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Power of Doubling: Population Growth and Resource Consumption

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***Abstract*—**Sustainability starts with conserving resources for future generations. Since human's existence on this earth, he has been consuming natural resources. The resource consumption pace in the past was very slow, but industrialization in 18th century brought a change in the human lifestyle. New inventions and discoveries upgraded the human workforce to machines. The mass manufacture of goods provided easy access to products. In the last few decades, the globalization and change in technologies brought consumer oriented market. The consumption of resources has increased at a very high scale. This overconsumption pattern brought economic boom and provided multiple opportunities, but it also put stress on the natural resources. This paper tries to put forth the facts and figures of the population growth and consumption of resources with examples. This is explained with the help of the mathematical expression of doubling known as exponential growth. It compares the carrying capacity of the earth and resource consumption of humans' *i.e.* ecological footprint and bio-capacity. Further, it presents the need to conserve natural resources and re-examine sustainable resource use approach for sustainability.

***Keywords*—**Consumption, exponential growth, population, resources, sustainability.

I. Introduction

GROWING population accompanied by high resource consumption globally has imposed concerns for sustainability. Humans' life is dependent on natural resources. Since humans' existence, he is consuming natural resources in the form of abiotic resources (land, water, air and minerals) and other biotic resources. The symbiotic relationship between human and nature existed in past. Societies were based on natural resources. However, post-Industrial Revolution brought a change in human lifestyles, which has started imposing a severe danger due to excessive exploitation of resources.

In the last few decades, technological developments and globalization brought about huge change in the consumptive pattern of societies. It has resulted in increased consumption of energy, water, minerals and fossil fuels; increased use of land area; and increased waste generation. The environmental consequences due to this speedy consumption pattern are observed in climate change. Natural resources are depleting, ecosystems and the ecological systems are degrading and many species are under the threat of extinction [1].

Currently, humans extract and use around 50% more natural resources than only 30 years ago, at about 60 billion tons of raw materials a year. People in rich countries consume up to 10 times more natural resources than those in the poorest countries [2]. This situation creates argument like 'are natural resources exist for humans or nature should be independent of humans' or 'natural resources are fulfilling needs of current generations or can they do so for future generations as well' or 'should we conserve resources or deplete resources for development'. To understand this, there is need to understand the dynamics of human-environment interactions.

This paper elucidates the concept of exponential growth and how it is related with the growing population and resource consumption pattern. It further tries to explain the need for understanding earth's carrying capacity through ecological footprint and bio-capacity. Exponential resource consumption by the increasing human population is explained with the case examples of rice grains and chessboard story and other depleting resources. At the end, it tries to put forth the need to conserve resources for sustainability.

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II. Exponential Growth

A. Rice Grain and Chessboard

The story of rice grains and chessboard [3], [4] paves a path in understanding exponential growth. Once upon a time the King was pleased with a nobleman for his services. The King wanted to reward him by his choice. The nobleman comes with a chessboard and requests the King to give him rice grains. He insisted the gains should be given for 64 days symbolizing the 64 squares on chessboard. It should start with one grain on the 1^{st} square of chessboard on day one, two grains on the 2^{nd} square on day two, four grains on the 3^{rd} square on day three, likewise doubling the grains every day until the 64^{th} square. Although King was a good chess player, he was unaware of the amount of rice to be given to the nobleman. He was delighted with the modest sounding reward.

The quantity of rice grains on the chessboard square is expressed in Table I. All went well initially but, the requirement for 2^{n-1} grains on the n^{th} square demanded over a million grains on the 21^{st} square and 10^9 *i.e.* one billion grains in the 31^{st} chessboard square (Fig. 1 and Table I).

One billion is a fascinating number. To get the sense of scale of 10^9 in the context of 'Time' [5], it is supported by following scientific evidence:

- 10^9 seconds ≈ 31.7 years
- 10^9 minutes ≈1,900 years ago, Golden age of India (Gupta Empire) emerged and the Roman Empire flourished
- 10^9 hours ≈ 114,000 years ago, modern human beings lived in the Stone Age (Middle Paleolithic)

- 10^9 days ≈ 2.7 million years ago, Australopithecus, an ape-like creature related to an ancestor of modern humans, roamed in the African Savannas
- 10^9 months ≈ 82 million years ago, dinosaurs walked on the Earth during the late Cretaceous
- 10^9 years ago ≈ first multicellular eukaryotes appeared on Earth
- 13.7×10^9 years is the Universe's age [6]

To count from one to one billion in a single sitting, it takes approximately 95 years [7].

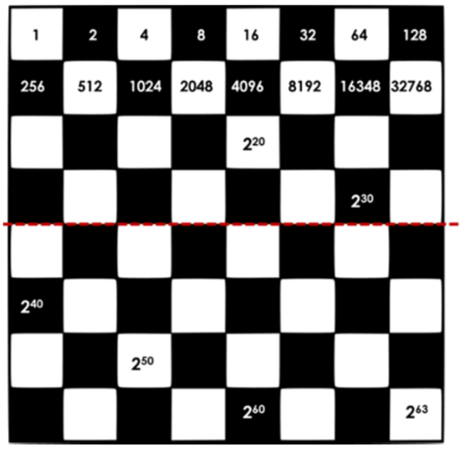


Fig. 1 Chessboard representing the number of rice grains

TABLE I
RICE GRAIN IN CHESSBOARD SQUARES

Square		Mathematical Expression
1st		$=1= 2^0$
2nd	1x2	$= 2 = 2^1$
3rd	2x2	$= 4 = 2^2$
4th	4x2	$= 8 = 2^3$
5th	8x2	$=16 = 2^4$
	....	
11th		$=1024= 2^{10}\sim1000=10^3$
	....	
21st		$=2^{20}\sim10^6$ =1 million =10 lakh
	....	
31st		$=2^{30}\sim10^9$=1 billion

Table II represents another interesting observation; the sum of grains in all preceding squares is always less than grains in the succeeding square.

TABLE II
GRAINS IN SQUARE AND PRECEDING SQUARE OF CHESSBOARD

Square	Preceding Square	
$2^2 = 4$	$> 2^0 + 2^1$	$= 2^2 - 1 = 3$
$2^3 = 8$	$> 2^0 + 2^1 + 2^2$	$= 2^3 - 1 = 7$
$2^4 = 16$	$> 2^0 + 2^1 + 2^2 + 2^3$	$= 2^4 - 1 = 15$
$2^5 = 32$	$> 2^0 + 2^1 + 2^2 + 2^3 + 2^4$	$= 2^5 - 1 = 31$

1) Guess the Quantity of Rice Grains

After few days, the King was not realized he did not enough grains to be reward the nobleman. What sounded like a modest reward, which was very easy to be given initially, became very tough later. But how is this possible?

Equation (1) represents the number of rice grains on the first half of the chessboard. Assuming 25 milligram as the weight of one rice grain, the rice grains in first half will weigh 107,374 kg (about 100 metric tons). The first square of second half contains more grain than entire first half. Equation (2) represents the number of rice grains on the entire chessboard.

$$1 + 2 + 4 \ldots + 2{,}147{,}483{,}648 = 2^0 + 2^1 + 2^2 \ldots + 2^{31} = 2^{32} - 1$$
$$= 4{,}294{,}967{,}295 = 4.29 \times 10^9 \quad (1)$$

$$2^0 + 2^1 + 2^2 \ldots + 2^{63} = 2^{64} - 1$$
$$= 18{,}446{,}744{,}073{,}709{,}551{,}615 = 1.84 \times 10^{19} \quad (2)$$

The rice grains in 64th square are 2.31×10^{11} tons and the entire chessboard is 4.61×10^{11} tons. This is around 4400 times more than India's annual rice production. India's rice production in 2011-12 is 1.05 x 108 tons [8]. The weight of the rice grains on the entire chessboard would make a pile of rice larger than Mount Everest. This is around 1,000 times the global production of rice in 2010 (464,000,000 metric tons) [9].

B. Exponential Growth

The rice grains and chessboard story represent exponential growth. It increases at a constantly growing rate. It is very slow in the early stages, but quickly accelerates. The graph in Fig. 2 illustrates how exponential growth $f(x) = 2^x$ (red) surpasses both linear $f(x) = 50x$ (green) and cubic $f(x) = x^3$(blue) growth for the first 12 units on x axis. Up till 5 units, the exponential growth was not noticeable, but suddenly at 9 and 10 units the exponential growth exceeded linear and cubic growth, respectively. Exponential growth is frequently measured in terms of doubling time. The shorter the doubling time, the faster is the rate of growth. Similarly, exponential decay occurs when the growth rate is negative.

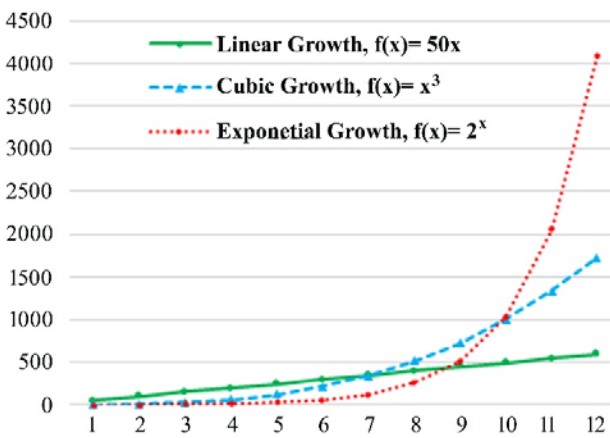


Fig. 2 Comparison of linear, cubic and exponential growth

III. HUMAN POPULATION

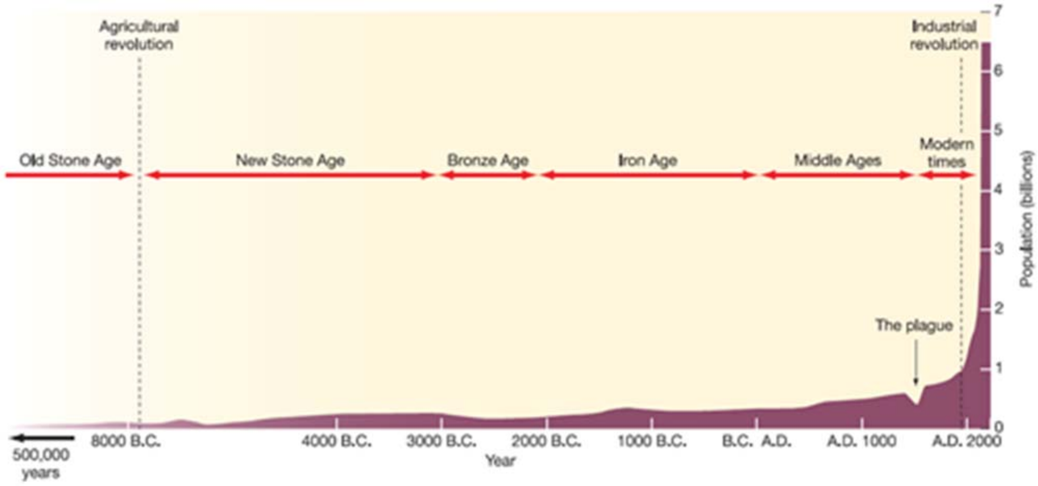
A. Population Growth

Growth is affirmative change which happens over a period of time. It is necessary for the socio-economic development of society. Growth can continue endlessly. If growth perpetuates forever, then it will require infinite amounts of land, energy and other resources to keep the growth going; however, resources are finite.

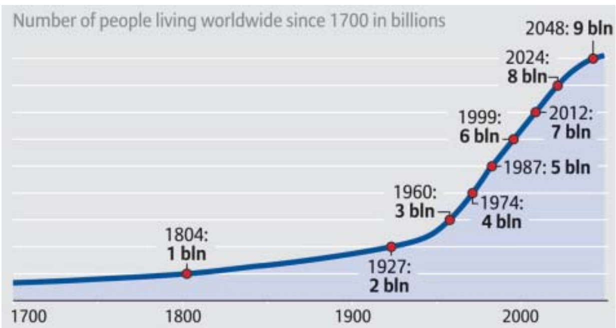
B. History of Human Existence and Exponential Growth

In the history of human settlement, population growth was constant. The global human population was 15 million before the invention of agriculture [10]. It increased to 250 million by the 1st century AD. It took 1,804 years for the population to reach one billion (=1000 million). It took another 123 years to double the population to reach two billion in 1927, but it took only 33 years to reach three billion in 1960. The global population climbed to 4 billion in 1974 (14 years), five billion in 1987 (13 years), six billion in 1999 (12 years) and 7 billion in 2011 (in just 11 years) [11]-[13].

Unless the population growth rate is reduced drastically, the population will continue to grow. It was estimated that the global population will reach 7 billion in 2013 (i.e. 14 years later), but this figure was surpassed in October 2011. It is further estimated it will take 15 years to reach eight billion (in 2028), another 16 years to reach nine billion (in 2054) and 100 more years to reach 10 billion (in 2183) [11]. Fig. 3 represents this population growth pattern. It shows exponential growth which is referred as the 'J' curve.



(a) World Population 10,000 BC–2000 AD [13]



(b) World Population since 1700 [14]

Fig. 3 World Human Population

In the 20th century alone, the world population has increased from 1.65 billion to 6 billion. The current global human population is twice of what it was in 1970's. A recent United Nations projection indicated that the world population will reach 10 billion in the year 2056 (much earlier than previously estimated) [12].

If a population has a constant growth rate through time and is never limited by anything like food, disease and other species, and resources remain unlimited; as well, environmental conditions are constant, then it is known as exponential growth [15]. But this exact situation is practically impossible. There are various factors that affect the growth pattern of a population (including human and all other species) like environmental factors, food resources, species interactions, natural calamity and human interventions.

C. Exponential Growth and the Rule of 70

Rule of 70 is used to identify the time to double when something is growing exponentially.

$$The\ Rule\ of\ 70\ is\ \frac{70}{\%\ Growth} = Doubling\ Time \tag{3}$$

For example, if a town's population growth rate is 2% per annum, then with the doubling rule, the population doubles in 35 years (70/2=35). Also, say a town's population is due to double in 70 years. Then the population growth rate is 1% per year (70/70=1). Just a 1% annual increase causes a doubling in 70 years [16].

Similar to the story of the rice and the chessboard, if a population begins at 1 million and grows at a steady 3% annually, it will add 31,000 persons in the first year and almost 61,000 in the second year. At this growth rate, its doubling time is 23 years (70/3 =23).

The population growth rate of 1.2%, if applied to the world's 6.5 billion population in 2005, it results in an increase of about 78 million people annually. Even if growth rates decline, the number of people added to the global population will remain high for several decades because of the large and increasing population size [17].

Population growth represents exponential growth resulting in exponential resource consumption.

IV. Resources

Resources are a life source for humans. Without them, neither the economy nor society could function. It provides food, water and air for survival; energy for electricity and mobility; wood and metals for making furniture and daily use items, minerals for medicines and agriculture; and construction materials for shelter.

Humans' use both abiotic resources like land water and metallic minerals (gold, iron, etc.); and biotic resources like live stocks (plants and animals) and minerals (coal and petroleum). Amongst these, few are renewable like solar and wind energy, but most are non-renewable resources. Minerals and fossils take a very long geological time to form. Metallic minerals can be recycled but not coal or petroleum. Many renewable resources can be depleted by human use but they can also be replenished by preventative and alternative means. For example, renewal time for agricultural is short, water is long and forests is still longer. The destruction and depletion of resources depends on the speed and quality of consumption.

The prices of fossil energy, raw materials and other resources are too low and cannot match with the real cost of the current level of resource use by the people worldwide [2]. Globally, the fuel is available at comparative lower price without including its environmental cost. If the external cost of its formation is added, it should cost much higher. Also, the post-fuel use imposes environmental threats like climate change, pollution and noise which further add to the external cost.

Resources are characterized by their utility; there is limited availability, and so there is a potential for depletion. Thus, conservation and sustainable patterns of resource use are essential for achieving sustainability.

A. Earth's Carrying Capacity

Resource consumption is understood through ecological footprint. An ecological footprint is a measure of human impact on the Earth's ecosystems. It is measured as the natural capital consumed per annum. It measures the capacity of available natural resources to assimilate and rejuvenate the amount of resources consumed and waste generated by the humans [18], [19].

Humanity is imposing heavy demand on the planet earth. Humans are taking much more resources from ecosystem and nature than it can replenish imposing threats for the future generations. Currently, humanity uses equivalent to 1.5 planets to provide the resources used and absorb the waste, i.e. it takes the earth one and half year to regenerate the resources used in a year. If current lifestyle continues, then second planet identical to Earth will be required by the 2030 to meet the growing demands for energy and resources [20] (Fig. 4).

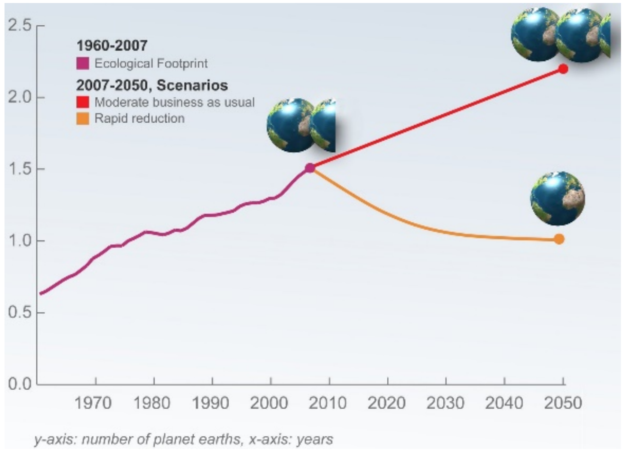


Fig. 4 Projected Growth Trend [21]

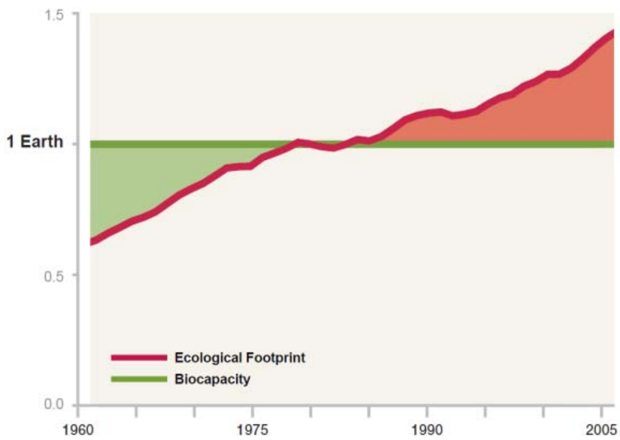
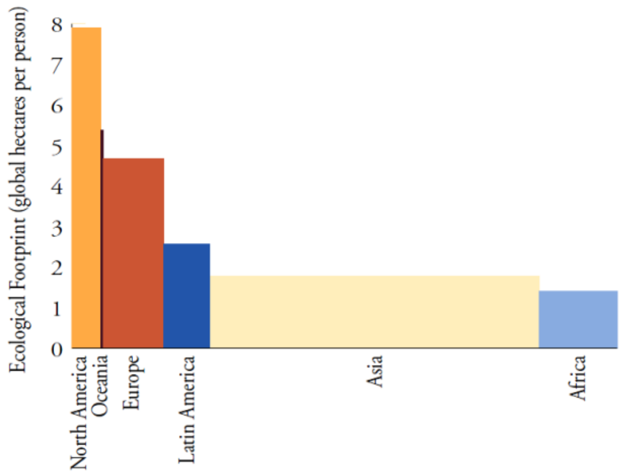


Fig. 5 Human Demand on the Biosphere, 1961-2006 [21]

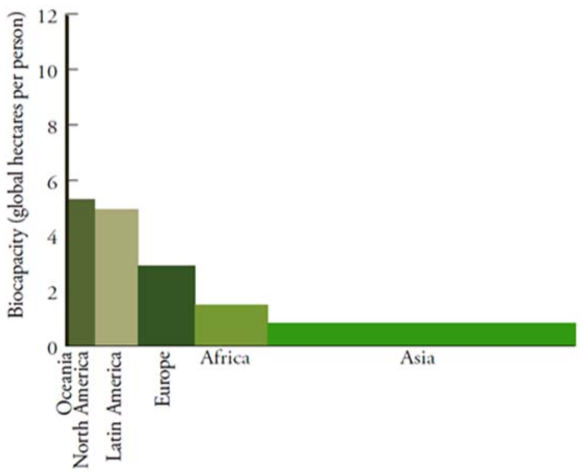
Average world bio-capacity is 1.8 global hectares per person; it means that there is an ecological deficit of 0.9 global hectares per person. In 1961, human used a little more than half of the Earth's bio-capacity and in 2006, it increased to 44% more than available bio-capacity [20], [21] (Figs. 4 and 5). It means there is serious ecological debt and it is growing every day. If the current population maintain the lifestyle similar to European standard of living (half of average American), then the Earth could support only about 2 billion people [16]. Thus, it's crucial to understand the resource consumption pattern to fulfill future needs.

2.7 hectares of the world's surface is used to supply food, fuel, raw materials and other natural resources to an individual. More than half of the ecological footprint is due to human's carbon footprint and others are due to cropland, grazing land, fishing grounds and developed land.

An average ecological footprint is 2.7 hectares (unevenly distributed between low, medium and high income countries). The ecological footprint of high-income countries is five times that of low-income countries [22]. The ecological footprint of all seven regions is more than its bio-capacity (Fig. 6).



(a) Ecological Footprint



(b) Bio-capacity

Fig. 6 Ecological Footprint, Bio-capacity and Population by Region, 2007 [23]

B. Resource Consumption and Exponential Growth

In 1789, Thomas Malthus predicted the future and suggested the population would increase geometrically, doubling every 25 years, and food production would grow arithmetically, which would lead to famine and starvation [24]; but, he overlooked the potential of farming and other technological development [25].

Increase in human population and consumption pattern has resulted in a rise in resource demand and use. Evidences of unsustainable resource use is noticed everywhere. Human intervention is putting high pressure on nature. The growing human population overexploits the earth's natural resources through land development, infrastructure development (dams/water management, energy production, mining and transport corridors, agriculture, aquaculture, hunting, poaching, fishing and pollution. Various problems related to the high usage of resources are degrading environment, depleting resources over-consumption, tragedy of the commons and myth of superabundance.

The world usage of natural resources is exponential [26]. For many resources the usage rate is growing faster than the population, it means both the growing population and average consumption per person in increasing. The resource consumption is driven by both population and capital growth. Over time, these resources have deceased in quantity and quality but increased in cost. For example, the world's known reserves of chromium are about 775 million metric tons, of which about 1.85 million metric tons are mined annually. At the current rate of use (Static Index), the known reserves would last for about 420 years. However, the actual consumption of chromium is increasing at the rate of 2.6% annually, so it will last for only 95 years. Suppose, there are five-fold more undiscovered new reserves, then the extended lifetime of the reserves will increase from 95 years to only 154 years. If it is assumed that 100% chromium is recycled, so that none of the initial reserves were lost, then demand will be fulfilled for another 235 years [27]. Table III represents the current mineral reserves and their projected availability with static and exponential index.

C. Ravaging Natural Resources

The seven plus billion population is ravaging natural resources. Few case examples are as follows:

According to the Living Planet Index (LPI), the populations of mammals, birds, reptiles, amphibians and fishes has declined by 52 percent since 1970 i.e. the population sizes of vertebrate species have dropped by half in less than forty five years [28].

The species in tropical regions (23.5° North to 23.5° South latitude) declined by more than 60%, while species in temperate zones (23.5° to 66.5° north and 23.5° to 66.5° south latitude) increased by 31 percent since 1970 [22] due to the anthropogenic and climate change.

Fish, one of the leading source of protein is severely impacted, with a nearly five times increase in global catch, from 19 million tons in 1950 to 87 million tons in 2005 [22]. In 2002, 72 percent of the world's marine fish stocks were being harvested faster than they could reproduce [29]. Overfishing has put a threat over 2 billion people as it is a primary protein source [30].

Water extraction from global aquifers is 3.5 times faster than rainfall can naturally recharge them [31]. The world's 37 largest aquifers were studied between 2003 and 2013 by Jay Famiglietti from California. It was found that 13 aquifers were being depleted with no or little natural replenishment.

Amongst these, eight aquifers were classified as "overstressed", and another five were classified as "extremely" or "highly" stressed depending upon the level of replenishment in each [32].

TABLE III
NON RENEWABLE NATURAL RESOURCES [27]

Resources	Known Global Reserves (tons)	Static Index (years)	Projected Rate of Growth (% per year)	Exponential Index (years)	Exponential Index 5 times known Reserves (years)
Aluminum	1.17×10^9	100	6.4	31	55
Chromium	7.75×10^8	420	2.6	95	154
Coal	5×10^{12}	2300	4.1	111	150
Copper	308×10^6	36	4.6	21	48
Iron	1×10^{11}	240	1.8	93	173
Lead	91×10^6	26	2.0	21	64

Worldwide, forests are rapidly destroyed. In the past decade alone, about 130 million hectares of forest were lost [33].

To fulfill the needs of the growing population a great extent of forest land is cleared for agriculture. This practice also degrades the soil and results in erosion. Half of the topsoil on the planet has been lost in the last 150 years majorly due to deforestation, over grazing and use of agrochemicals [22]. Loss of topsoil happens 10-40 times faster than it is formed. Around 10 million hectares of croplands are lost due to soil erosion annually, thus reducing the lands available for food production [34]. Global farmland is losing rapidly. About 75 million hectares cultivated land is lost every year due to soil erosion and urban sprawl [22]. The United States is losing mostly prime farmland for development at a rate of two acres (0.8 hectare) per minute; it is the fastest such decline in the country's history [35].

Food is most necessary for human life. Land is the primary resource for producing food. In 1970, globally, the potential land for agricultural was about 3.2 billion hectares (Fig. 7). About 0.4 hectares per person of arable land (land capable of being cultivated) are needed at present productivity. The arable land need thus reflects the population growth 'J' curve. The projection in the 1970s represents the need for arable land, with the existing population growth rate. As population grows, the available arable land decreases because it is removed for urban development. The dotted curves indicate land requirement with doubled or quadrupled productivity [27].

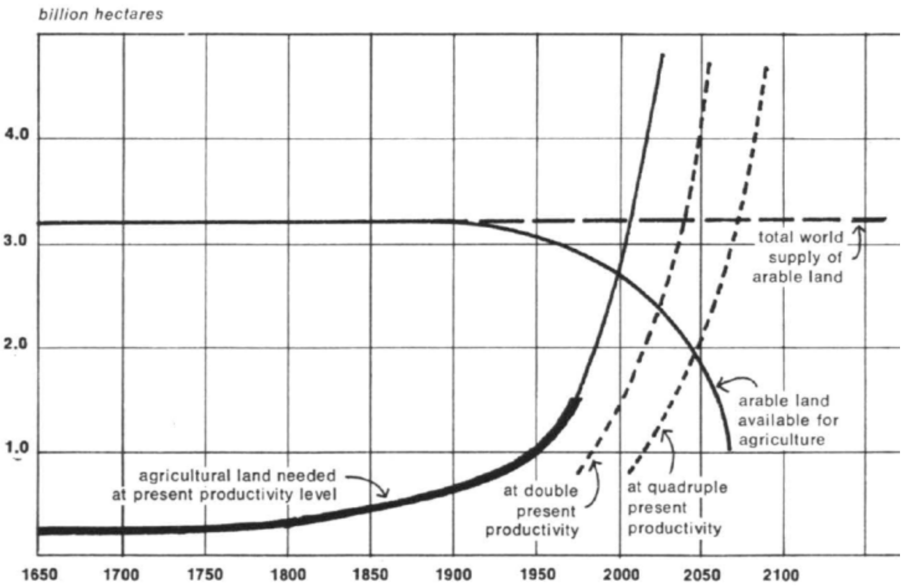


Fig. 7 Projected Arable Land Requirement [27]

Current lifestyle depends on exponential growth of the economy. Economic recession happens when there is no exponential growth for more than three consecutive quarters. The capitalist economic growth is also contributing to rising energy consumption. Since the 1970's, world energy consumption has been growing at 2.3% a year. With this growth rate, world energy consumption will increase to 130% till 2050 [15]. If this growth rate continues, energy consumption will increase 10-fold each century and the entire planet will reach boiling point in just four centuries. With these trends, there is need to drastically reduce the emissions intensity of world energy consumption.

The consequences of the above can be observed in climate change. There is a creation of massive waste and pollution. It is difficult to answer how many people can be fed on this earth and for how long? How many resources can we lose before humanity's own existence is threatened? The answer depends on the trade-off between producing more food, goods and other services with humans' needs and desires.

The exponential growth is observed in the physical necessities. There is another category of vital components for growth, which consists of the social necessities. The society depends on peace, social stability, education, health, employment and development. These social factors are much more difficult to assess or predict. The growing population is increasing social unrest, resulting in resource conflicts and wars, refugee migration, overcrowding, traffic congestion, political problems, higher basic needs costs, and youth unemployment, etc.

V. Re-examining Sustainable Resource use Approach

A. Conservation Measure

The human population is exploiting earth's natural resources (renewable and non-renewable - fossil fuels, minerals, biota, sunlight, water and land) for its survival without or with little conservation resulting in 'unsustainability'. A few groups or institutions like the environmentalist, ecologist, and strategists, as well as the World Wildlife Fund, the United Nations, etc. have realized the scale of the problems. They are advocating protection and better management of the earth's resources and habitat. This needs to be ingrained and implemented across the life cycle from extraction, production, consumption to its disposal. It will require more equitable resource governance, appropriate institutional arrangement, financial support and incentive to conservation, innovative and efficient resource management and above all, healthy consumption patterns. By now, the scale of the problem is sensed and some steps are taken from local to global levels. Conferences like the Stockholm Conference on the Human Environment (1972), World Commission, United Nations Conference, World Summit on Environment and Development (1982, 1992, 2002 and 2012), Intergovernmental Panel on Climate Change, etc. try to address the resource conservation and sustainable developments. The norms like pollution controls, forest conservation, endangered species regulations, etc. and the environmental taxes (polluter's pay, precautionary principles, external cost, etc.) are initiated at various forums.

B. Weak and Strong Sustainability

The debate between environment and economy is observed in weak and strong sustainability. Weak sustainability states that as long as the shrinking 'natural capital' is being replaced by gains in the 'human capital', total capital will stay constant and the current level of consumption can continue. Increased income level will augment environmental protection. Conversely, strong sustainability believes 'natural capital' and 'human capital' are complementary and not interchangeable. They consider the earth as finite and strongly believe that no habitable future is possible unless the demand is profoundly reduced [19], [36]. For sustainability, all capitals (environmental and socio-economic) should be maintained looking at its mutual interaction and interdependence.

C. Bacterial growth example

Bacteria reproduce by prokaryotic fission (divide by binary fission). One cell divides into two, two into four and continues the process in a geometric fashion. Assume that bacteria have all the food they need, but the limit to its growth are the walls of bottle. Say, in one minute it grows and divides into two cells. It continues to grow every minute until one hour, when the bottle fills up. When is the bottle half full? It is fifty nine minutes almost approaching an hour.

Currently, scientist, and professionals like environmentalist, ecologist, planner socialist, etc. are showing concerns towards environmental degradation and resource depletion. If the life on the earth since the first microorganism to the last living creature is assumed to be equivalent to one hour, similar as in the bacteria case, then it can be assumed that currently this is the 59^{th} minute on earth. Thus, there is a threat that by the time the efforts for sustainability are taken, the 59^{th} minute will be have passed.

VI. Conclusion

The world population doubled twice in the past century, energy consumption doubled about four times faster than that and the number of goods (like automobiles) has double more than 10 times the population. When the resource consumption grows, the doubling time is frightening, as it means during this doubling time, the resource use is more than in all history before that time. It will not take time to reach a square on the resource consumption chessboard that cannot just be filled. Earth is a finite planet, and exponential consumption of finite resources will lead to unsustainability.

Currently, population growth has declined to 1.13% per year from 2.19% in 1963. The annual growth rate is declining and it will continue to do so in the coming years. It can become as low as 0.5% by 2050. The declining growth rate may result in doubling time for population as two centuries [12]. The population growth may stabilize, but can a zero population growth rate be sustainable? Also, can this earth sustain the increasing 8 or 9 billion population with the appropriate standard of living?

Weak sustainability theorist supports that there is no need to worry as alternative sources of energy and population de-growth will resolve the environmental problem. This is being very optimist and assuming a new planet is available for survival as in the case of bacteria where a new bottle is accessible, but how much more time is required to fill a few more bottles. On the contrary, a strong sustainability thinker believes it is difficult to meet the resource needs for more than few years; otherwise, stop growing. Thus, there is an urgent concern for the widespread need to recognize that we cannot continue consuming more and more, and deplete the earth's finite resources.

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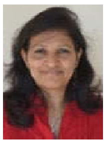

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