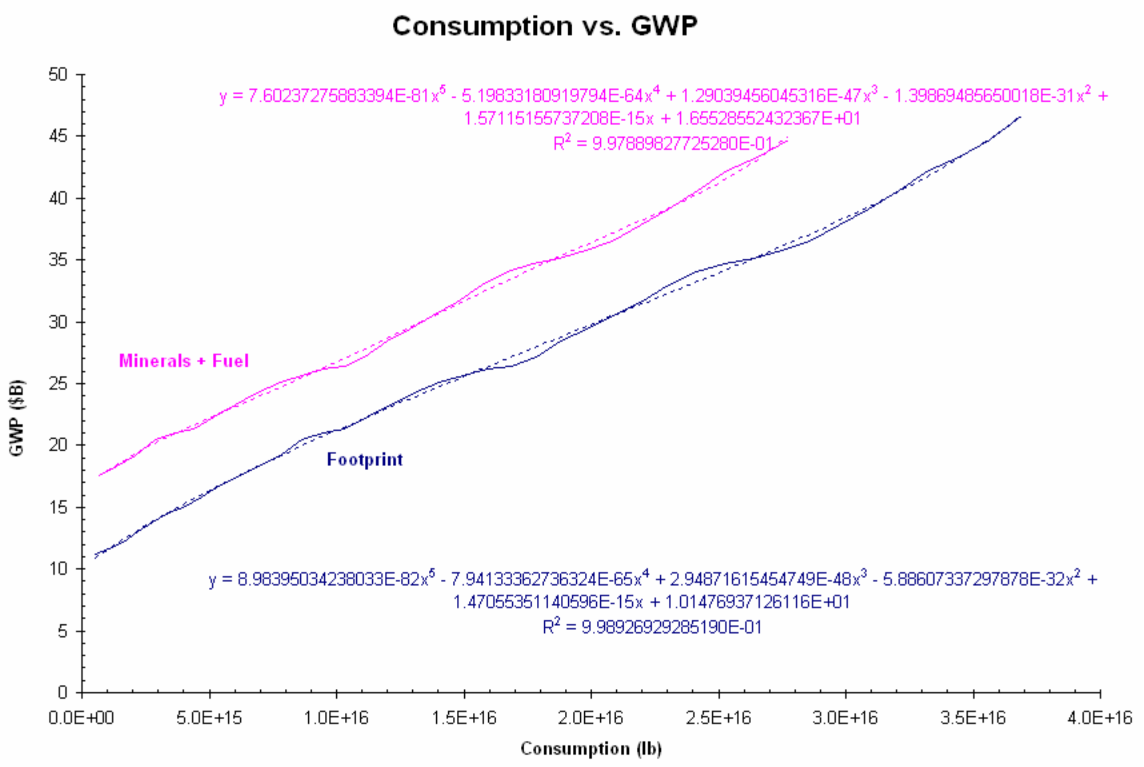

Figure 8: Consumption plotted against Gross World Product.

Step 11: Average Depth of Material

Using data for the expected density of material as a function of depth, the depth as a function of mass was calculated (see **Figure 9**).[14] Curve fits were done on the data to predict the depth for a given total mass. For example, to a depth 24 km (78,740 ft) the depth in feet for mass (M) was found to be:

$$9.43626164797753\text{E-}43\ M^2 + 5.96881627469352\text{E-}21\ M + 1165.50363132298$$

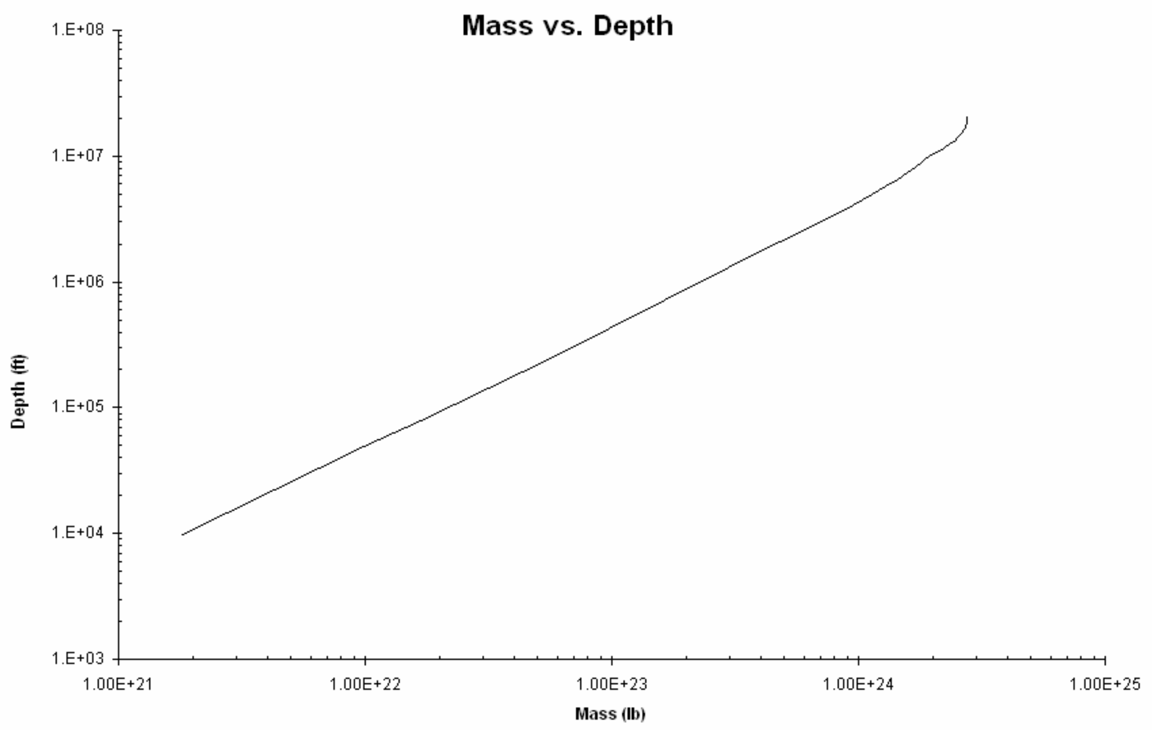

Figure 9: Depth as a function of total mass, moving inward from the surface of the Earth.

Steps 12-15: Spatial Limit of Growth

Given that the number of stars per cubic light year is 0.004 and that the consumable mass per star system is 0.01 solar mass, then the density is the product of these two numbers: $3.63 \cdot 10^{25}$ pounds per cubic light year. Growth was modeled as an expanding sphere.

For a constant growth rate *g* (percent divided by 100) in total mass, starting from a mass *M0* (in pounds) and growing until a maximum speed *Smax* (as a fraction of the speed of light) is reached, then with a density *Dmass* (pounds per cubic light year), the maximum time (*Tmax*, in years from the start) and distance *Rmax* (in light years) that the growth rate can be sustained is:

$$\mathrm{Tmax} := \frac{\ln\left(36 \cdot \mathrm{Dmass} \cdot \mathrm{Smax}^3 \cdot \frac{\pi}{\mathrm{M0} \cdot \ln(1+g)^3}\right)}{\ln(1+g)}$$

$$\mathrm{Rmax} := \frac{3}{\mathrm{Dmass}} \cdot \left(\mathrm{Dmass}^3 \cdot \frac{\mathrm{Smax}^3}{\ln(1+g)^3}\right)^{\frac{1}{3}}$$

These relationships are graphed in **Figure 10** and **Figure 11** for realistic values of the variables.

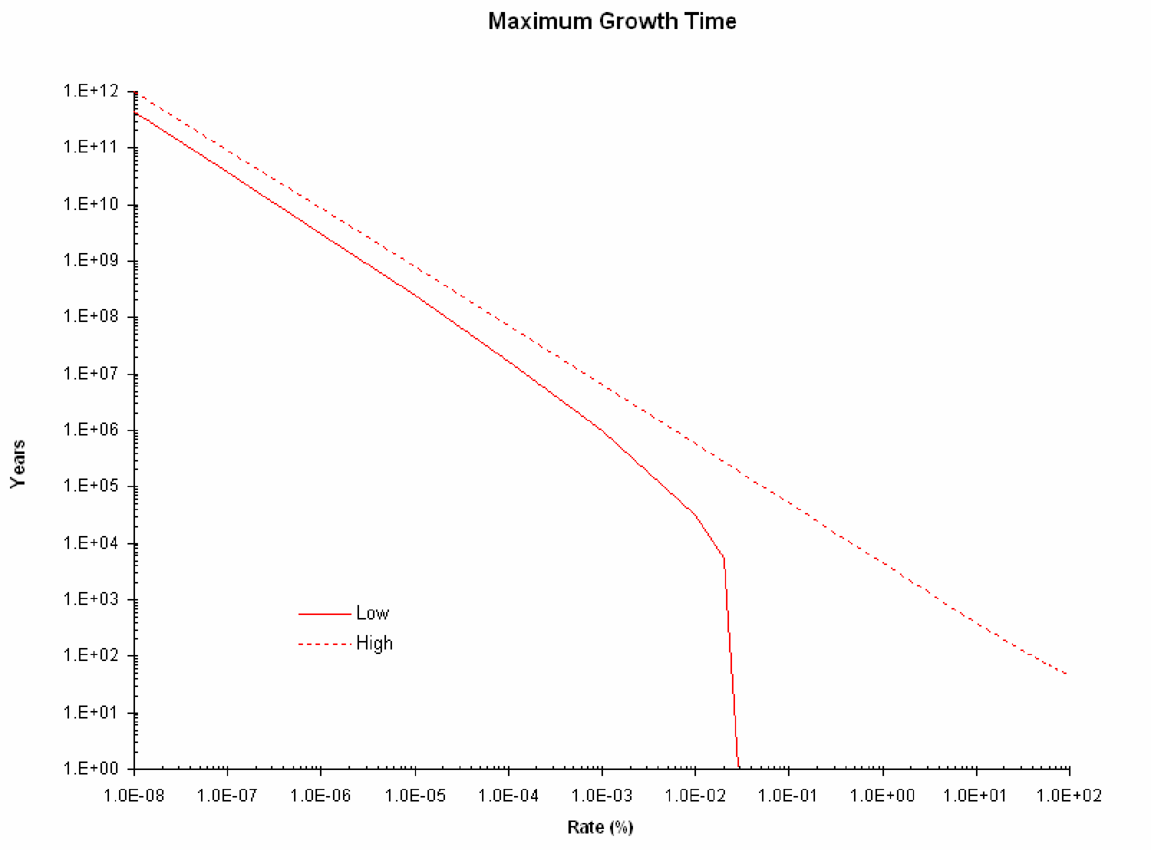

Figure 10: Maximum time that growth in total mass can be sustained at a constant annual rate of increase. The two curves bracket the possibilities. In the low case, the speed never exceeds the current amount, and the total mass per solar system is 1000 times the initial mass ($2.7 \cdot 10^{15}$ lb in 2000). In the high case, the density is the average density and the maximum speed is 0.5c (0.5 times the speed of light, c). Note that for the high case, the maximum growth time can be approximated by 1350/Rate. This approximation holds even if the starting mass is 1/100 of its assumed value.

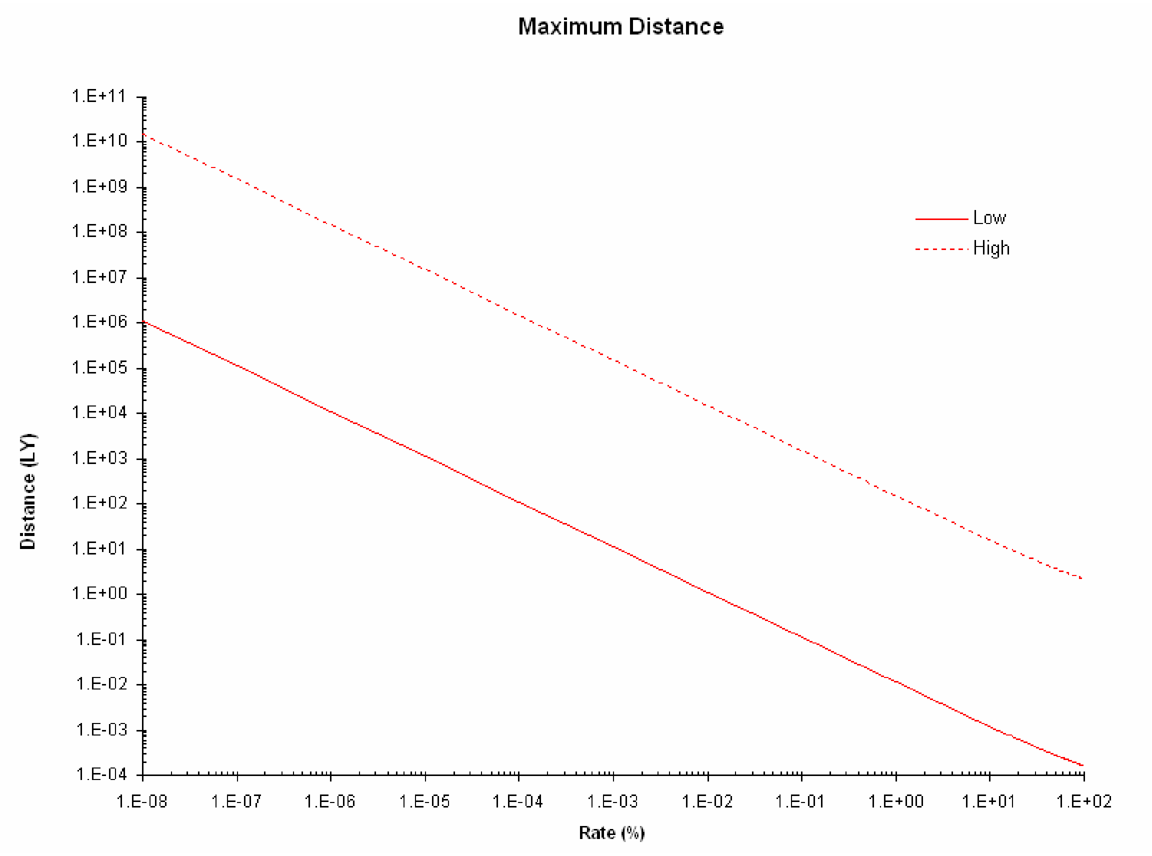

Figure 11: Maximum distance that growth in total mass can be sustained at a constant annual rate. Conditions are the same as in **Figure 10**. Note that the high case can be approximated by 180/Rate and the low case can be approximated by 1/(75·Rate). This approximation holds even if the starting mass is 1/100 of its assumed value.

Before the maximum speed is reached, the change in mass per unit time is

$$\frac{d}{dt}M0\,(1+g)^{t} = M0\cdot(1+g)^{t}\cdot\ln(1+g)$$

When the maximum speed is reached, the mass is

$$36\cdot\pi\cdot Dmass\cdot\frac{Smax^{3}}{\ln(1+g)^{3}} = Mmax$$

This applies where *Mmax* is greater than the initial mass.

After the maximum speed is reached, the total mass is

$$\frac{4}{3}\cdot\pi\cdot\left[\left[Rmax + Smax\,(t - Tmax)\right]^{3} - Rmax^{3}\right]\cdot Dmass + Mmax$$

The change in mass per unit time is therefore

$$\frac{d}{dt}\left[\frac{4}{3}\cdot\pi\cdot\left[\left[\,\mathrm{Rmax} + \mathrm{Smax}\cdot(t - \mathrm{Tmax})\,\right]^3 - \mathrm{Rmax}^3\right]\cdot\mathrm{Dmass} + \mathrm{Mmax}\right] = 4\cdot\pi\cdot\left[\,\mathrm{Rmax} + \mathrm{Smax}\cdot(t - \mathrm{Tmax})\,\right]^2\cdot\mathrm{Smax}\cdot\mathrm{Dmass}$$

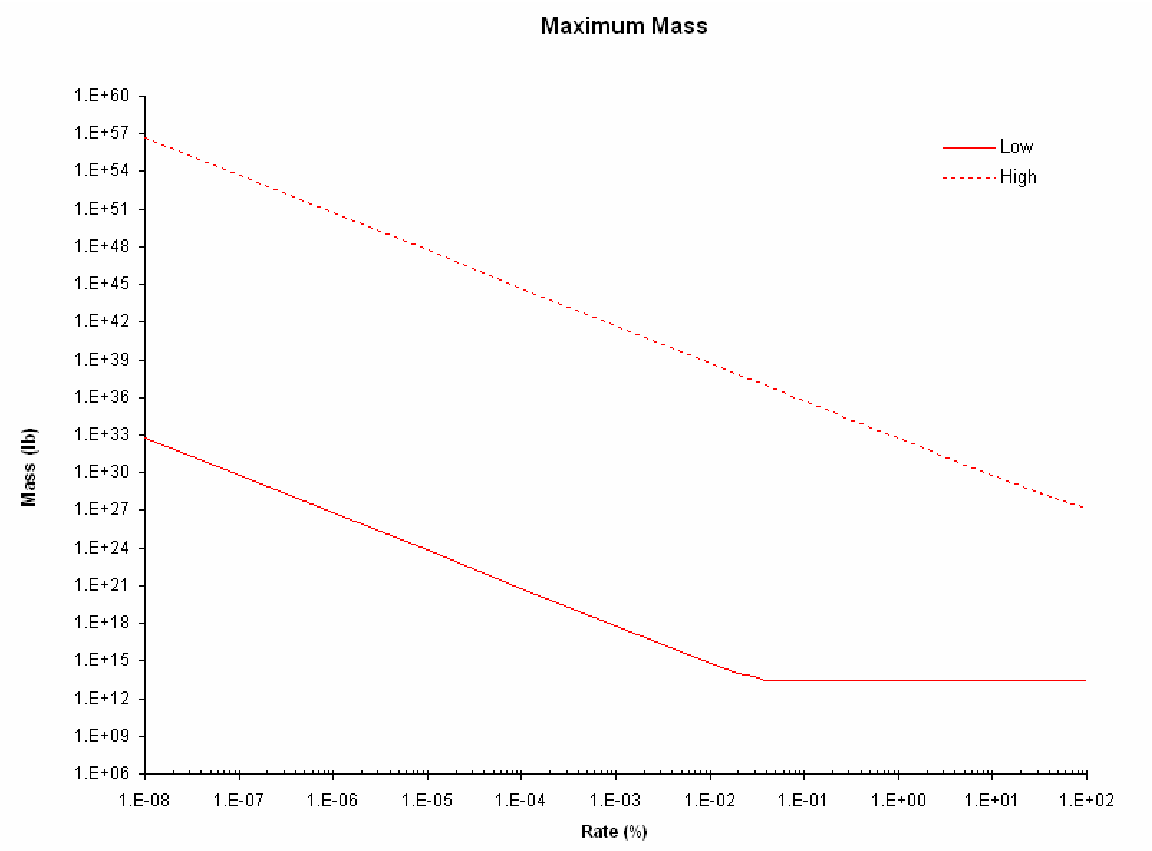

Figure 12: Maximum mass reached at a constant annual rate. Conditions are the same as in **Figure 10**. Note that the high case can be approximated by 10^{33} /Rate^3. This approximation holds even if the starting mass is 1/100 of its assumed value.

Other variables besides total mass that may include the settlement of space include population and GWP (LPI applies strictly to Earth).

To project population, the ratio of total mass to population mass was calculated for a total mass unmodified by speed. This ratio was then applied to the total mass modified by speed to calculate the speed-modified population mass. This new population mass divided by 135 pounds yielded the population.

To project GWP, new values were calculated for consumption using the speed-modified total mass and speed-modified population mass, along with the assumption that natural systems on Earth were the only ones reprocessing mass, at the same rate. The resulting speed-modified consumption was used with the relevant curve fit for GWP to project GWP.

Projections

The following sections discuss projections into the future for several conditions.

- *Low Case*: Incorporates the worst case curve fits.
- *High Case*: Incorporates the best case curve fits.
- *Combination*: Combination of low case and high case curve fits:
    - Consumption - Low case function is used.
    - Population Mass - Low case and high case functions are averaged.
    - LPI - Low case and high case functions are averaged.
    - GWP – Low case function is used.
- *Historical*: Actual values for past years.
- *Exponential Growth*: The low case projections for consumption are used until 2005, after which a constant annual growth rate of 2.51 % (the value projected by the low case for 2005) is applied to consumption. The high case curve fits for human weight and GWP as a function of consumption are used.
- *World3*: For comparison, projections from 2005 through 2070 are shown that are based on the business-as-usual scenario from theWorld3 model by Meadows, et al.[15]

To evaluate the reliability of the projections, **Figure 13**, **Figure 14** and **Figure 15** show well they do when used to predict data from past years.

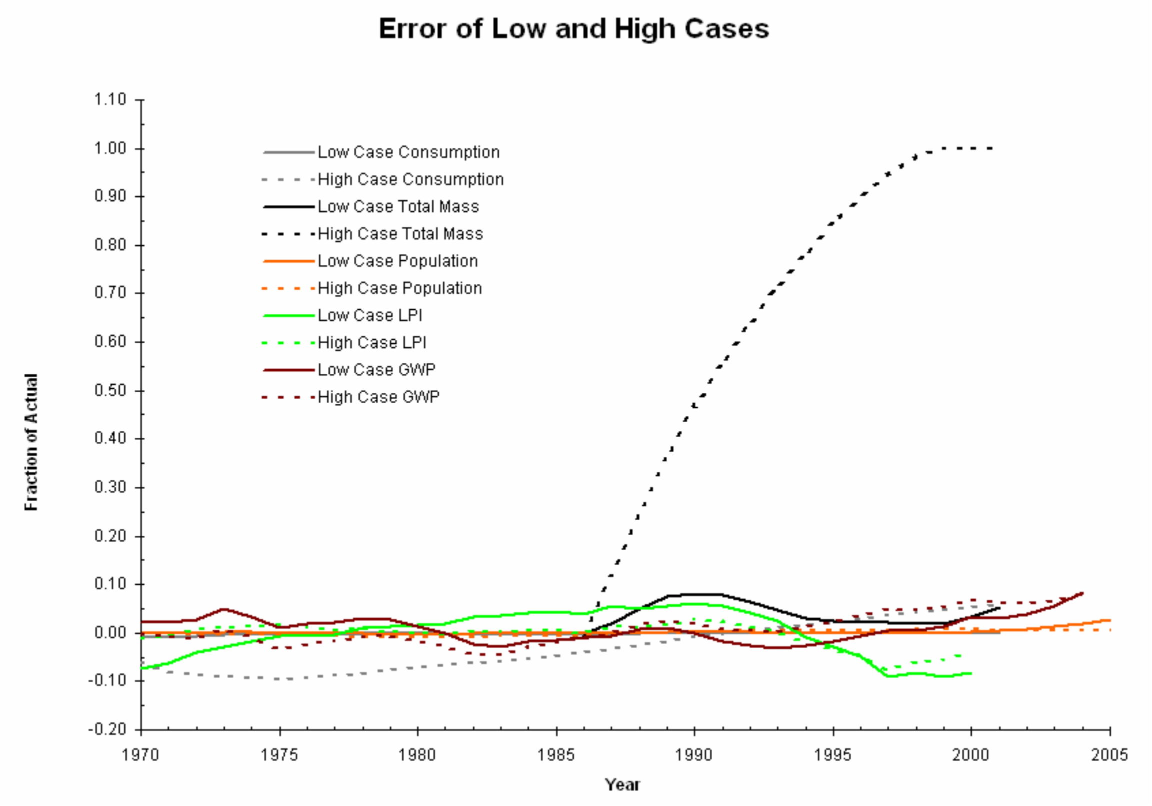

Figure 13: Historical error for the low case and high case.

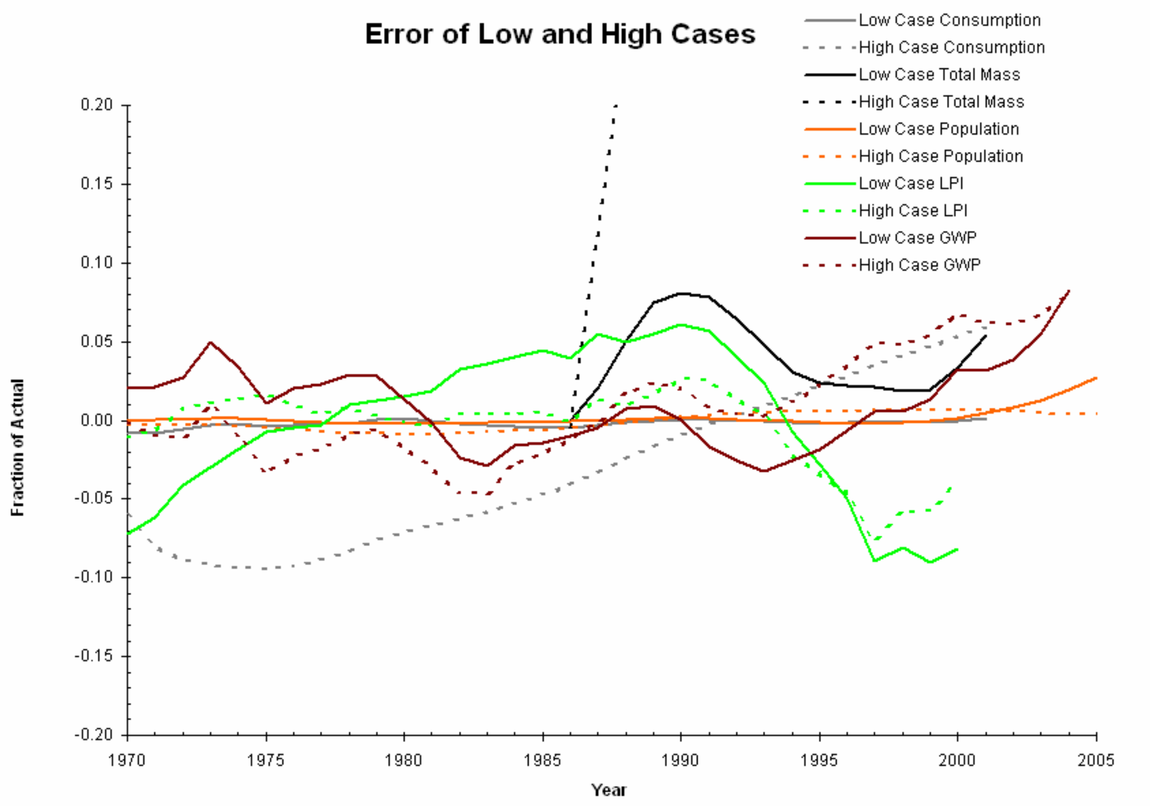

Figure 14: Historical error for the low case and high case (close up).

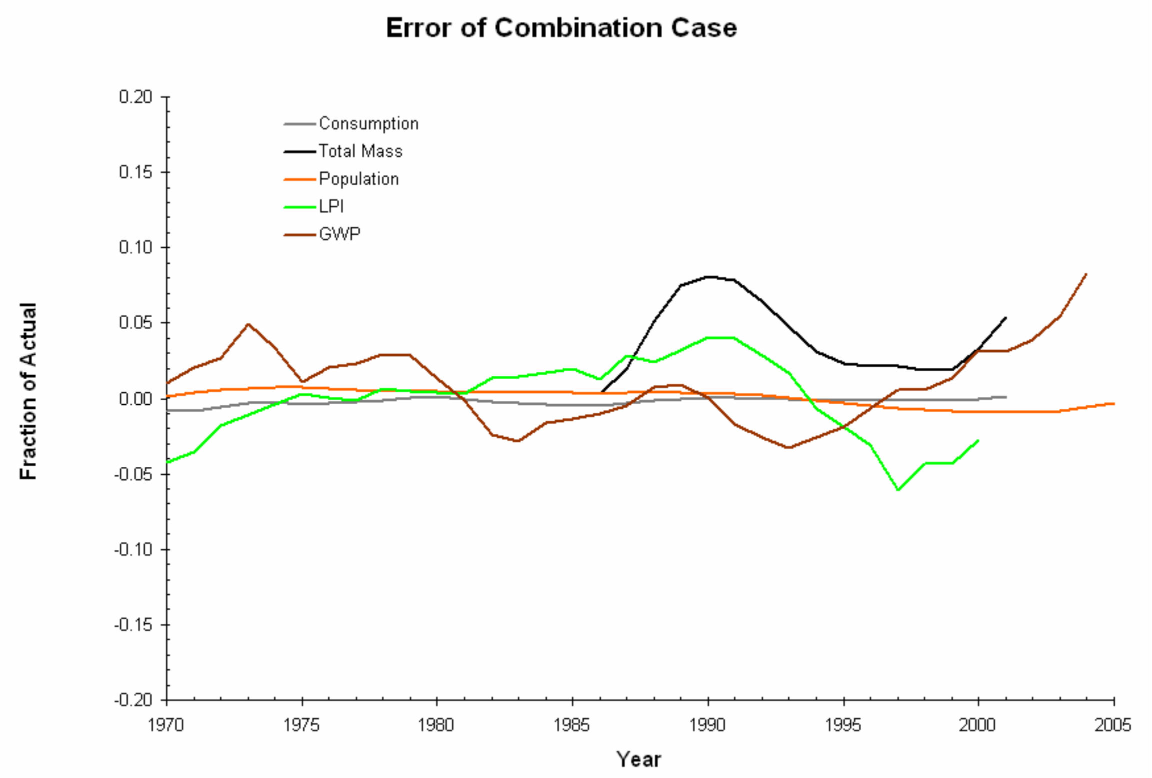

Figure 15: Historical error for the combination case.

Consumption Projection

Figure 16 and **Figure 17** show projections for consumption over the near-term and long-term, respectively.

The low case projects consumption to drop to zero (corresponding to its 1960 value) in 2026; while the high case grows steadily into the far future, approaching two quintillion pounds by the end of the next millennium.

Exponential growth could at best be maintained until the maximum speed was reached, which under the most optimistic conditions would be in 3390.

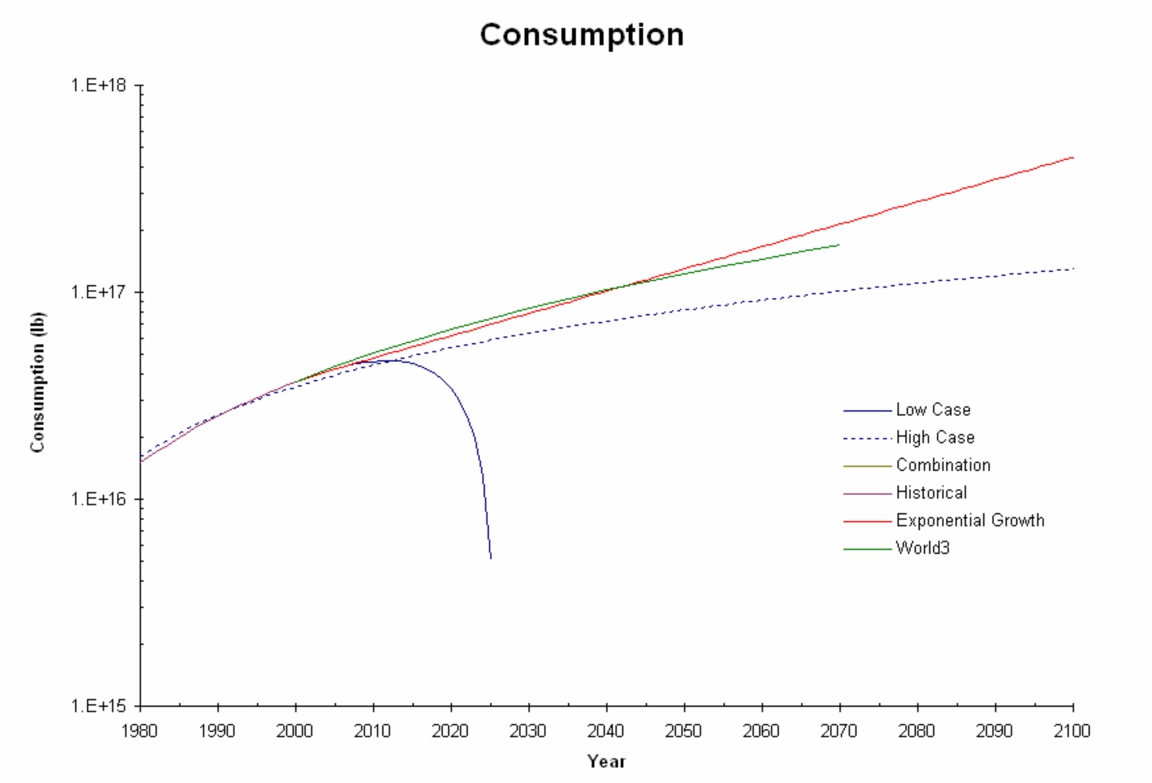

Figure 16: Consumption through the end of this century.

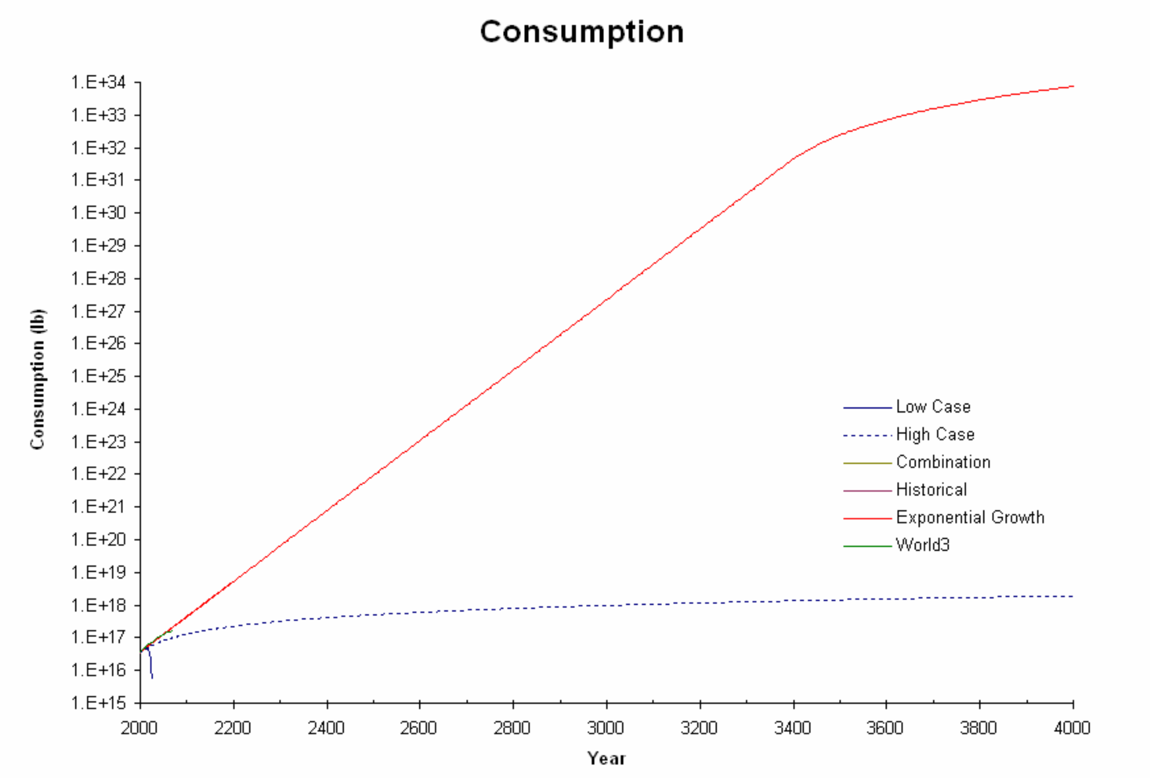

Figure 17: Consumption through the end of the next millennium. The exponential growth curve shows the effects of reaching a maximum speed in space: the growth rate slows noticeably after that point. Here and in the long-term graphs which follow, the maximum speed is 0.5c and the density is $3.63 \cdot 10^{25}$ pounds per cubic light year (see **Steps 12-15: Spatial Limit of Growth**); effectively we would be consuming all non-stellar mass.

Total Mass Projection

Figure 18 and **Figure 19** show how total mass is projected to vary over time. The curve representing historical values assumes, like the Global Ecological Footprint, that in 1986 we consumed more each year than Nature could reprocess.

If the low case and combination projections can be believed (they are nearly indistinguishable in the graphs) the total mass may have already started to dramatically drop. The reason for this is that the annual addition to consumption is smaller than the amount that Nature can reprocess. By 2012, Nature will be reprocessing everything we consume; this will last until the population collapses in 2028 (see **Figure 22**).

If the high case were to be realized, Nature would be already reprocessing what we consume, and the total mass would approach and remain at just the mass of humanity. For this reason, the high case can be considered sustainable.

Exponential growth could at best be maintained until the maximum speed was reached, which under the most optimistic conditions would be in 3390.

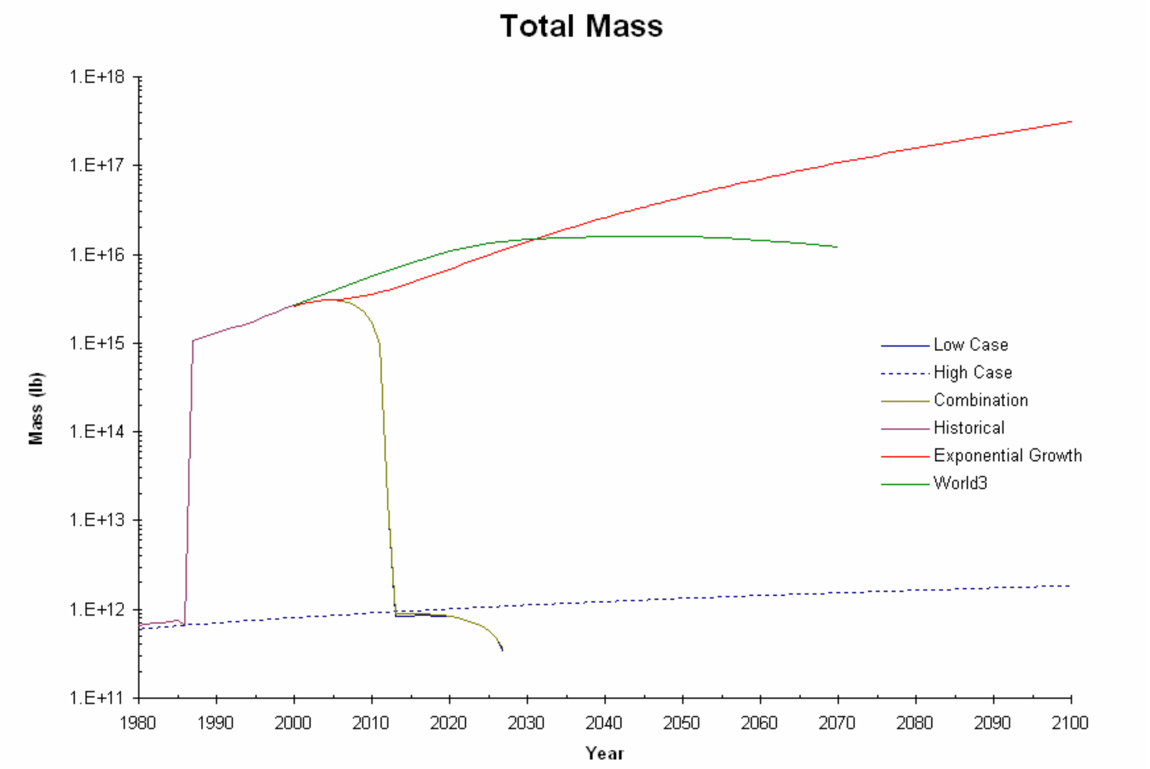

Figure 18: Total mass through this century. Note that the values for the low case and combination drop below zero in 2011.

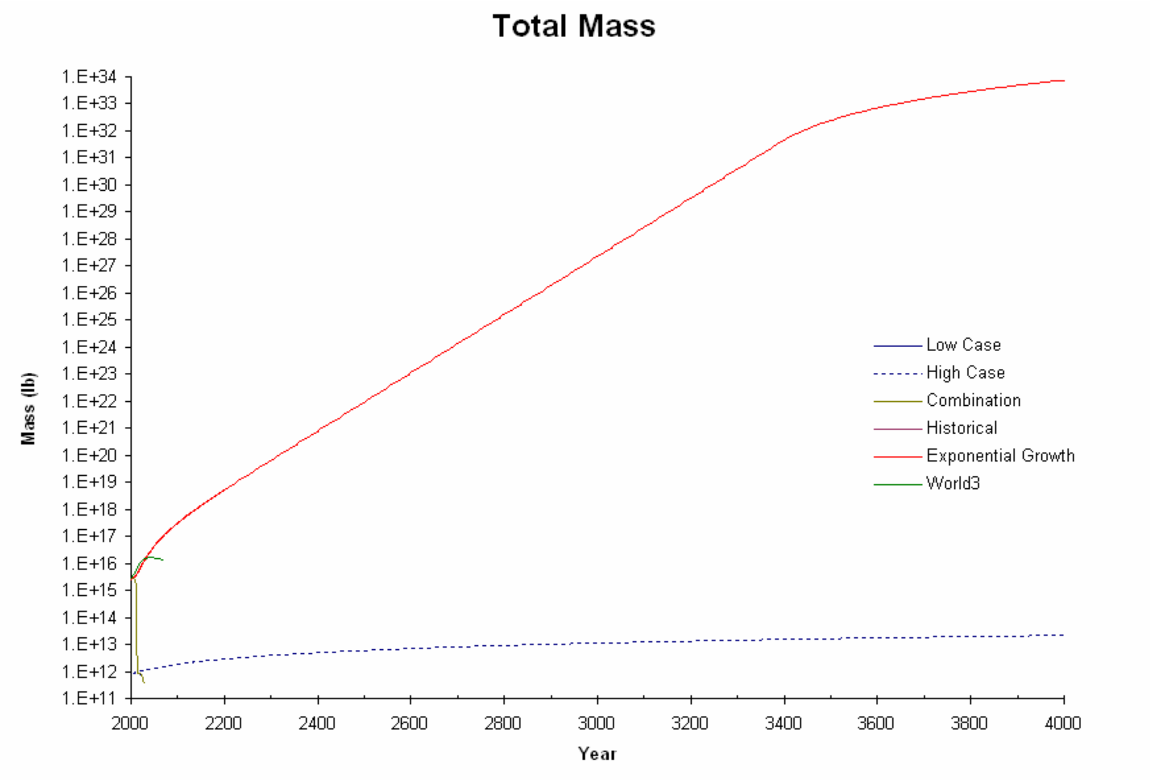

Figure 19: Total mass through the next millennium.

Depth Projection

Figure 20 and **Figure 21** show the average depth of consumed mass and human mass accumulated since 1986 if it was spread evenly over the Earth's surface.

In 2000, the depth would have been about one-eighth of an inch. In the low case and combination, the depth will never get more than this. The high case would already be zero, since Nature would be reprocessing the mass.

If we sustained exponential growth past 2005, focusing on just our planet, we would need to totally consume the Earth by 2730.

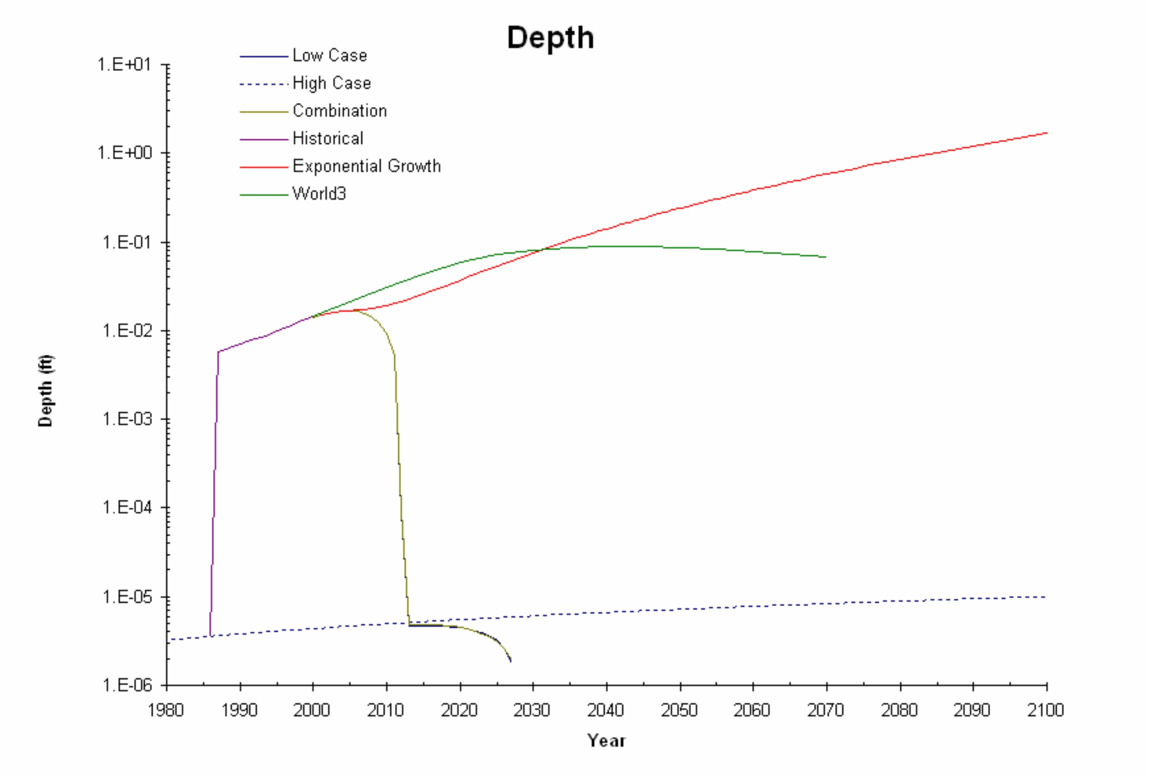

Figure 20: Depth through the end of this century.

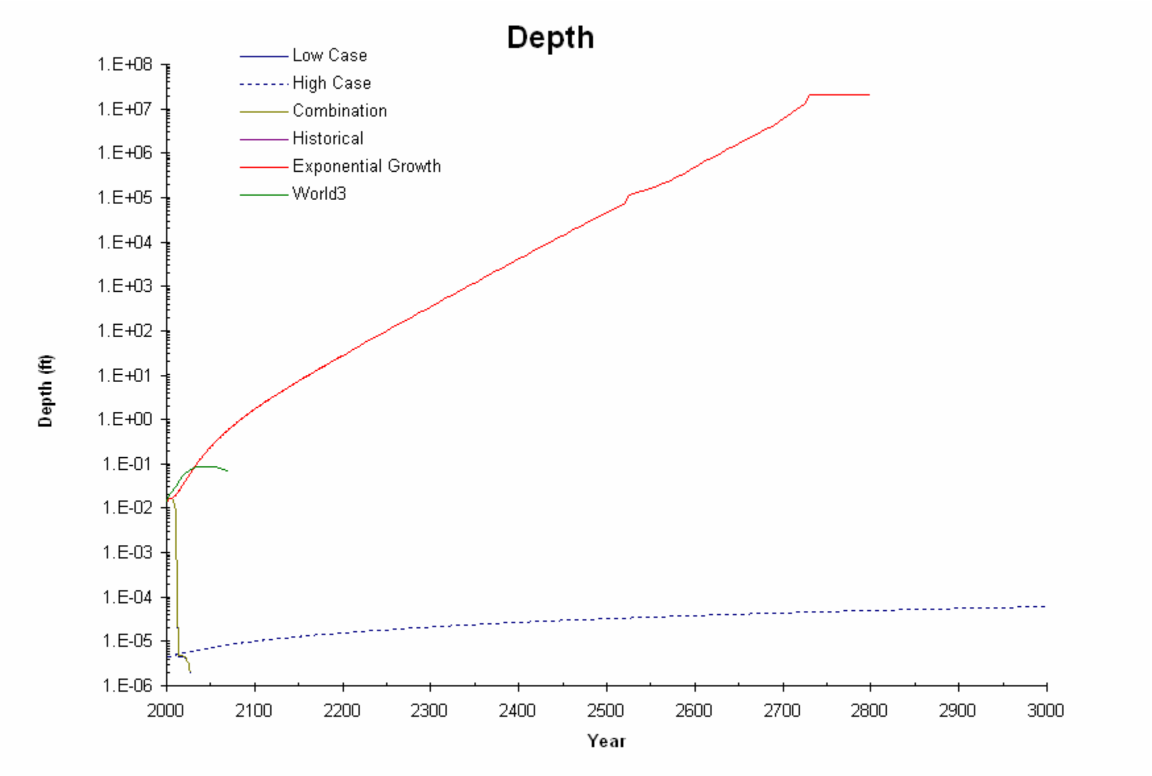

Figure 21: Depth through the end of this millennium.

Population Projection

Figure 22 and **Figure 23** illustrate projections for population.

In the low case, population would have started leveling off in 2005, and will begin dropping by 2017. By 2028 the population will be zero.

In the high case, the population would gradually slow down its increase over time. By 4000 it would exceed 160 billion people.

Like the low case, the combination drops to zero in 2028. Interestingly, this practically coincides with the peak of the World3 curve.

Like total mass, exponential growth (at the same rate as the mass) can only be sustained until the maximum speed is reached.

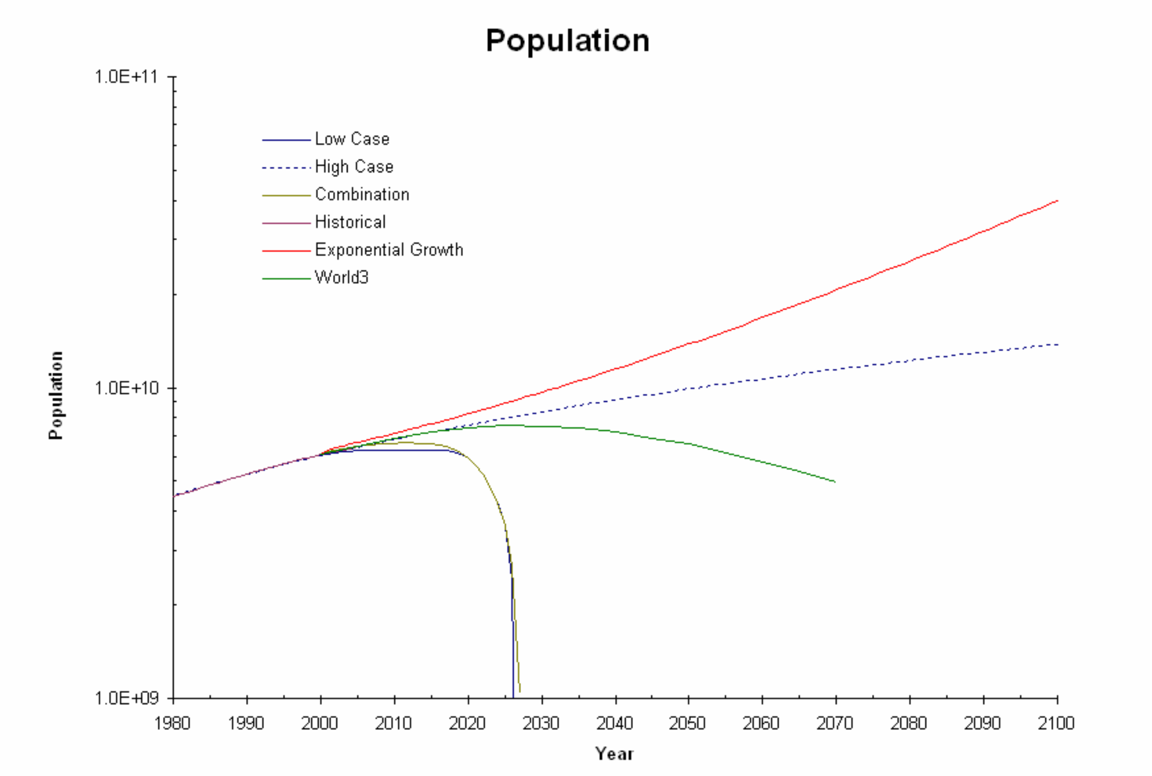

Figure 22: Population through this century.

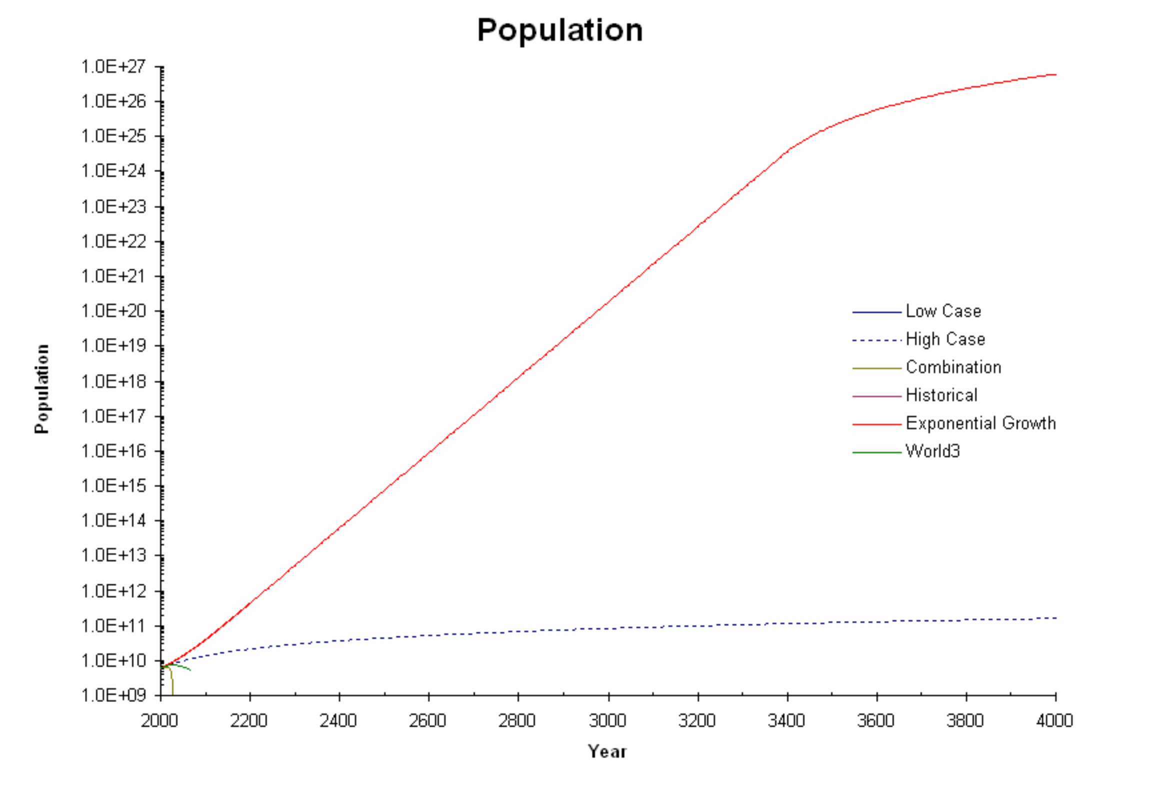

Figure 23: Population through the next millennium.

Population data since 2000 comes within one percent of the combination of the low case and high case.[16] The World3 projection for 2005 is also within one percent of the actual value. The following table compares these numbers (population in billions):

Year	Population	Low Case	High Case	Combination	World3
2001	6.16	6.13	6.12	6.21	N/A
2002	6.23	6.18	6.19	6.29	N/A
2003	6.30	6.22	6.27	6.35	N/A
2004	6.38	6.25	6.35	6.41	N/A
2005	6.45	6.28	6.43	6.47	6.49

The following table lists projected values for population after 2005.

Year	Low Case	High Case	Combination
2006	6.29	6.50	6.52
2007	6.30	6.58	6.55
2008	6.29	6.66	6.59
2009	6.29	6.74	6.61
2010	6.28	6.81	6.62
2011	6.28	6.89	6.63

Year	Low Case	High Case	Combination
2012	6.27	6.97	6.64
2013	6.28	7.05	6.63
2014	6.29	7.12	6.62
2015	6.29	7.20	6.59
2016	6.29	7.28	6.54
2017	6.27	7.36	6.46
2018	6.22	7.43	6.34
2019	6.10	7.51	6.18
2020	5.91	7.59	5.94
2021	5.64	7.66	5.64
2022	5.27	7.74	5.26
2023	4.83	7.82	4.80
2024	4.29	7.90	4.26
2025	3.59	7.97	3.60
2026	2.44	8.05	2.65
2027	0.05	8.13	1.04
2028	0	8.21	0

Living Planet Index (LPI) Projection

Projections for the Living Planet Index are shown in **Figure 24** and **Figure 25**.

For the low case, high case, and combination, the LPI reaches a minimum and then increases. The increase corresponds to the decreases in the rate of consumption.

Continued exponential growth totally decimates other species by 2034. At that point, we may literally need to be able to eat rocks.

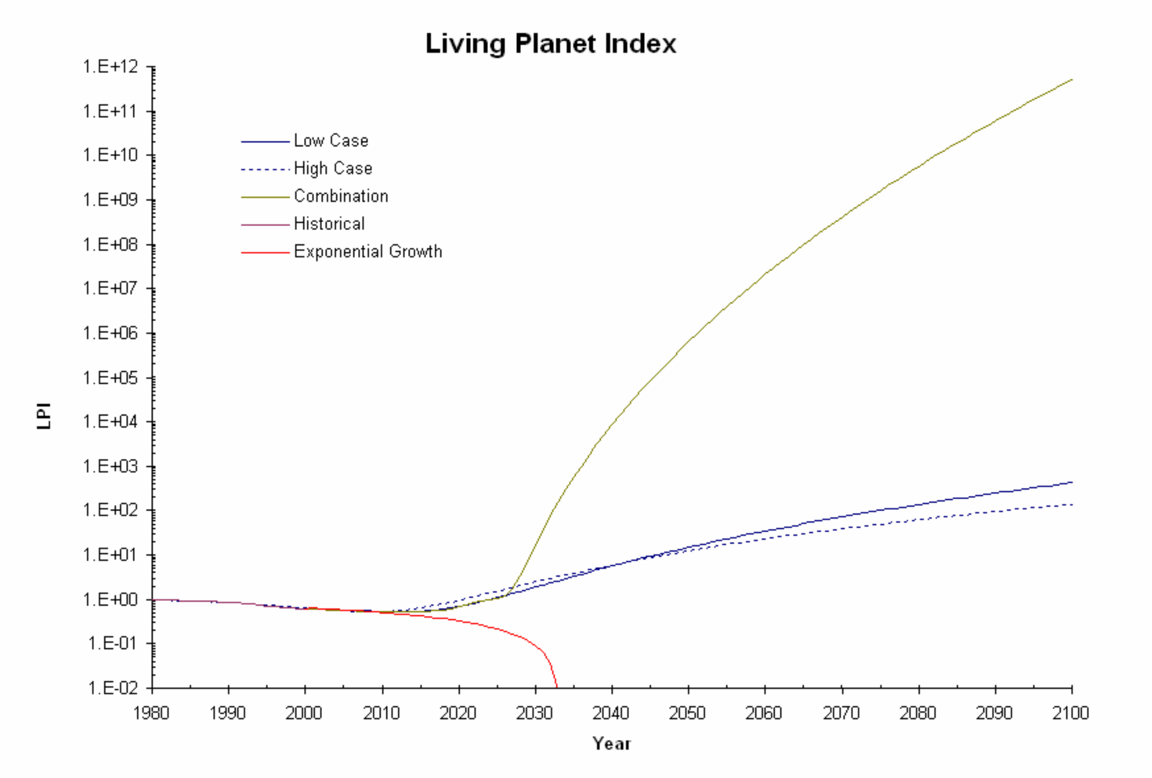

Figure 24: Living Planet Index (LPI) through this century. Here and in the next graph, the combined numbers may be excessive.

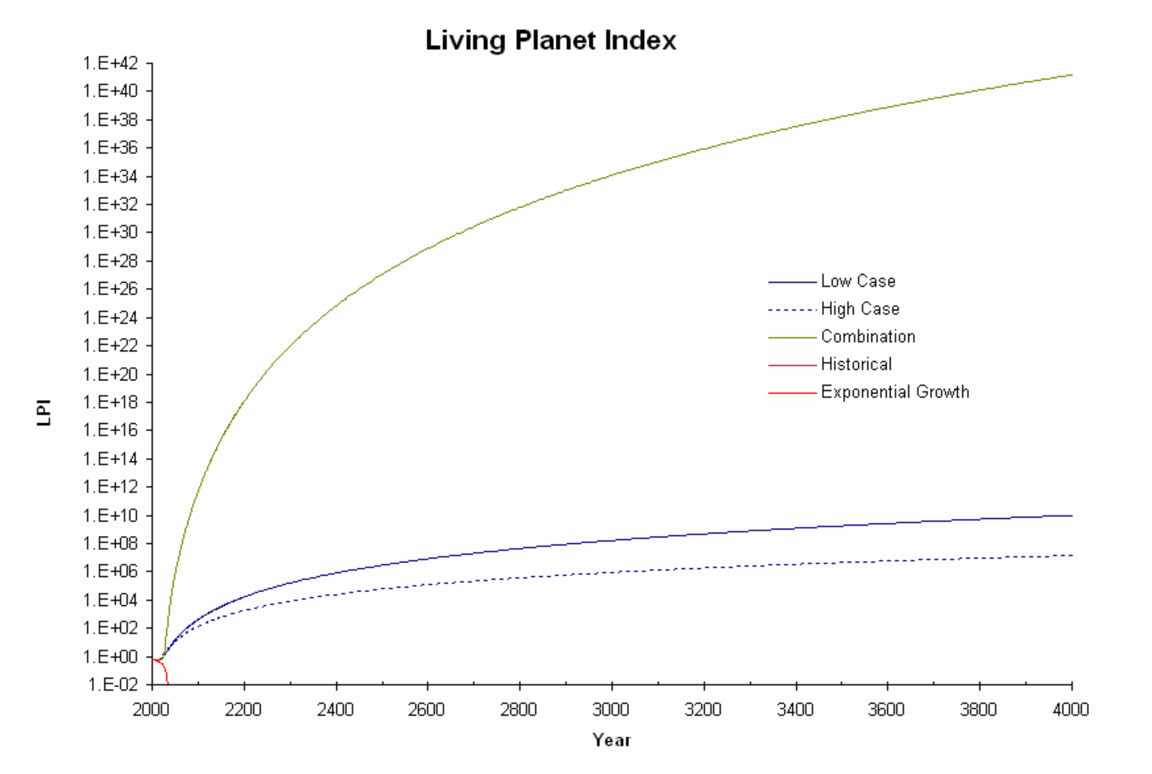

Figure 25: Living Planet Index through the next millennium.

Gross World Product (GWP) Projection

Figure 26 and **Figure 27** show projections of Gross World Product.

As the population decreases in the low case and combination, so does the GWP.

In the high case, the GWP climbs steadily, approaching $23 quintillion before the end of the next millennium.

Exponential growth may lead to a GWP (or perhaps more aptly, "Gross Universe Product") over $\$2 \cdot 10^{97}$ by the end of the next millennium. Like mass and population, its growth slows after the maximum speed is reached.

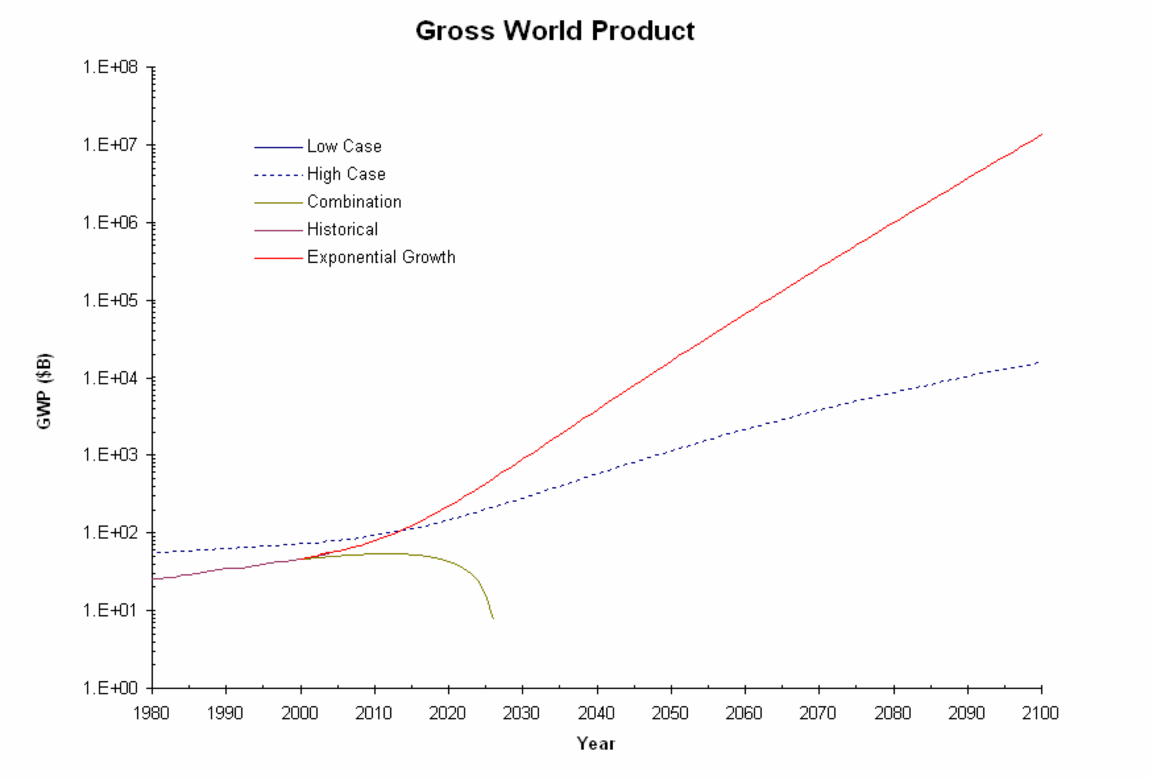

Figure 26: Gross World Product over the remainder of this century. Note that the combination and low case drop to zero in 2027.

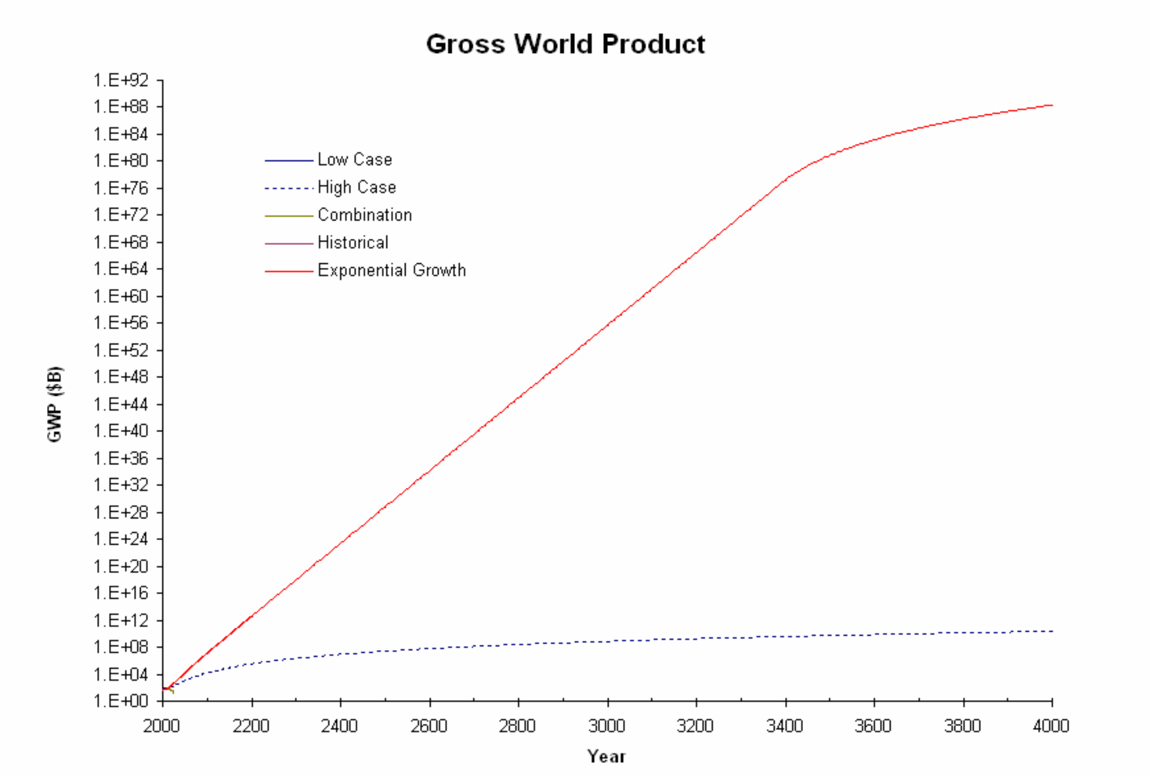

Figure 27: Gross World Product through the next millennium.

In the following table, data for GWP since 2000 is compared with the projections.[17]

Year	GWP	Low Case	High Case	Combination
2001	47.7	46.2	44.8	46.2
2002	49.2	47.3	46.2	47.3
2003	51.1	48.3	47.7	48.3
2004	53.7	49.3	49.3	49.3

Discussion

The key premise of this paper is that consumption is intimately related to some very important variables, chief among them the number of people in the world. Certainly, population does seem to track consumption very closely over time. For more than 30 years, the amount of products and waste we have been creating every year, dominated by fossil fuel consumption, has gradually slowed, and population growth along with it. Within the next 20 years, we will learn whether this deceleration will be modest over the long term, whether it will lead to a sudden, catastrophic end to our civilization, or whether it will result in something else. An attempt has been made here to discern the range of possible futures that follow from historical trends in consumption, the most likely of these futures, and how physical limitations affect the most optimistic of scenarios for growth in consumption.

The low end of the range of possible futures, representing the most pessimistic projections, has the population leveling off and then plummeting into collapse in about 20 years. The high end of the range of possibilities projects a steady increase in population over time, and involves the equivalent of sustainable behavior: consumption at levels that Nature can deal with. Unfortunately, there is every reason to believe that we are *not* living within Nature's limits, among them the significant loss of other species and the major climate changes currently underway that are traceable to human activity.

The most likely future considered here (which has the most success in generating the known data) results from a combination of functions used for the low and high ends of the range. As seen in **Figure 22**, it too projects population collapse. By comparison, another possibility, the World3 model by Meadows, et al, spreads out the time involved in that collapse, but not by much.

If somehow we could remove the negative impact on population from too much consumption, as supposed in the optimistic exponential growth projections, it would still be impossible to continue consuming mass even at current rates. In less than 30 years we could effective decimate the biosphere (as evidenced by the Living Planet Index; see **Figure 24**), and as a minimum we would have to depend on something besides other life for food. Settling other worlds won't help: we would reach our maximum speed before the end of the next millennium, after which growth would be forced to slow down (although if we moved into space, at least growth wouldn't stop altogether).

For the rest of this discussion, we will only consider the combination curves. The near-term projections, normalized to their values in the year 2000, are displayed in **Figure 28**.

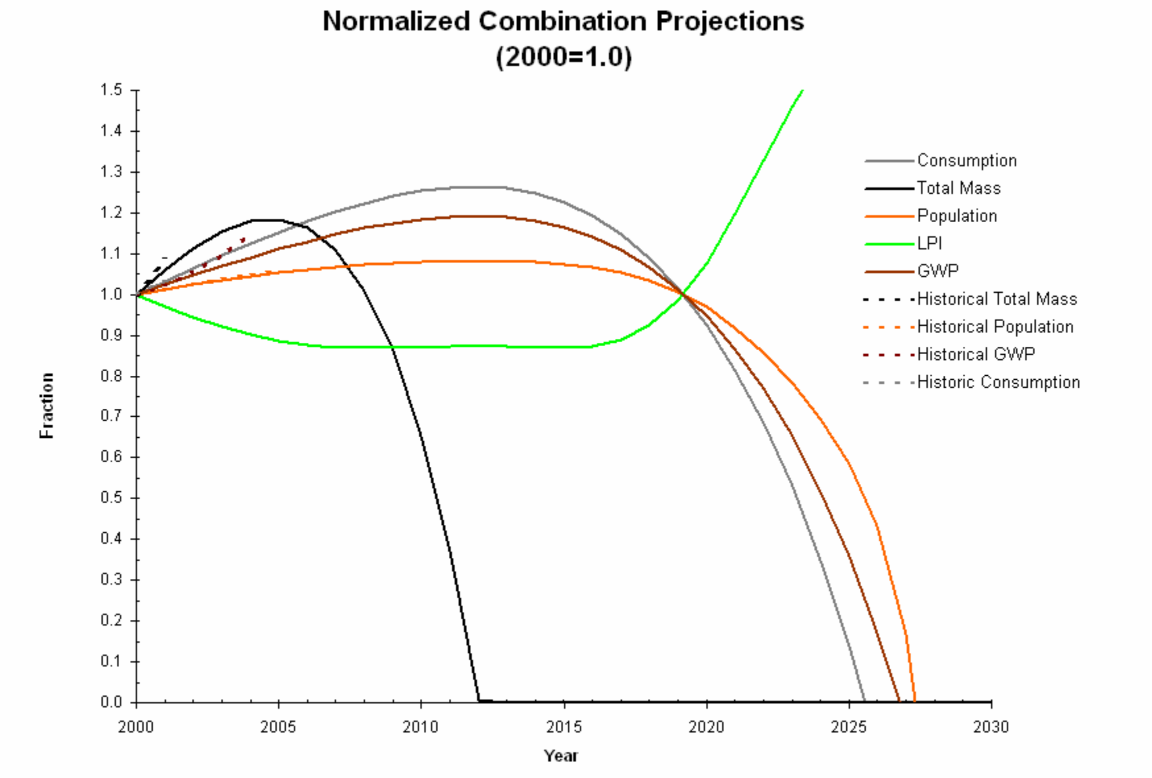

Figure 28: Normalized combination projections and historical data (scaled to values in 2000). Historic consumption through 2001 is indistinguishable from the projection on the graph. Recall from **Figure 15** that the expected maximum error in projections is less than 10%.

Following are the functions for (respectively) consumption, population, LPI, and GWP, where *T* is the year, in a form that can be copied into a spreadsheet:

Mcon = -10772465.265625*T^6 + 127945111457.844*T^5 - 633162512279137*T^4 + 1671088835943820000*T^3 - 2.48084997925145E+21*T^2 + 1.96423869417563E+24*T - 6.47993752043924E+26

Pop = (((0.0000110468885670478*Mcon + 429359094690.97)+(-1.8681750468152E-55*Mcon^4 + 1.5524989965808E-38*Mcon^3 - 4.9384882718241E-22*Mcon^2 + 0.00001766583857818*Mcon + 406241018911.22))/2)/135

LPI = ((1.06394285942008E-66* Mcon ^4 - 8.92847878544354E-50* Mcon ^3 + 2.08887853927044E-33* Mcon ^2 - 2.24380280356455E-17* Mcon + 1.09136788795097)+(-1.34644327601909E-17* Mcon + 1.15666478417805))/2

GWP = -5.7522070759244E-34*Mcon^2 + 9.3637317580443E-16*Mcon + 11.4106556873325

Note that where functions have been averaged, they are shown.

A maximum population of over 6.6 billion people is projected to occur by 2012, when the consumption reaches its peak value.[18] Shortly afterwards (as shown in **Figure 29**), annual per capita consumption, which is projected to be decreasing since 2000, will go below zero. Total mass, also decreasing during that time, will level off at the mass of the population.

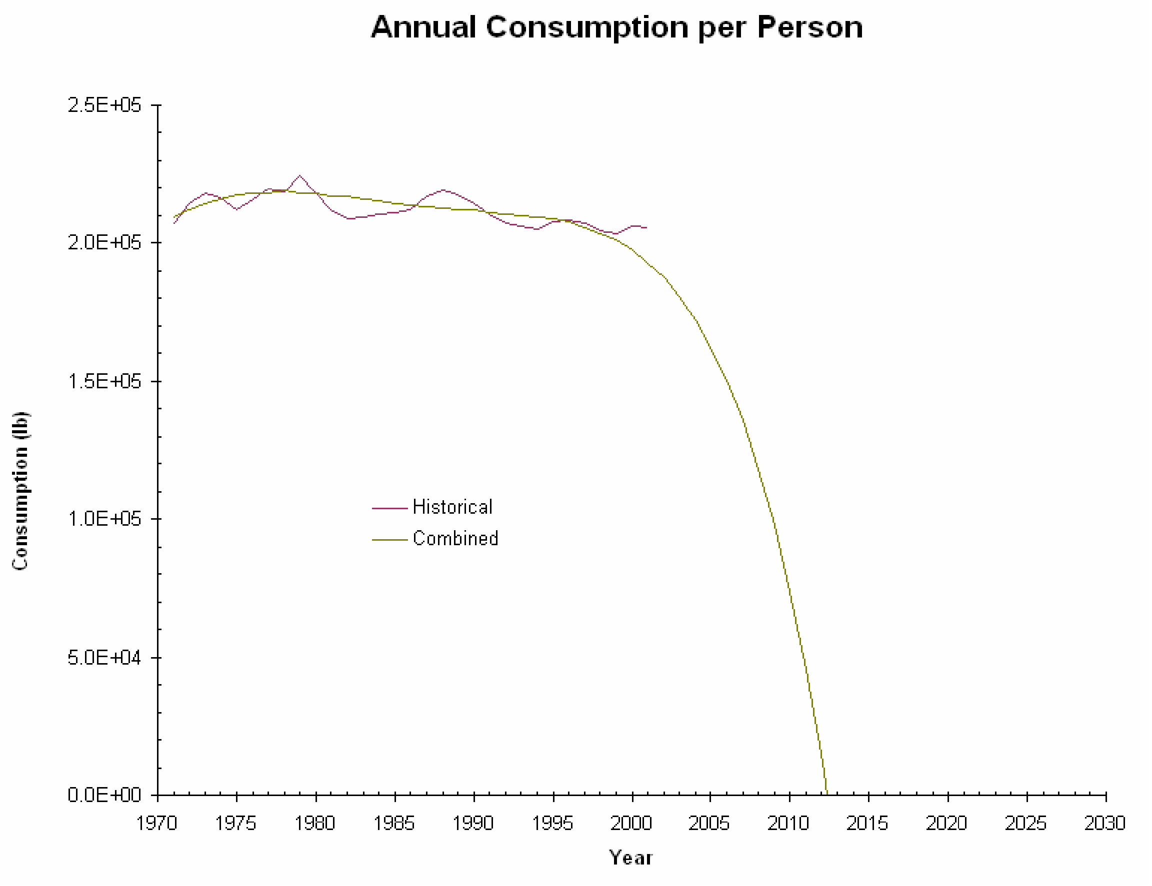

Figure 29: Amount consumed per person. Assumes previous year's population consumed entire amount.

The most straightforward interpretation of the consumption peak and what happens afterward involves so-called "peak oil." Recently, forecasts have been made that oil supply will peak by 2010, after which it will become progressively more expensive to extract and use.[19] **Figure 1** clearly shows how fossil fuel consumption and the Global Ecological Footprint closely track each other. Since energy is required for converting material from one form to another, it makes sense that the consumption of the most commonly used fuel would correspond closely to the consumption of everything else. Principal among the fossil fuels is oil. As oil becomes more expensive, other fuels will become relatively less expensive, and will be substituted for it. Among these alternatives is biodiesel, which is recycled waste from agricultural production.

After the consumption peak we would be converting more previously consumed material than new material (thus reducing the net consumption). Per capita "re-consumption" would be dominant. By 2026, net consumption would drop below the level it was in 1960 and within two years the population would reach zero.

There are several ways to explain the corresponding reduction in population. One is that the process of re-consuming would be very unhealthy, leading to more fatalities; certainly pollution and toxicity of products have already increased death rates. Another explanation is that people would stop reproducing so they can have more for themselves. Perhaps scarcity would lead to violence on a huge scope. All of these dynamics would be operating simultaneously. Or maybe there is another explanation, either working alone or in tandem with one or more of the suggestions here. Because the projections are based in history, the answers should be found there.

Would the population actually reach zero? No one can really say. In 1800, before fossil fuels became our dominant energy source, there were nearly one billion people in the world. Two millennia ago, there were around 300 million people.[20] Perhaps the population may fall to a number that is closer to one of these numbers. However, natural systems were much more robust then; they may not support as many people in their present, weakened state. One thing we can say is that when the world economy crashes, in 2027, the population is projected to be under 100 million.

If these projections are accurate, what can we do to avoid catastrophe? One obvious solution is to reduce the rate of fossil fuel consumption until other (preferably renewable) energy sources are developed to the point that they can support our civilization. If we are also approaching a peak with other consumables, this will reduce their consumption as well, and buy us time to find alternatives that are safer and more easily reprocessed. There is another benefit to this strategy: reducing global warming, which threatens the survival of our species along with others. This approach, strongly championed by the sustainability community, is already being implemented, and may be partly responsible for the observed reduction in consumption.

Just as we simulated the effects of constant exponential growth, we can simulate solutions such as this.

If each year of consumption following 2008 was modified to instead take 10 years, the result would appear like **Figure 30**.[21] The peak consumption would occur in 2047, the economy would crash in 2184, and the population would crash in 2202.

Waiting until after the consumption peak to make changes would carry a severe penalty, as illustrated in **Figure 31**. If the change started in 2015 then the economy would crash in 2121 and the population would crash in 2140.

We must be careful, once we do have alternative fuels available and in use, to avoid exponential growth, and be mindful of any limits similar to what we’re encountering with fossil fuels and possibly our other consumables.

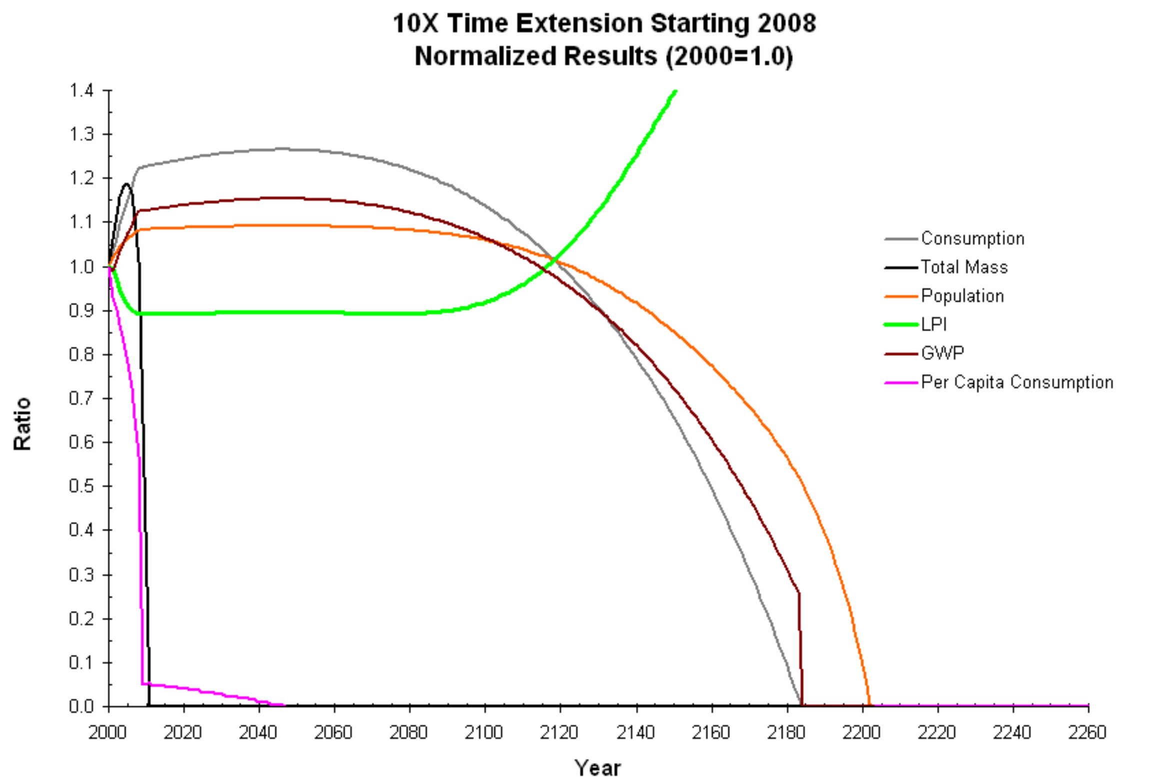

Figure 30: Simulated effects of reducing consumption growth in 2008 to multiply the remaining time by 10. Per capita consumption is annual.

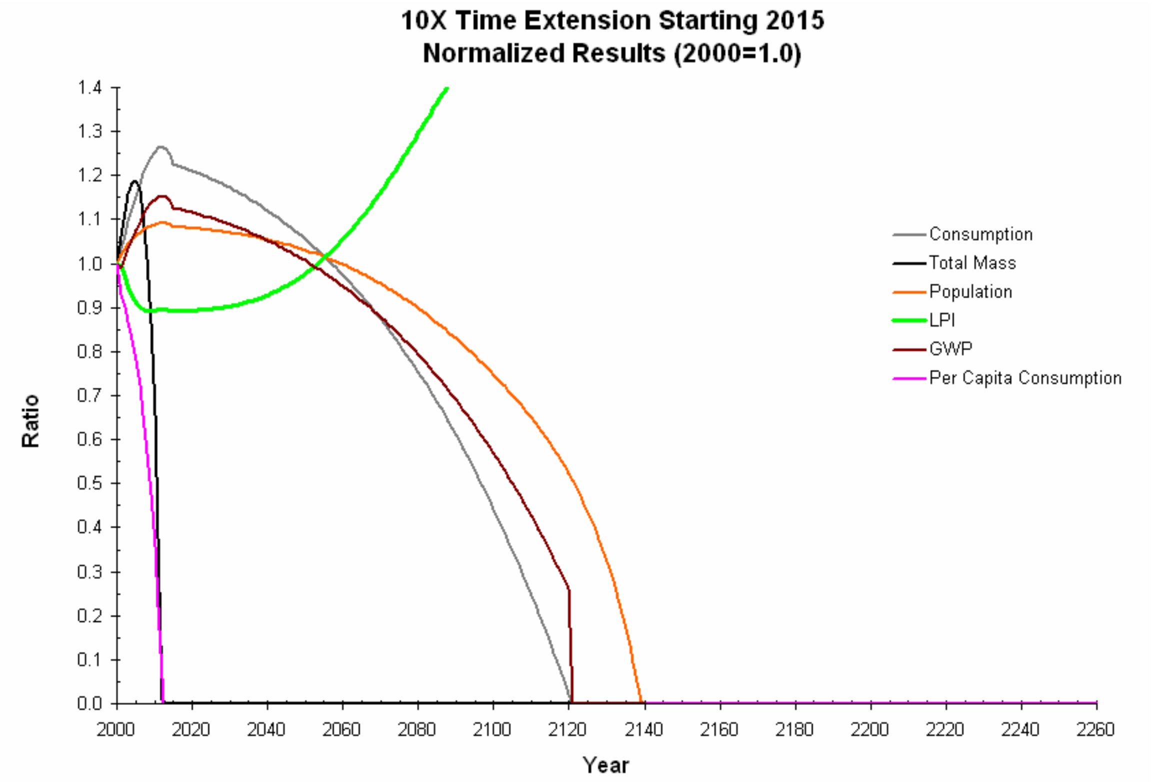

Figure 31: Result of waiting until after the population peak to reduce the rate of consumption.

Conclusion

Historical trends strongly indicate that we may be very near a threshold in our ability to convert natural resources into products and waste as we have been doing over at least the last 40 years. Exceeding this threshold could catastrophically affect the size of our population in the near future.

Our best hope for long-term survival on Earth is to reduce our overall consumption as much and as soon as possible and avoid increasing it afterwards, even with new energy sources. As conditions (such as climate) change, we will probably need to adjust by consuming resources to create new infrastructure, but after that we should reduce consumption again to the bare minimum.

Once and for all we must dispense with the idea that exponential growth in consumption is sustainable. In even the most optimistic scenarios, involving relativistic speeds and the ability to consume all non-stellar mass, physics limits this kind of growth. If we do settle other worlds, which we will need to do for the long-term survival of life, we should consume only as much and as fast as necessary to develop the infrastructure to sustain long-term existence on those worlds, then limit additional consumption until conditions change.

Notes

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[1] Paul Hawken, Amory Lovins, L. Hunter Lovins, ***Natural Capitalism: Creating the Next Industrial Revolution*** (Little, Brown and Company, 1999), pp. 52-53. The number is conservative because, as they point out, it doesn't account for non-domestic waste.

[2] ***Living Planet Report 2004*** (WWF International, 2004), p. 22.

[3] ***Living Planet Report 2004***, Table 2.

[4] Here are some examples. The ratio for energy consumption in 2000 was 0.25 (***Statistical Abstract of the United States 2004-2005***, Table 1366). In 1998, the ratio for aluminum production was 0.19 (***Business and Industry Review*** Encyclopædia Britannica. Retrieved January 12, 2006, from Encyclopædia Britannica 2006 Ultimate Reference Suite DVD).

[5] ***Living Planet Report 2004***, Table 3.

[6] The latest values are published in ***Living Planet Report 2004***.

[7] The mass of the planets alone is about 0.006 solar mass. No one yet knows the total mass of asteroids and comets, but it probably is not as much as all the planets. As with the Earth, we will assume that our current ratio of "useful" mass to waste mass remains the same. Note that if, as intuition suggests, there is less useful mass on other worlds, the observable effect on the variables we are measuring will be an *increase* in the rate of mass consumed, since we will be "consuming" more waste.

[8] Since the historically consumable mass comes from the Earth's crust, such an estimate is likely to be only valid to the maximum depth of the crust (15 miles).

[9] Technically, this is assumed to be the amount consumed from 1998 to 1999, which arguably was not consumed by all of the people who were alive in 1999, but a major fraction of them. Since the consumption was an understatement (see Note 1), this number was used anyway. In other references to per capita consumption (see **Discussion**), per capita consumption is defined as the amount consumed by the population of the year the consumption began.

[10] The Global Ecological Footprint data is for 1961 to 2000, from ***Living Planet Report 2004***, Table 3. The non-fuel minerals and metals production is for 1970 through 2000, from "Production of Non-fuel Minerals and Metals, 1970-1999" found in ***Signposts 2004 Trends Dataset*** (Worldwatch Institute, 2004). Fossil Fuel consumption is for 1961 to 2000, from "World Fossil Fuel Consumption, 1950-2003" found in ***Signposts 2004 Trends Dataset***.

[11] Population data is from "World Population, 1950-2003" in ***Signposts 2004 Trends Dataset***.

[12] Data from ***The Merck Manual of Medical Information: Second Home Edition*** (Pocket Books, 2003), p. 880. Only heights were used for which male and female data were available.

[13] Using medium variant crude birth rates and death rates (per 1,000 people) from ***World Population Prospects: The 2004 Revision Population Database*** (United Nations Population Division, 2005); http://esa.un.org/unpp .

[14] Density data are from "Earth."Encyclopædia Britannica. 2005. ***Encyclopædia Britannica 2006 Ultimate Reference Suite DVD*** 29 Dec. 2005.

[15] Data was used from Scenario 1 of Dennis Meadows, World3 - 03 global simulation model as presented in Donella Meadows, et al, ***Limits to Growth - the 30-Year Update*** (Chelsea Green Press, 2004). The ecological footprint projections were used to derive consumption, and the population projections were used to derive human mass.

[16] Population data are from ***Total Midyear Population for the World: 1950-2050*** (U.S. Census Bureau, 4/26/2005). ***Time Almanac with Information Please 2006*** (Information Please, 2005), p. 702 quotes the 2005 population from *The World Factbook 2005* as 6,458,141,043 (6.46 billion) people.

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[17] Data derived from "Eco-Economy Indicators: DATA - ECONOMIC GROWTH - Gross World Product - GDP GWP Per Person" (Earth Policy Institute, 2005); http://www.earth-policy.org/Indicators/Econ/Econ_data.htm using the ratio of the value in one year to that of the year before it.

[18] Here and elsewhere years are rounded to the nearest whole year.

[19] Several good resources exist on the Internet describing this issue. See in particular http://www.hubbertpeak.com .

[20] "World Population Since A.D. 1" in ***Signposts 2004 Trends Dataset***.

[21] To obtain this result, for each T in the combination functions (p. 37) substitute $[T_0 + (T-T_0)/M]$ where T_0 is the year the change starts (in this example, 2008), and M is the multiplier (10). The ratio of the first year's annual change in consumption to the previous year's annual change in consumption, roughly corresponding to the necessary per capita change in the first year's consumption required to achieve a given multiplier M, is well approximated by the relation $[1 – 1/M]$ for $M>4$. The closer to the peak T is, the worse this approximation gets.