How large is the global population when limited by long term sustainable global metal-, energy- and phosphate supply?

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Abstract

The WORLD7 model was used to make an assessment for the sustainable metal usage and the resources available within the planetary limits to human society, in order to estimate demands on recycling and maximum metal consumption per capita for different metals. The metals were selected for their importance in society. The calculations of critical metal use show that we have substantial metal usage above the sustainable rates, needing a reduction in net use of more than 95% for many metals. Alternatively, the issue was turned around, asking, if this is how much metals that is available, how many people for how long can we support with it? A sustainability gap can be determined, alternatively, that the global population needs to come down in size to somewhere between 1.5-2 billion people, combined with improved recycling efficiencies. How a global population contraction can take place is not discussed.

1. Introduction

We have in the past worked with a concept called critical loads for acidifying substances and their exceedances (Sverdrup et al., 1990, 1992a,b, 2005, 2006, 2012), but also for use of phosphorus and limitations to populations (Ragnarsdottir et al, 2011, Sverdrup and Ragnarsdottir 2011, 2012, 2013a,b,c). Critical loads for sulphur and nitrogen was developed as a measure for how much acidifying and eutrophying pollution ecosystems can take without becoming damaged in structure, content or function for the future (Nilsson and Grennfelt 1988, Sverdrup et al., 1990). We will adapt this philosophy to finding the maximum metal use rate that is still sustainable within the global boundaries. This is an assessment for metals, to later to be integrated with a similar study using phosphorus and food, soil and land and energy, fossil and renewable.

1.1. Earlier work

Earlier estimates in billions of people of the Earth's ability to feed people, vary widely, depending on what was considered to be the limiting factor and the assumptions made. Many of the assumptions violate the basic thermodynamic principles of living on a finite planet. Many of the references are found in Cohen (1995), we have not re-listed them here.

2. Objectives and scope

The objective is to calculate a sustainable metal use, by setting a minimum time to exhaustion, we can by mass balance derive an estimate of a long-term sustainable metal use within that time frame. We will discuss the ramifications of setting a time limit, and discuss what that really means. Our scope is to cover the main metals for society. We will not address specifically the critical rate fossil hydrocarbons, nuclear fuels, phosphorus, water or any other resource than a selection of industrially important metals in this study. In this study, we do not assess if there is enough energy available for the manufacture of the sustainable metal extraction rates calculated. This will arise at a later time, constraining the total metal production that will be possible.

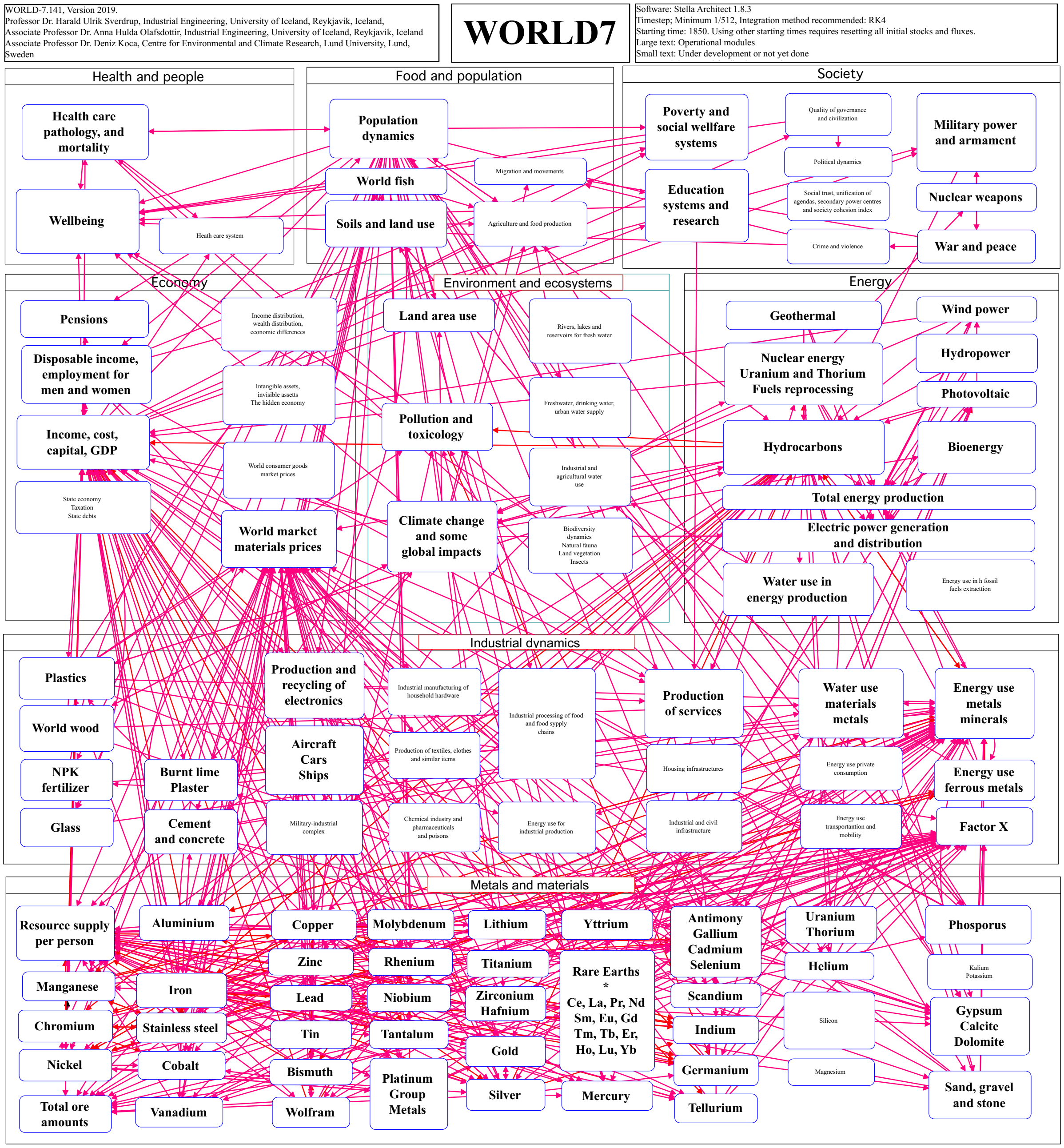

Figure 1. Overview of the WORLD7 model

The consumption is much determined by the population size, and we may ask the question of:

1. What is the sustainable metals extraction rate and the sustainable metal use rate in society?
2. If the global population was limited by long term metal supply, how large could it be?
3. Which other essential resources for population sustainability depend on availability of metals?
4. How is the sustainable population size set by metal supply determined by different time horizons?

3. Method

The methods used are mass balances and simple calculations, using data and results from earlier studies (Ragnarsdottir et al, 2011, Sverdrup and Ragnarsdottir 2011, 2012, 2014a,b,c, Sverdrup et al., 2006). The methods are described in these earlier studies. Reserve estimates are important, and they are based on several methods such as estimates from geological surveys, fit of data to Hubbert's resource extraction functions We will employ mass balances to calculate the quantitative estimates as outlined in the theory section. For the estimation of reserve size, we have employed a number of methods.

4. Theory

The hypothesis is that if the laws of thermodynamics are universally valid and unbreakable, then that has significant ramification for human's use of resources and possibly also effect on what is the sustainable global population size. The concept that metals available for mining are finite resources implies that metal extraction from the Earth's mines will one day decline and approach exhaustion. The results presented in this paper are based on the work modelled in the WORLD7 model. This section describes the main assumptions and thinking behind some of the most important factors in regards to the scope of the paper.

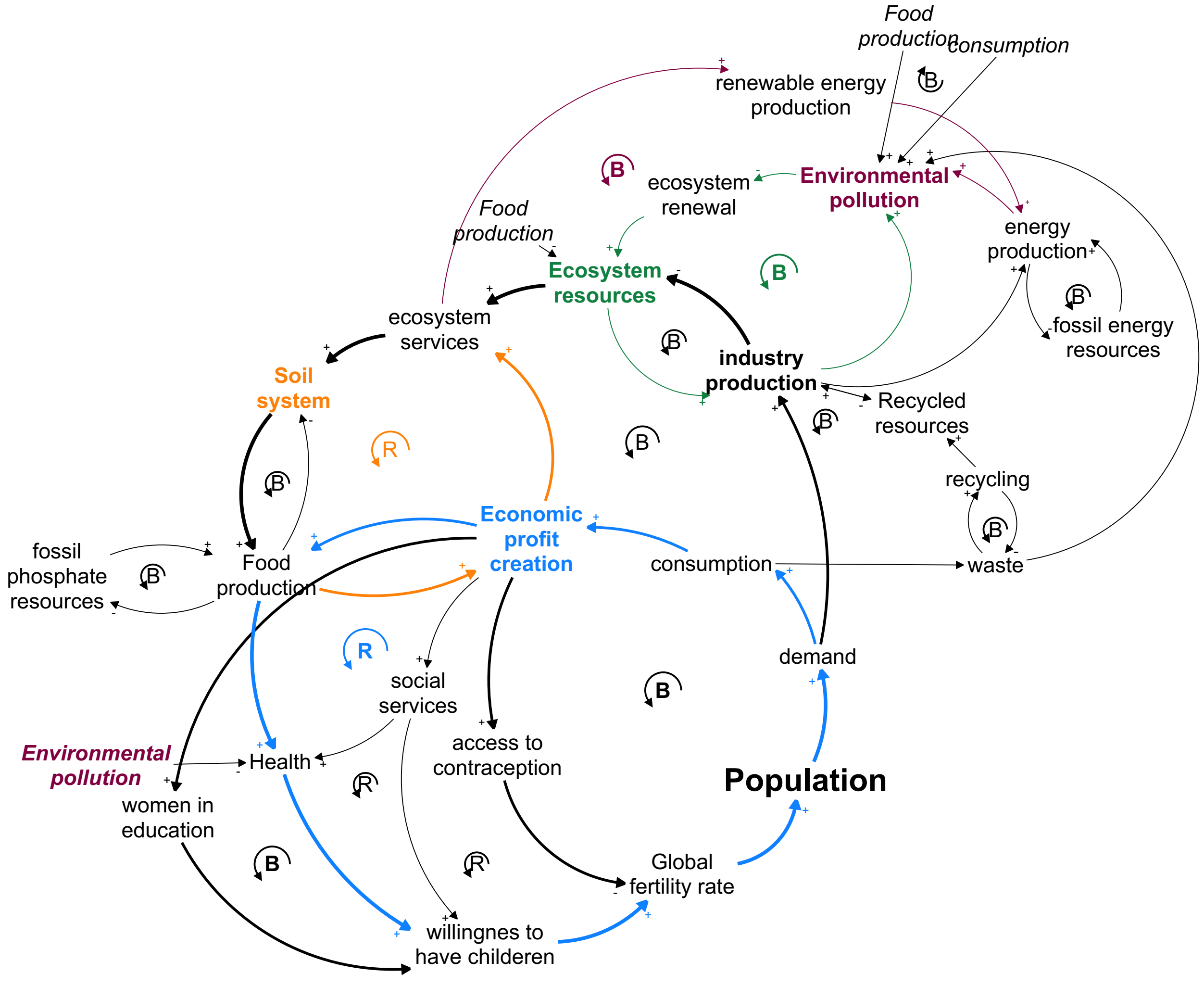

Figure 2: Aggregated version of some of the feedback loops that affect the population variable.

4.1. The WORLD7 model

Figure 1 shows an overview of the WORLD7 model, all the white boxes represent submodules that are functioning in the current version of the model. The submodules are linked with the pink lines in the figure.

The WORLD7 model consists of hundreds of feedback loops. Figure 2 presents a highly aggregated causal loop diagram (CLD) with a special focus on connecting the sectors mentioned in the title of this paper. It is noted that the CLD is intentionally made as simple as possible and in many cases the links would need considerable disaggregation in order to truly show the causal relations represented in the WORLD7 model. This CLD is an attempt to capture some of the core links in the model. It is emphasized that Figure 2 this is on a very aggregated level and these are just some of the loops shown here. The figure shows 4 reinforcing loops. The loops are marked with numbers and appropriate letter, R for reinforcing loops and B for balancing loops. The balancing loops, balance the reinforcing loops (R) and slows them down. Looking at the reinforcing loops, the first one goes from fertility rate through population, more population means more demand resulting in more consumption and more economic profit creation that also has a positive effect on the food production and then helath and willingnes to have childeren. Then from economic profit we also have yet bigger push from the social services to bothe health and willingness to have childeren. Also one that goes through the soil system and food production that also have a positive feeedback to the economic growth variable that gives the same push eventually to population. Then we hava a number of balancing loops to dampen the population growth, f.x. fram the economic growht we have a positive effect on the number of women in education that will actually decrease the willingness to have childeren and also more access to contraception that will have same effect.

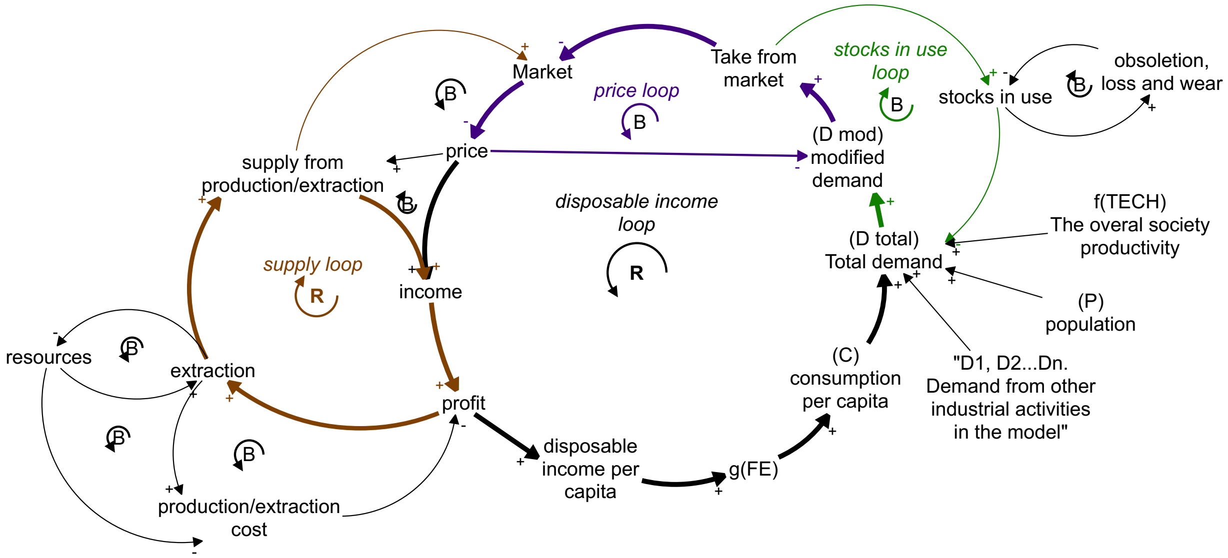

Figure 3 simplified CLD based on the market model in the WORLD7 model

A simplified CLD representing the market model applied in the WORLD7 model is presented in Figure 3. The demand is causally linked with the population size as well, as both demand per capita as well as the number of consumers represented by the global population size matters for the future sustainability of human civilization. The GDP has a positive link to the demand, and the demand has a positive link to what we call a modified demand. The modified demand is the demand that has been adjusted for price, i.e. if the price increases one is likely to buy less than the mind desires. The modified demand is the amount that is taken from the market (through delivery). The amount on the marked affects the price based on market dynamics, more supply, less price and vice versa.

4.2. Planetary limit

A planetary limit, it the limit to how much we can extract from the global resource base, mostly depending on the ultimately recoverable reserve and the timeframe we are adapting, but also how much pollution the global environment can take, a global critical load. The timeframe is a separate issue to set in itself, inherent to the definitions of sustainability (Sverdrup and Svensson 2002, 2004). Depending on the present extraction rate, we may be under- or over-extracting with respect to this limit. In the concept of a planetary limit, lies the that there is no “other resources somewhere else”. The concept says, this is what we have. In sustainability, one important very concept is that we must be able to become sustainable with the knowledge and resources we have now, without having to depend on miracles to happen in the future. We need to address the issue of a far too large global consumption, where one root cause is the size of the global population. Consumption is governed by a very simple equation as suggested by Ehrlich et al., (1992), in a variant of his “I=PAT equation”. We will call the consumption rate C instead of I according to the modified Ehrlich equation:

$$C = N * A * (1-X_R) * E \qquad (1)$$

The equation clearly states that there are four different parameters we can elaborate with in order to design the consumption rate at a sustainable level:

1. A is affluence or net consumption per capita
2. N is population or more specifically the number of consumers
3. X_R is the degree of recycling of the amount supplied to society,
4. E is the resource efficiency of producing the affluency A

By recycling and improving efficiencies and yields (E), we may reduce net consumption per capita (A), however if that is less than the increase in population (P) or recycling (X_R), we are effectively losing the race. Our observation is that this is the case we can see today. The improvements that can be made on recycling (X_R) and efficiencies (E) have clear limitations, where fas so far the population (P) has been steadily going up, to a point where the consumption volume is exceeding the planetary supply capacity. The recycled fraction X_R is defined as:

$$X_R = \frac{R}{(M + R)} \qquad (2)$$

Where mining rate is M and recycling is R. The system has the capacity to accelerate until the reserves on both sides have been exhausted and the population size has grown exponentially. Metals are very essential for food production as a main component of tools and machines. The system has its own internal feedbacks leading to population growth and increase in the use of metals. Metals are very essential for food production as a main component of tools and machines. By recycling and improving efficiencies and yields, we may reduce net consumption per capita, however if that is less than the increase in population, we are effectively losing the race. The improvements that can be made on recycling and efficiencies have clear limitations, whereas so far the population has been steadily going up, to a point where the consumption volume is exceeding the planetary supply capacity. Figure 2 shows how the effect of recycling works on supply. We may derive an estimate of the sustainable global population from just mass balance. This leads to the equation given as the minimum over all the metals is assessed in the study:

$$\text{Sustainable population size} = \min_i \left(\frac{\text{Sustainable Metal Use}_\text{i}}{\text{Consumption per capita}_i * (1 - X_{Ri})} \right) \qquad (3)$$

Where all the metals we want to use in the assessment. The real flow to society becomes amplified by recycling, because part of the outflow becomes returned to the inflow. The maximum sustainable mining rate is given by the size of the mineable reserve and how long it must last. The sustainable consumption rate is determined by how efficient that mined amount can be used:

$$\text{Sustainable metal use} = \frac{\text{PRR}}{t_\text{Limit} * (1 - X_R)} \qquad (4)$$

Where t_{Limit} is the time to "doomsday" in years from now, implying after this point in time, the society cannot get any more metals. The critical rate (CR) is defined by either of the three following definitions;

1. The maximum net use in society of a metal that will allow supply to occur for the time horizon adopted for sustainability
2. The mining rate that can be allowed for the time horizon adopted based on the remaining extractable reserves
3. The maximum allowable losses from the system, losses that are irreversible and that cannot be retrieved on an operational basis, depending on recycling efficiencies

The critical rate is equal to the maximum allowable loss rate society can tolerate and still be sustainable. The critical rate for a metal will be a multi-parameter estimation that will have to occur in several steps. The Critical Rate, is the minimum of the sustainable metal use and the Ecologically Sustainable Mining Rate, set by ecological implications of the mining activity and the activities associated with metal refining and bringing the metal to use in society. The Ecologically Sustainable Mining Rate is not addressed in this study. The priorities of the economic system come after the limitation of the physical reserves and the ecological limitations in priority and thermodynamic ranking. If saving the economy implies ruining the reserves or the ecology, then that is by definition not a sustainable economy.

The system is driven by two reinforcing loops, one involving global population size – metal consumption – food and another involving metal consumption – waste – recycling – metal available, both that work to make both metal consumption and global population rise. The amount of metal either in use or stored inside the system (dS/dt), the mining rate (M), recycling (R), change in the stock (S) and waste losses (L) Based on mass balance, we have the general equation of continuity for any metal:

$$\frac{dS}{dt} = M + R - L \qquad (5)$$

The net flux needed to keep society going is depending on the gross flux and the recycling fraction;

$$\text{Net input} = (M + R) * (1 - X_R) \qquad (6)$$

At the critical rate, we assume we would like a steady state, that is the net accumulation stops.

$$\frac{dS}{dt} = 0 \qquad (7)$$

That implies that short term accumulation can go on, but that all metal if used in a bridge or a car, will eventually be disassembled and the metal again returned to the market after a certain period of years. We can set the differential in Equation 6 to zero (Eq. 8), it is reduced to:

$$\text{Sustainable Metal Use} = M + R = L \qquad (8)$$

This equation tells us, that the less we loose and the more we recycle, then the less we need to mine. That is a sustainable society, only the losses will have to be replaced and that the losses must be less than the sustainable mining level. The potential for use is society, depend on both the losses, and how much we can recycle to amplify the amount mined to match society needs. This may seem trivial, but the actions of modern society tell us that it is not. At present, neither the society's needs nor the sustainable mining rate have been part of the consideration. Presently, humans rather mine at maximum technically feasible rate and immediately consume it all. Many metals are not or only poorly recycled. We most probably have an exceedance situation for many metals, where the present consumption is larger than the sustainable consumption; we have what some call an "overshoot" (Meadows et al. 1972, 1992, 2005);

$$\text{Exceedance} = \text{Present metal use} - \text{Sustainable metal use} \qquad (9)$$

This we will see in the results from our calculations later. The consumption reduction in % of today's use is calculated as:

$$\text{Reduction need} = 100 * \frac{\text{Present metal use} - \text{Sustainable metal use}}{\text{Present metal use}} \qquad (10)$$

This assumes the continued increase in output stops at today's rate and does not increase further.

4.3. The issue of mineable reserve size

In an earlier study (Ragnarsdottir et al. 2012, Sverdrup et al 2013a,b), we have made a study of how to estimate the ultimately recoverable reserves (URR). A false assumption overheard many times in discussions are "we can always go to mine lower ore grades, and thus URR is basically endlessly large". However, as the ore grades go down, the energy and extraction costs rise exponentially as more and more dead rock must be moved and processed, putting an effective stop to mining lower ore grades. Thus, URR is a finite number we can estimate with a robust methodology (Sverdrup et al. 2013a,b). The presently remaining recoverable resources (RRR) are the resources we can reasonably well be certain we actually have access to and R is the fraction of the supply coming from recycled material. From simple mass balance it also follows that URR is the sum of the presently available resources and the amount already dug up:

$$\text{URR} = \text{RRR} + \text{EA} \qquad (11)$$

Where URR is Ultimately Recoverable Reserves, RRR is recoverable remaining reserves and PEA is the presently extracted amount. We have defined the improvement factor as the inverse of the fraction that the sustainable metal consumption makes up of the present consumption. Generally, we get that there is a huge overconsumption of metals today. For the calculation, we have assumed significantly higher recycling rates than today, these can be seen as necessary target recycling rates. It is a task for future governments to incorporate such metal use efficiencies and build them into politics and attitudes. We have assumed the highest recycling rate for bulk metals to be 80% and for specialty metals of great value to be 90%. Higher recycling rates are very difficult to achieve in real life. The numbers are based on present global populations, with no net growth in material consumption after 2013.

For many metals we have we have documented a declining development (Sverdrup et al. 2011, 2013). Mining costs are strongly connected to energy prices as expressed by for example the oil price (Sverdrup 2013b). The lower the ore grade, the less metal is recoverable from the reserves. This puts an upper limit on the possible operational size of the Ultimately Recoverable Reserves (URR), somewhat different depending on the regression line we choose. One limit goes at an ore grade of 0.0002% or at about 2 gram/ton, possibly a lower estimate at about 0.00005% or 0.05 g/ton (Lenzen 2008, Prior et al. 2013). A reasonable limit is at about 0.5-1 g/ton, were gold is now (2013), below that the productions costs would be so high that the market would no longer be there for most metals.

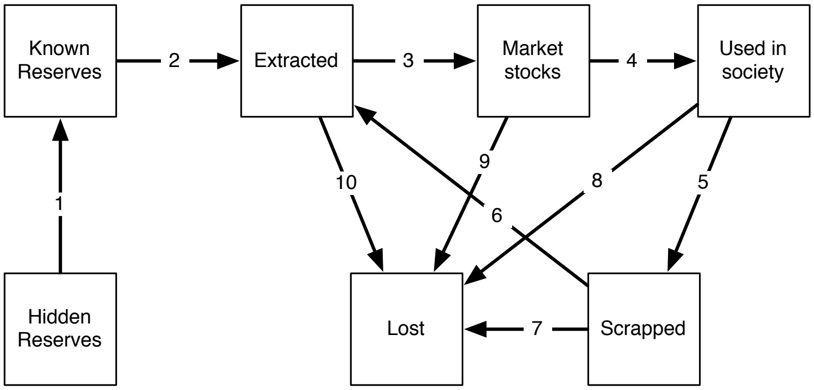

Figure 4. The flow chart for phosphate applied in the WORLD7 assessment model.

Figure 4 shows the flow chart for how most resources including phosphate are handled in the WORLD7 model, based on mass balance perspective. They can eithver be hidden (not found yet) from there they flow to be known reserves, after being found. From there they are counted up as extracted (after the action) and from that stock they flow either to the market or get lost. From the market they get used and go to lost and from the society they get either scrapped or get lost. From the scrapped stock part gets back to the extraction stock but some fraction gets lost.

4.4. Recycling and the price of metal

Recovery rates from ore is important as it puts a limit on the ultimately recoverable reserve estimates. URR not only depend on ore grade, but also on the fact that the lower the ore grade, the lower will the metal recovery rate be. Recycling rates we use in two ways; exploring what they are today, and what they need to be in order to have a sustainable supply to society. Recycling is a way to virtually increase a metals utility by using it several times. Thus may a society's need for a 100 units per year be fully sustainable with a supply of 10 units, provided the recycling is capable of returning 90 units to reuse. An amplification by a factor of 10 is thus achieved.

5. Results

5.1. Population overshoot

Figure 5 shows the sustainable estimates from 1687 to the present and plotted over the population estimate, the World3 model and the United Nations 2013 statistics based past record and future extrapolations. The plot suggests that the World is in population overshoot.

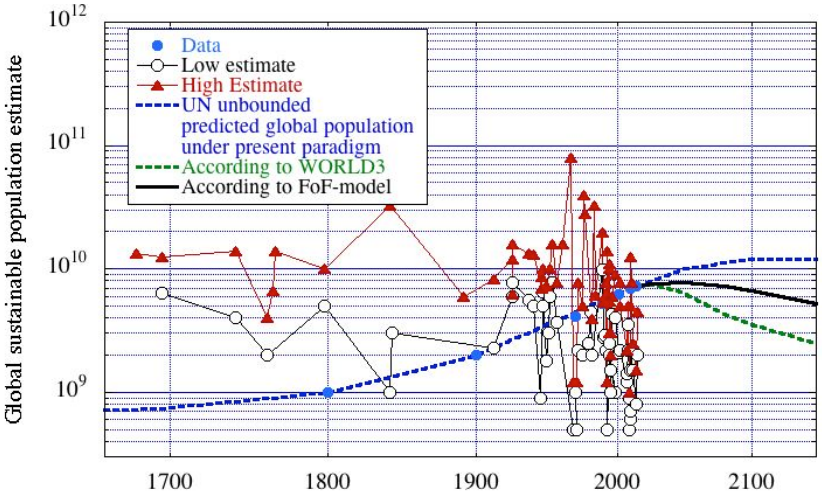

Figure 5. The estimates of sustainable estimates from 1687 to the present and plotted over the population estimates of the WORLD7 model, the World3 model and the United Nations statistics based past record and future extrapolations.

5.2. Present extraction rates, recoverable reserves and sustainable rates for the main metals

Burn-off estimates made by Ragnarsdottir 2008, Ragnarsdottir et al. 2011b, Sverdrup et al., 2014a,b,c, are indicative diagnostic indicators, sometimes signalling trouble of unspecified problems in the future. However, the estimates have a problem unless the estimates of reserves are ready carefully assessed and estimated, not overlooking significant hidden reserves. Until the mid or late 1990'ies, most reserve estimates for most resources were steadily increasing. The implications of the thermodynamic limitations of mass and energy conservation and the entropy laws set hard limits to how much metal is available. For metals, recycling can be a very important tool where in a steady state situation, only the losses from the system needs to be replaced. We can increase efficiencies and recycling to a certain degree, but driving systems without materials and energy is not possible. However, 100% efficiency does not exist for thermodynamic reasons. All processes have efficiency or recovery limitations.

Table 1 shows the fossil energy estimation of sustainable consumption of different metals, based on a 5,000-year time horizon and a high degree of recycling regarded as a necessary efficiency target. We have elaborated with different consumption levels, population levels and used the sustainable production according to the 5,000-year time perspective, employing equations 3 and 4. The ¾ -billon people world scenario is a viable alternative, if we incorporate certain consumption reductions for some metals.

Table 1. ***Fossil Energy Estimation*** *of sustainable consumption of different fossil resources and sustainable population based on present energy production methods in million ton OE.*

Fossil hydrocarbon fuel	Sustainable extraction, million ton oil equivalents/year				
	500 yrs	1,000 yrs	2,500 yrs	5,000 yrs	10,000 yrs
Oil	600	300	120	60	30
Coal	2,800	1,400	560	280	140
Natural gas	650	325	126	64	32
Shale gas	770	385	154	77	38,5
Exotic fuels	248	124	62	31	15,5
All hydrocarbon	5,120	2,560	1,024	512	256
Traditional nuclear energy	500	250	100	50	25
All renewable	2,400	2,400	2,400	2,400	2,400
Sum sustainable energy production	8,020	5,210	3,524	2,962	2,681
Present extraction of energy	*-14,000*	*-14,000*	*-14,000*	*-14,000*	*-14,000*
Excess consumption	5,980	8,790	10,476	11,038	11,319
% Reduction	-42.7%	-62.8%	-74.8%	78.8%	-80.8%
Sustainable population, million	3,713	2,641	1,789	1,505	1,363

Table 2. ***Summary of energy;*** *Estimation of sustainable consumption of all available energy resources, million ton oil equivalents year*

Source	Present extraction 2013	Sustainable extraction	Sustainable extraction	Sustainable extraction
		2,500 year	5,000 year	10,000 year
Oil	4,000	120	60	30
Coal	4,500	560	280	140
Natural gas	1,800	64	64	32
Shale gas	200	154	77	38.5
Exotic fuels	100	62	31	15.5
All hydrocarbons	**10,600**	**1,024**	**512**	**256**
Uranium 235	950	100	50	25
Plutonium	50	0	0	0
Thorium breeder	Not operative	22,000	11,000	5,500
All nuclear	**950**	**22,100**	**11,050**	**5,525**
Hydropower	1,400	4,500	4,500	4,500
Biomass	800	1,200	1,200	1,200
Solar direct harvest	200	1,200	1,200	1,200
All renewable	**2,400**	**6,900**	**6,900**	**6,900**
Sum	14,000	30,024	18,000	12,963
-Present consumption	-14,000	-14,000	-14,000	-14,000
Balance	0	+16,000	+4,000	-1,037

Table 2 shows a summary of energy for the estimation of sustainable consumption of different metals and the present overshoot. Assessment of the effect of choosing different time horizons. 10,000 years corresponds to the time to the next ice age, as well as the length of time we had urbanization on Earth. 5,000 years is the length of written history, thus the timespan we require children to learn about. 2,500 years is the time since the rise of the first democracies and the high civilization of antiquity. Adopting a shorter time horizon, is equivalent to omitting teaching history in school. We get huge present overshoot in consumption today, regardless of time horizon. Table 3 shows the sustainable population size within the planetary boundaries and Table 4 shows the estimation of sustainable consumption of phosphate.

*Table 3. **Metals**. Sustainable population size within the planetary boundaries. Estimation of sustainable global population based on sustainable metal consumption of different metals, assuming on a 5,000-year time horizon. BAT is best available technology. Present population is set at 7,100 million.*

Metal	Population in million persons sustained					
	Maximum at present use and recycling	Exceedence at present consumption and recycling	Present BAU consumption and BAT recycling	50% of BAU consumption and BAT recycling	25% of BAU consumption and BAT recycling	10% of consumption and BAT recycling
Aluminium	2,100	5,000	2,800	5,600	11,200	28,000
Chromium	121	6,979	191	383	766	1,915
Cobalt	425	6,675	710	1,420	2,840	7,100
Copper	187	6,913	249	498	996	2,490
Gallium	34	7,087	135	270	540	1,350
Germanium	125	6,975	500	1,000	2,000	5,000
Gold	190	6,910	192	384	768	1,920
Indium	66	7,034	199	398	796	1,999
Iron	618	6,423	989	1,978	3,955	7,910
Manganese	180	6,920	206	412	824	2,060
Molybdenum	355	6,745	568	1,136	2,272	5,680
Nickel	198	6,902	265	530	1,060	2,650
Platinum	2,955	4,145	3,322	6,644	13.288	33,220
Selenium	100	7,000	277	554	1,108	2,770
Silver	350	6,750	405	810	1,620	4,050
Tantalum	522	6,578	696	1,392	2,784	6,960
Tellurium	100	7,000	298	594	1,192	2,980
Tin	1,500	5,600	1,803	3,606	7,212	18,030
Vanadium	265	6,835	533	1,066	2,112	5,330
Zinc	180	6,920	355	710	1,420	3,550
Minimum	34	-	135	270	540	1,350

*Table 4. **Phosphorus** estimation of sustainable consumption of phosphate, based on a 10,000 year time-to-doom horizon and different levels of recycling. Million ton phosphate rock/year. The present total consumption is 310 million ton per year.*

Material source	Sustainable extraction	Sustainable consumption			
		Recycling 16%	Recycling 50%	Recycling 70%	Recycling 80%
Rock mines	0.8	0.9	1.6	2.6	3.9
Soils	19.9	23.6	39.7	66.2	99.3
Total	20.6	24.6	41.3	68.8	107.0
Consumption		-198.8	-198.8	-198.8	-198.8
Deficit		-174.2	-157.6	-130.1	-91.8
Reduction task		-87.6%	-79.2%	-65.4%	-46.2%
Population, mill		880	1,476	2,527	3,933

5.1. Resource efficiency

Metals are in principle indefinitely recyclable, however never with 100% yield. However, proper recycling may cause a significant reduction in the supply rates to society. We need to watch out when increased resource efficiency use is about to be achieved. Earlier experiences show that earlier gains in efficiencies have been used to expand the total volume, and not to do the same with less. Thus, some strong thinking and strong policies needs to be developed. We need to consider that diffusive losses are permanent losses that will not be recovered again in the era of humans. Thus we need to think of how to avoid or prohibit diffusive losses of important metals. Very clearly, the more valuable a metals is, the more of it we keep in society. For aluminium, recycling policies have been quite successful. In the continuing assessment we have adopted 5,000 years as a demonstration example.

5.1. Decoupling

Decoupling is a concept where we produce the same with less use of resources. For many European countries the trend seems to be going in the right direction. However, if outsourcing of production to low cost, low sustainability regime countries are phased in and the externalities brought home, all improvements disappear (Bringezu 2010, Fischer-Kowalski 2008). Some of the data, actually suggest that the resource units used per produced unit has slightly increased, making the situation worse. According to the data we have available, it seems like the strategy to persue decoupling has been successful to a very limited degree, if at all.

5.1. Sustainable consumption within sustainability constraints

The metals produced in the large amounts and used to build the world are: iron (1,200 million ton), aluminium (40 million ton), manganese (18 million ton), copper (16 million ton), chromium (16 million ton), zinc (11 million ton) and nickel (1.7 million ton) are all produced in amounts above 1 million ton per year. The big 6 metals (Iron, aluminium, chromium, manganese, copper and zinc) amount to 1,300 million ton metal per year, requiring at least energy equivalent to 1,400 million tons of oil per year in the future. In the not so far future, the available energy to mine all of this will have to come from hydropower, solar collectors and biofuels, and possibly nuclear energy based on thorium. Table 3 shows estimation of sustainable global population based on sustainable metal consumption of different metals, assuming on a 5,000-year time horizon. BAT is best available technology. Present population is set at 7,100 million, and the sustainability of that population is indicated by the colour. Sustainable means 100% supply capacity with respect to the need or more. The amounts shown for especially iron, aluminium, zinc, manganese and copper require large amounts of energy for their extractions and processing. Table 4 shows the phosphorus estimation of sustainable consumption of phosphate, based on a 10.000 year time-to-doom horizon and different levels of recycling. Even with 80% recycling there will be a deficit.

6. Discussion

6.1. Policy implications

From the results we may develop some policy considerations. The policy implications are large, as some of the necessary changes would take a long time under normal condition. However, probably such long times are no longer available, and a sense of urgency will be needed. Population numbers need to have come down by at least 60% by 2100 if difficulties are to be avoided (Morrigan 2007, Jackson 2005, Meadows 1972, 1992, 2005, Heinberg 2011, Sverdrup et al., 2013). That will be a very large challenge to do within the framework of democracy. But as Ehrlich (1968) said "..either we deal with overpopulation in time, or it will deal with us", and doing nothing, has a good likelihood of being unpleasant. Important for adapting a policy is to have a defined policy target, in our case sustainable consumption and then measure that against actual consumption, in order to monitor a sustainability gap. The size of this gap must be used as a policy success criterion, and the larger the gap, the more policy must be set in. For going towards sustainability, we need to address very tough policy challenges such as those given in the Ehrlich equation (Eq. 1):

1. Net consumption per capita
2. Population, the number of consumers
3. Degree of recycling of the resource amount supplied to society,
4. Resource efficiency of producing the net consumption per capita

Taking in the state of the issue, probably all of these may have to be addressed very soon. So far, progress on resource efficiency was off-set by a steady increase in consumers, and we have not been gaining in the race. Targets for a policy would be:

1. A governance policy to address the populations issue and bring down populations size by as much as 75% of the present. That will be extremely difficult, but necessary, and waiting may only make matter worse and cause the required reduction to be much larger. A plan should be made for each country as well as globally. On top of this comes the demographic transition, with a wave of elderly going through many populations. Because of significant delays, these issues cannot wait any longer. Population reduction can cause by three very different approaches to achieve the goal of a population decrease:
    I. A democratically decided policy to managed decrease of birth-rates, but through efficient social programs and social reforms based in democratic processes (Establishment of women's full rights, higher education for all, information about and access to safe contraception, provision proper life quality, dignified care of the elderly), is known to bring down fertility rates. This implies no violation of human rights, nor any use of force beyond what a democracy can decide and agree on. Many Western European countries have such policies in place by design or by fortunate accident, and do see a population decline at present.
    II. Forced management by top down dictate, like China's one-child policy. This is difficult to achieve under democratic conditions, and normally requires some kind of use of force, mild or strong. Chine has had success with its program, having reduced net population growth to zero by 2020.
    III. Mismanagement or doing nothing. By doing nothing, we are leaving the system to self-regulate (Ehrlich 1968, Meadows et al., 1972, 1992, 2005). That implies that resource restriction may cause case a population decline by increasing mortality, potentially a decline in birth rates, for the population through famine, illnesses, erosion of essential structures in society or man-made disasters like chemical pollution, war, violent conflict and or establishment of brutal oppression.
2. A sustainability policy taking a total grip on the economic system, in order to adapt it to a functioning economy under resource constraints. In needs to develop a new economic and social policy and grips must be taken to adapt sustainability-oriented market rules, in order to contain consumption, enforce recycling, limit corruption and limit wasteful or frivolous use. Commodity speculation must be banned as they tend to distort the market price mechanisms severely, promote a culture of consumption, and cause socially unfair redistribution of wealth (Extortion of rent for no service). Commodity-based derivatives serves no industrial purpose and is nearly useless and damaging. Any sustainability policy must have quantitative and verifiable goals, in order for success to be monitored and used for adaptive management with respect to future goals.

Of the options under point 1, we do know that option (I) is preferable as it stays within democracy and what we see as civilized politics, that option (II) has shown some success in China, and that option (III) is utter unpleasant and sometimes make things worse.

A host of policies will be needed targeting beside mining consumption and recycling, also consumption behaviours and population policies. However, that alone is not sufficient. Further measures for many countries will involve social policies and strengthening of human basic rights, introduction of participatory real democracy and efficient governance. All the time, there needs to be a surveillance through a measurement of the gap between the sustainability goal and the present situation, putting further impetus into further actions (Haraldsson et al., 2007).

6.2. About future generation and what constitutes a proper time horizon

By using up the resources we are indeed using them up in a way that we may be robbing future generations of possibilities. Not discussing it is also a way of indeed setting a time to doomsday, but refusing to recognize it and refusing to take any responsibility of those actions. Closing our eyes will not make the issue go away. Setting the time to "doomsday" in years, implying after this point in time, the society do not have, do not want to or cannot get any metals, and thus will be in very deep trouble.

It is a very troubling concept for many, as it has complicated and challenging moral implications and large ramifications for generations to come (See Ainsworth and Sumaila 2003, Boetteke 1997, Greer 2008, Hall et al., 2001, Hall 2008, Heinberg 2011, Morrigan 2010, Pontin and Rodrick 2007, Ponting 1993, Leslie 1998, Brandon Carter 1983, Gott III 1993, 1994, Sverdrup et al., 2002, 2013 for a discussion of time and sustainability). However, setting this time limit brings some very pertinent issues to the surface, and thus needs discussion. We have chosen to study three time horizons in this study; 2,500, 5,000, 10,000 years. They represent three different horizons;

- 2,500 years is the time since the beginning of classical antiquity and the emergence of modern society for the first time. This is the time when cities, bureaucracies, public office, democracy and complex manufacture of machines started.
- 5,000 years is the time since metal started to be used across society, the time since the emergence of the first metal-based technologies.
- 10,000 years is the time since the last ice age and the expected time until the next ice age will be in progress. When the era of ice age is reached, then all rules for society change anyway, thus that situation needs a completely different approach.

Saying "we would like sustainability" without specifying the time horizon is not removing the issue, it is just applying bad science practices by not stating the assumptions made. If the time horizon is unstated or unconsidered, it is even poorer practice. Thus, sustainability for any finite resource demands a clear assumption of a time horizon, with the follow-on ramification that no responsibility is taken for the time after the limit.

6.3. Future populations size and erosion of the sustainability potential

Population size is a real issue and we are on an impossible planetary track at the moment. Not dealing with it is very dangerous, and unattended will inevitably lead to a thermodynamically induced correction (Ehrlich, 1968; Ragnarsdottir et al., 2011). The global population passed 1 billion in 1800, 2 billion in 1927, 3 billion in 1960, 4 billion in 1974, 5 billion in 1987, 6 billion in 1999 and 7 billion in 2011 and 8 billion in 2022. Continuing business-as-usual, projections are that we would be more than 10 billion in 2050 and approaching 30 billion in 2100. Probably, serious problems will arise when 9 billion is passed as the resource base for food production will have been greatly exceeded (Sverdrup and Ragnarsdottir 2011). Already now, soils, agricultural land, waters, oceans and ecosystems we depend on for life support are being rapidly destroyed, eroded or degraded, reducing their regenerative capacity. This is already lowering the global carrying capacity, suggesting that we are in a process of running out of time.

6.4. On the essentiality of metals

One may justly ask, why do we want to evaluate a maximum population based on metals. The metals have little or no nutritional value for humans. However, they are essential for our present lifestyle and the level of production of all the things needed to support our lives. Without substantial amounts of metals, there will be problems in providing the equipment for food production, for providing the infrastructure needed to create the energy needed to produce food, machines, to do mining, run power plants or build homes. Thus, the assumption we have made is that if something similar to our present lifestyle should continue, then, the available metals will be sufficient for supporting a quantifiable number of people.

5.3. Running out of resources

Running out of resources is a metaphor for resources running into scarcity, causing increasing prices on resources, which may later affect the demand for these resources. Thus we will never physically run out of metals, but they may become so scarce that the high price will change the way we use them and how much we can afford to use them (see, Table 1 , Table 2).

5.4. Substitution

Some materials are qualitatively substitutable, but in terms of presently used amounts, they are not. A quick glance at Tables 1, 3-5 can verify that at an instant. Quantitatively we can only substitute a metal with one higher up in Table 5, it can never from below as the amounts available would be insufficient. That severely limits the possibilities for substitution.

7. Conclusions

All natural resources of geological origin are finite, and for all practical purposes, non-renewable. This applies to all fossil fuels, all nuclear fuels (uranium and thorium), all metals and minerals. There is no talk about sustainability in the use of any of these without a defined time horizon. The implication of setting a time frame, implies setting a day for doomsday, with all that comes with it. It is evident that many of the most important natural resources for human society may run into scarcity within the next decades, unless substantial changes to their management in society is changed. We need targets on the following items:

1. Global population size.
2. Maximize mine extraction rates for each metal within the sustainable based on several criteria:
    a. Available reserves, population target size and time horizon
    b. Environmental impact from the industry
    c. Availability of explosives, fuel, energy and metals for natural resource extraction.
3. Consumption patterns and amounts.
4. Accumulation in society as stock-in-use
5. Minimum allowable recycling rates for each metal

One key root cause for consumption beyond the planetary limits is a too large global population (Sverdrup and Ragnarsdottir 2011a, Meadows et al., 1972, 1992). Without change, disruptions in of human civilization is definitely an option. All the big infrastructural metals, like iron (peak year 2050), zinc (peak year 2035), copper (peak year 2048) threaten to run into scarcity in our times a decade after the peak years, aluminium production follows sooner than most would like to think. Without adequate amounts of cheap steel and oil (peak years 2012-2018, Hubbert 1972, Hirsch et al., 2005, Sverdrup et al. 2013f), we have very limited access to machinery, and human labour and animal traction will again become important sources of manufacturing energy. Tight recycling will be able to extend the lifecycle time of most metals until global population numbers will have declined to sustainable levels below 1.5 billion people sometime after 2100 (Sverdrup and Ragnarsdottir 2011a, Meadows et al., 1972, 1992). We can see from the scenario analysis the following points:

1. Business-As-Usual for metal use is in no way sustainable, regardless of how it is packaged. On the 50%-tile of the cumulative distribution of exceedence for metals, we have a reduction need for 90% for metals use to become sustainable, on the 90%-tile, the reduction need is 98% of today’s metal consumption.
2. If we assume we can make do with 10% of the present use and use the present best technical feasible recycling technologies and policies, we will be sustainable only for aluminium, cobalt, lead, platinum, rhenium, tantalum and tin.
3. The sustainable global population is in a size range of 1.5-2.0 billion, and must be reached before 2100, if we need to have aluminium, steel (iron, manganese, chromium, nickel, vanadium, molybdenum), copper and zinc available without exceeding the Critical Extraction Rate, and we need to make do with 10-25% of the present use per person. This will demand that we use the present best technical feasible recycling technologies and policies. If this is fulfilled, we would have a sustainable situation for aluminium, cobalt, germanium, indium, platinum, rhenium, selenium, silver, tin, tantalum will also be sustainable. Gold, tellurium, chromium, bismuth, antimony, gallium will all be in shortage. We will have to forsake certain technologies.

4. The amount of time we stay above the critical extraction rate, the resources will decrease fast, every day making the sustainable rate even lower, thus lowering the population sustainable level.

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