REVIEW ARTICLE
Reconsidering some of the Earth`s Biophysical Limits to the Long Term Sustainable Development of Humanity

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Abstract

Humans` existence as living organisms depends on some essential natural resources and ecosystem services. On the other side, nature has a certain speed of regenerating its resources required by humans. That`s why the nature`s speed of resource recovery should be taken in consideration by economic activities that use these resorces directly or indirectly, as it might be fundamental for the long term sustainable development of humanity. This requires the quantitative definition of the Earth`s biophysical limits that are crucial for the existence of life and monitoring of these limits by identifying the proper indicators of the Earth` performance.

Keywords: *Long term sustainability, Earth`s biophysical limits, Earth`s performance indicators*

1. Introduction

Basic human requirements as living organisms have not changed since the beginning of human history. Food, water, oxygen and clean water are essential factors for the survival of humans as a biological species, despite their level of historic development. Non essential requirements for human survival such as types of materials for housing, dressing, traveling, etc., which reflect different styles of living have dramatically changed in the course of human evolution, and they are subject to continuous changes in the future human societies. In the course of history humanity has continuously increased the amount and rate of appropriation of raw materials and energy resources. Starting from the second half of 20th century and onwards human pressure on natural resources was so obvious that it became part of international research agenda[1-4]. It became evident that natural resources left outside the economic models designed by the neoclassical economics, should no longer be neglected by humanity.
Several books attempted to change some paradigms of neoclassical economics[5-7]. It became clear that neoclassical economics could no longer serve as the golden tool in resolving the problems that humanity is facing in our time and is expected to face during the 21st century and later on. The cooperation between different domains of science, especially between systems ecology and economics may reveal to be very decisive in foreseeing and solving many problems related to human induced degradation of natural resources. In this context, this paper aims to a better understanding of some intersections between nature and human activities that are crucial for the long term survival of humanity on Earth.

2. Considering some main biophysical processes

Figure 1 illustrates some of the most important processes both in natural and human made systems. The Earth as a hole may be seen as a "factory" that produces a large number of "products". The general perception is that a human made factory may produce goods when two types of inputs are available: energy, raw materials (without forgetting the human labor). By analogy, Earth requires sun energy and raw materials to produce its resources needed for humans' survival. Sun energy is used to drive all natural processes in the biosphere, a small amount is stored via photosynthesis in the form of plant organic matter, and the rest is released again into space. The difference between the average Earth`s surface temperature and space temperature is created by the dynamic equilibrium of incoming and outgoing of sun energy. The heat energy contributed by the deep Earth and the tidal energy are of very small magnitude[8] in the overall Earth`s energy budget. Sun energy is several thousands larger than both of them taken together and thus the main driving force for most of the natural processes.

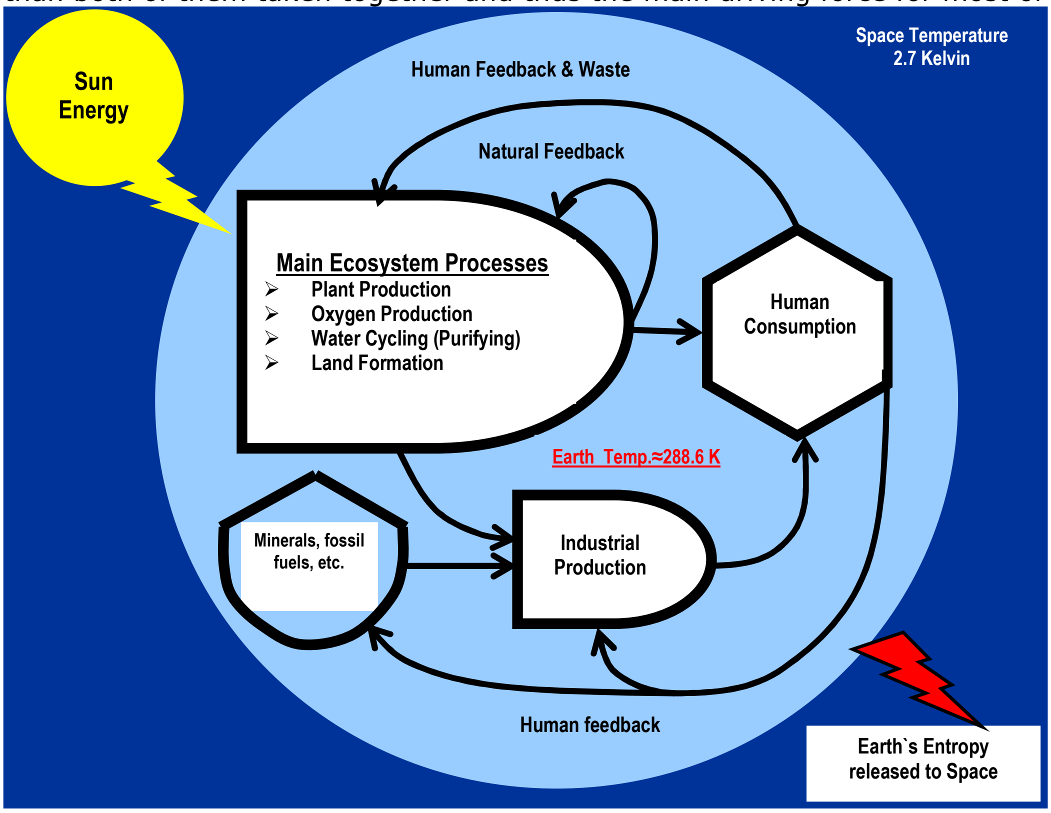

Fig. 1: A simplified view of the Sun-Earth-Space system, and some important energy and material stocks and flows on Earth.

Changes of Earth`s temperature either by fluctuations in sun`s radiations coming onto Earth, or by human induced irradiative forcing caused by gas emissions in the atmosphere (CO_2, CH_4, etc.) cause tremendous impacts on the life supporting processes, and particularly on plant photosynthesis which provides the food for all heterotrophic organisms on Earth.

Earth processes are closely related with each other. That means that a change in one of these processes is accompanied with the change of many other processes. A more detailed scheme of some ecosystems processes presented in figure 1 may reveal several causal links (figure 2). By using this figure we may find out which of the interrelated factors triggers changes the most, provided that we know the amount of energy and material flows.

3. Reconsidering some biophysical limits to consumption of renewable resources

A general criterion for approximately assessing human–nature interface might be the following sustainability inequality:

$$R>>F>>N \quad (1)$$

where R, F, and N represent respectively nature`s total renewable resources (R), human resource consumption which is used as af feedback to production processes (F), and human consumption of non-renewable natural resources.

This inequality may serve as a general rule to determine approximately whether or not human activities are within nature`s capacities to recover its resources. The components of this inequality can be calculated by using H.T. Odum`s emergy methodology[9] at different scales of human activity: from local to global. An application of this inequality for all the countries of the world has provided some insight on the level of sustainability for these countries[10-11].

This evaluation of sustainability is made from the energetic point of view only. The basic idea of the above mentioned sustainability inequality is that the upper limit of human consumption of natural resources is defined by sun`s energy spent to produce those resources.

Although this inequality might be a good tool for a quick evaluation of sustainability a more detailed look at different components of natural resources is required in order to enable concrete actions aiming at limiting the human consumption of resources within nature`s capacity to recover them.

Human society is a group of people who are first of all independent living organisms. That`s why before dealing with anything else they should survive as any other organism on Earth. This reasoning starts the theme of sustainability with a simple question: what are the most important natural resources humans (as living organisms) should consume to survive, despite their development stage as a society society?

The science of biology gives us the answer for the above question: any living organism on Earth (plant, animal, human) requires at least four basic natural conditions: food, water, oxygen and a suitable temperature that allows normal metabolic processes within individual living organisms. These resources are produced by Earth`s ecosystem processes that are driven by Sun`s energy which makes possible the recycling of different substances that are present on Earth.

The speed of production of the above mentioned renewable resources depends on the following inputs: the amount of sun energy and raw materials (substances) that are available per unit of time. Finding the equilibrium between natural resources recovery and their consumption by humans might be possible by using several criteria which are based on the measurements of energy and material flows and stocks.

3.1 A suggested biophysical limit due to food shortages caused by land degradation in the long run

The minimal condition for achieving the long term sustainability of land productivity is: human-induced Land degradation should be slower than / or equal to nature`s speed of land formation:

$$(\mathrm{Land_{Total}} - \mathrm{Land_{Used}}) * \mathrm{Rate_{Formation}} \geqq \mathrm{Land_{Used}} * \left(\mathrm{Rate_{Degradation}} - \mathrm{Rate_{Formation}}\right) \quad (2)$$

$$\frac{\mathrm{Land_{Used}}}{\mathrm{Land_{Total}}} \leqq \frac{\mathrm{Rate_{Formation}}}{\mathrm{Rate_{Degradation}}} \quad (3)$$

$$\mathrm{Land_{used}} \leqq \mathrm{Land_{Total}} * \frac{\mathrm{Rate_{Formation}}}{\mathrm{Rate_{Degradation}}} \quad (4)$$

Figure 2 shows that along with other biophysical limits, the limit of land use for food production is already transgressed by many folds compared to nature`s capacity to regenerate it. This conclusion suggests putting the land use and conservation on a very high priority agenda at national, regional, and global scale. Controlling land degradation will reduce human pressure by many folds for several natural resources at the same time. Going to the roots of land degradation which deals primarily with the extremely high population numbers in most of the world areas, may avoid or at least reduce the possibility of large scale human made disasters on regional and global level.

The problem of the overcrowded planet is often tackled by different authors[12-15] but has never been put on a very high priority agenda of the environmental policy making as the very basic cause of environmental degradation. Earth`s carrying capacity expressed in the form of an upper limit for population increase has to be one of the most important priorities now and in the coming decades. There are proposals for the reduction of global human numbers by keeping the fertility rate at approximately 1.5-1.8 over several generations in the 21st and 22nd century[16]. These types of proposals might present a starting point for concrete actions in this direction now.

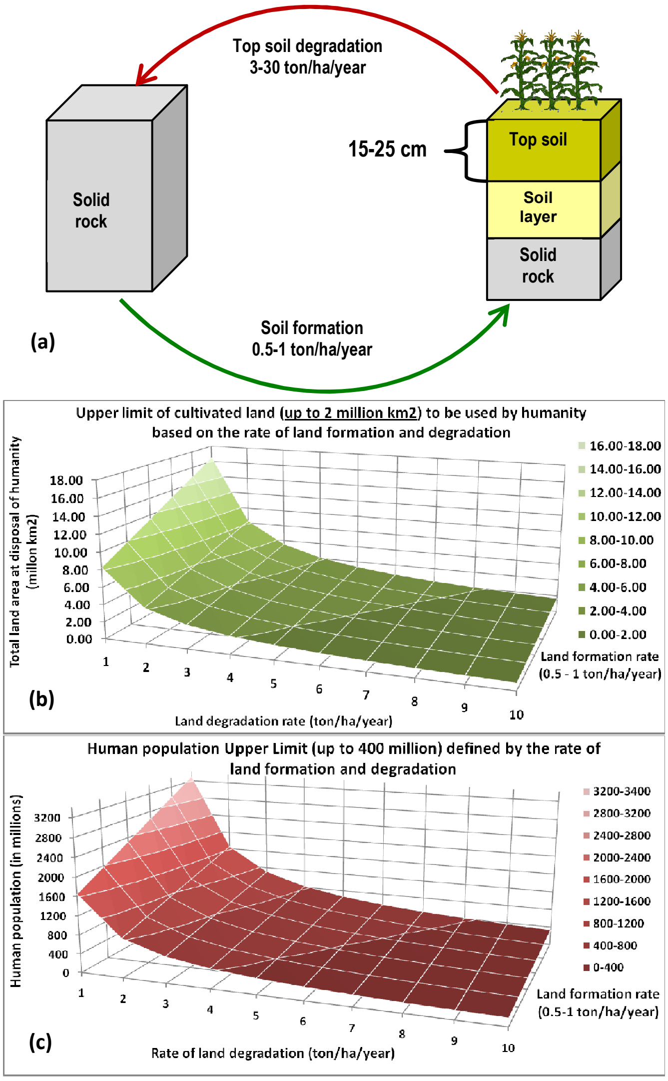

Fig. 2: (a) A schematic presentation of land formation/degradation processes; (b) a tentative sustainable level of land to be used by humanity based on the formula [4]; (c) a tentative sustainable size of human population assuming that each human being requires 0.5 ha of land (Pimentel & Pimentel, 2008), and the total good quality land is 16.51million km^2 at disposal of humanity for crop cultivation[17]. A more refined result may be obtained by applying the formula on a country by country basis.

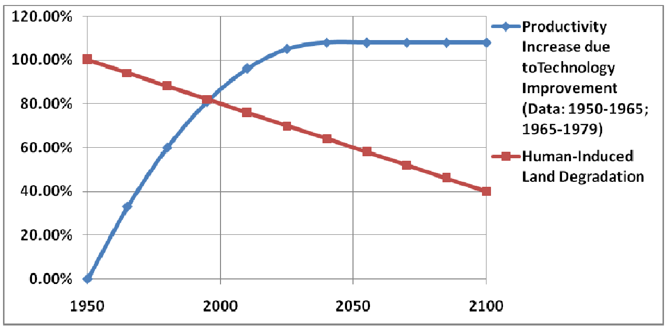

Fig.3: Projection of productivity increase due to technology improvement and productivity loss due to land degradation on global scale. It seems that technology innovations can not offset land degradation[18].

Due to soil erosion and other factors land productivity is being reduced[19-21]. Actually it seems that in the most densely populated countries (such as China, India) and countries like Saudi Arabia with vast desert areas land crisis has already started. The above mentioned countries have started to hire or buy agricultural land in other countries (especially in poor ones where land prices are low) to fulfill the growing demands of their increasing population with agricultural commodities produced elsewhere[22].

3.2 A revision of the upper limmit to carbon dioxide emissions

Oxygen production is inversely correlated with CO_2 emissions (figure 4). The importance of oxygen in the evolution of higher forms of life is recognized by different authors[23-25]. The atmospheric oxygen reservoir has been steadily built up for almost the whole Cenozoic era which comprises a time interval from 65 million years ago until present. At the same time, geological data show that most of the major extinctions of different species in the past Earth history might have been triggered by anoxia[26]. That`s why the projections of future trends of atmospheric oxygen concentrations might be an important indicator in designing the future of humanity on Earth. Nevertheless, although oxygen consumption rate by human activities of our time is much faster than its production rate by the world ecosystems[27], it might be very unlikely that oxygen concentration in the Earth`s atmosphere could fall below unacceptable levels that could endanger the existence of high forms of life on Earth (human species included) for several thousand years to come.

Reduction of atmospheric oxygen is inversely accompanied with the increase of carbon dioxide emissions at levels never recorded for the last 800 thousand years[28]. Figure 5 (a, b) is based on long term data of carbon dioxide fluctuations on the Earth`s atmosphere, starting from more than 1000 years ago till present[29]. It seems that CO2 concentration has never exceeded ice core data over the last 800 thousands years. That`s why figure 5 may illustrate the definition of the concepts buffering zone and tipping point of the ecosystems. It`s clear that the Earth ecosystems (land and oceans) were able to maintain atmospheric CO_2 concentrations within limits defined by very long term data. This ability may be defined as the buffering capacity of the ecosystems which was evident till the middle of the 19th century. After that moment a continuous trend of CO_2 increase clearly reveals the incapacity of the world ecosystems to control these emissions. This moment may be defined as the tipping point beyond which human induced atmospheric pollution (CO_2 emission) has not been sequestrated fast enough by the ecosystems through photosynthesis and ocean absorption processes.

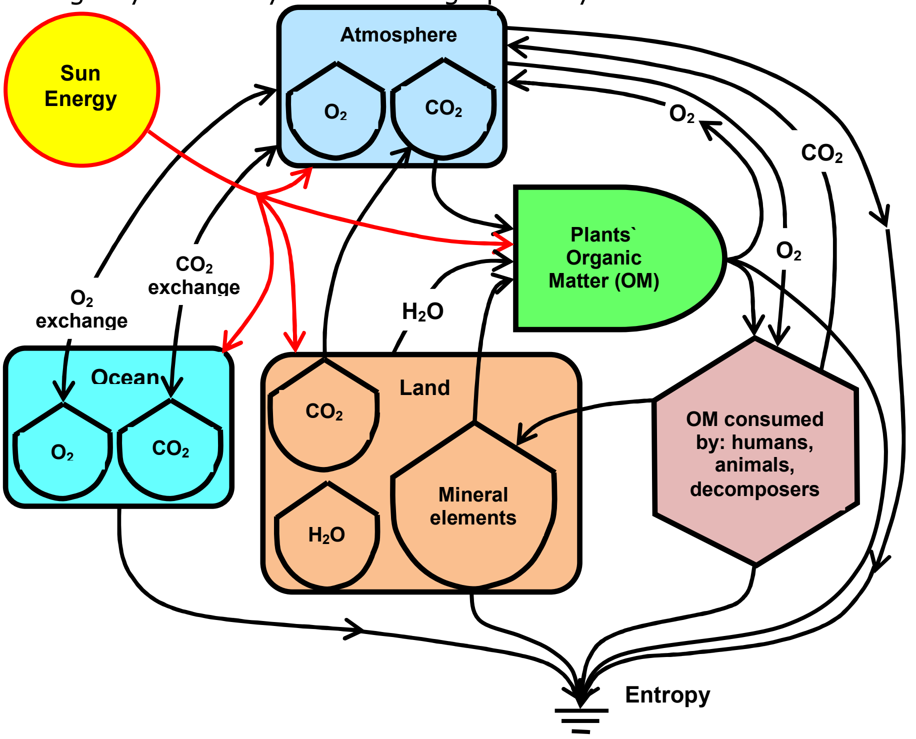

Fig.4: The influence of some natural processes on the amount of atmospheric oxygen and carbon dioxide emissions. The concept of entropy is used to describe "dispersed energy" which cannot be used to do work. The relation among energy, work and entropy may be presented in a simple form by the following equation: Energy = Work + Entropy. Energy is theoretically considered to be transformed 100 % into useful work. In this case concept of "energy" may be replaced by the concept "exergy" which by definition is the energy that is capable to do work.

Defining a reasonable upper limit to atmospheric carbon dioxide may serve as a key indicator of the Earth`s ecosystems performance. Several authors have concluded that human carbon dioxide emissions have started to influence Earth`s atmosphere since 8000 years ago[30-31]. Nevertheless these emissions have never exceeded CO_2 levels found in ice core data for the last 800 thousand years. This fact can be interpreted in the following way: although humans have added additional CO_2 through the land use changes, deforestation, etc for most of the Holocene era, nature has been able to counterbalance these emissions through different processes (figure 4). This counterbalancing effect continued until the middle of the 19th century (figure 5) with an average sequestration rate 0.43±0.78 Giga ton carbon/year (table 1).
In this study it is proposed to keep the upper CO_2 limit not higher than those revealed by ice core data: some 285 ppm, which is lower than CO_2 upper limits (named also boundary or target), proposed by other authors[32-33]. Using paleoclimate data as the main reference point in defining the most crucial biophysical limits might be a cautious attitude in environmental policy making, in order to avoid abrupt catastrophic shifts in Earth`s biosphere[34].
Based on the table 1 a reasonable rate of carbon emissions might be defined according to the atmospheric CO_2 concentrations over a thousand year time period. These emissions should be equal or smaller than the world ecosystems sequestration rate expressed in giga ton carbon (Gt):

$$\text{Emissions}_{\text{Human made}} \leq 0.43 \text{ Gt/year}$$

This rate might be considered a reasonable upper limit to annual CO_2 emissions rate as it is based on a thousand year data and screened against 800 thousand year CO_2 data. This rate is an approximate estimation and may be finetuned if additional annual CO_2 data will be available from ice core analyses for the last millenium.

Table 1: CO_2 emissions and global ecosystem`s sequestration over the time period 993-1940.

Time Period	Carbon Net Balance in Giga ton (Gt)		Average Rate (Giga ton C/year)	
993-1940	Emissions	Sequestration	Emissions	Sequestrations
	196.60	186.99	0.56	0.43
	Standard deviation		±0.68	±0.78

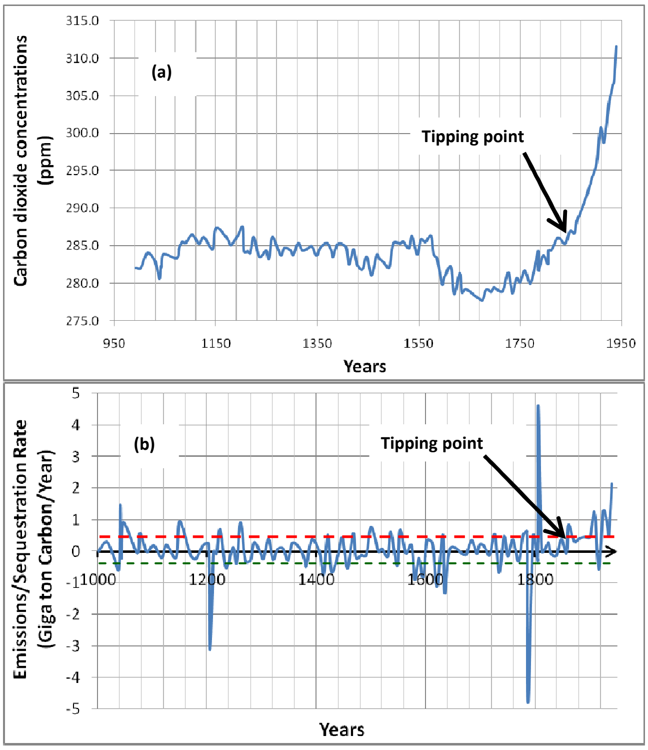

Fig. 5: (a) Carbon dioxide emissions (ppm); (b) Buffering zone defined by emissions/ sequestration rate (Giga ton Carbon/year). The tipping point marks the passage from the buffering zone to the uncertainty zone.

3.3 Average global temperature is an important indicator of Net Primary Production performance

Net Primary Production of plants provides the food for all types of organisms on Earth. At the same time NPP represents an amount of carbon dioxide sequestrated from the atmosphere for a certain period of time. This CO_2 sequestration is especially important for the plants that have long life cycles that last for centuries in the case of most woody plants. In the end of plats` life cycle part of this NPP production is buried in soil which stores part of atmospheric carbon for many thousands of years in the form of humus. We may assume that maximizing plants NPP makes possible a larger amount of carbon in soil. NPP is the result of two fundamental biological processes: photosynthesis and respiration. The relationship between them can be presented as follows:

Net Production of Photosynthesis = Gross Photosynthesis – Plant respiration

These processes are influenced by the environmental factors among which the most important are air temperature at surface level (figure 6a and 6b) and water content in soil. In this context monitoring temperature increase due to the positive feedback of atmospheric CO_2 increase by human activities is very important.

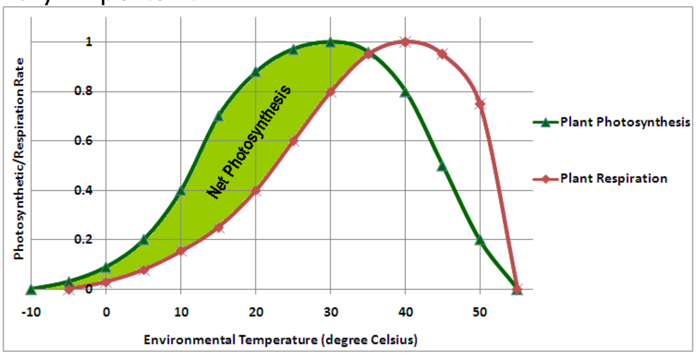

Fig. 6: Conceptual presentation: Influence of temperature in the relationship between Gross Photosynthesis Production and Plant Respiration. NPP is maximal between 10-25°C[35].

According to Cline[36] temperature increase by 2.6 – 3.6 degree Celsius will reduce considerably the productivity of agricultural plants by the 2080s. In his book he made his projections based on several models which take in consideration the scientific forecasts for temperature increase and water availability for agricultural production.

3.4 Water biophysical limit

From the total amount of water in the form of rainfall (some 40000km^3/year)[37] circulated by nature, humanity may potentially use some 14000km^3/year[38]. Growing need of the society for water in different sectors of activity will perhaps lead to water crisis after a few decades. This crisis may well coincide with an accentuated food crisis, thus reinforcing each other in exacerbating humanity`s problems of survival.

4. Nature`s speed of resource recovery and the golden rule level of capital

Neoclassical economics considers the ecosystems as a subsystem of the economic system. This perception of the environment was considered flawless when a small world population exercised a small pressure on the nature`s resources. This stage of humanity`s development is named an "empty world" scenario. In this case the speed of resource consumption by humans was slower than nature`s speed of recovering them.

Actually we are in a 'full world" situation as the consumption of natural resources by humans is faster than nature`s rate of resource recovery. In this paper we make a fine tuned interpretation of the supply-demand curves based on the resource rate of consumption and regeneration (figure 7a). The concept of the "tipping point" illustrates the moment when human consumption rate becomes faster than nature`s recovery rate. Between the tipping point and the "point of collapse" there is a zone of uncertainty in which a society ruled by neoclassical perception of the "empty world" can not or (for some reasons) does not like to see the decline of the very basic natural conditions required for its survival. The golden rule level of capital is an illustration of this contradiction (figure 7b) [39].

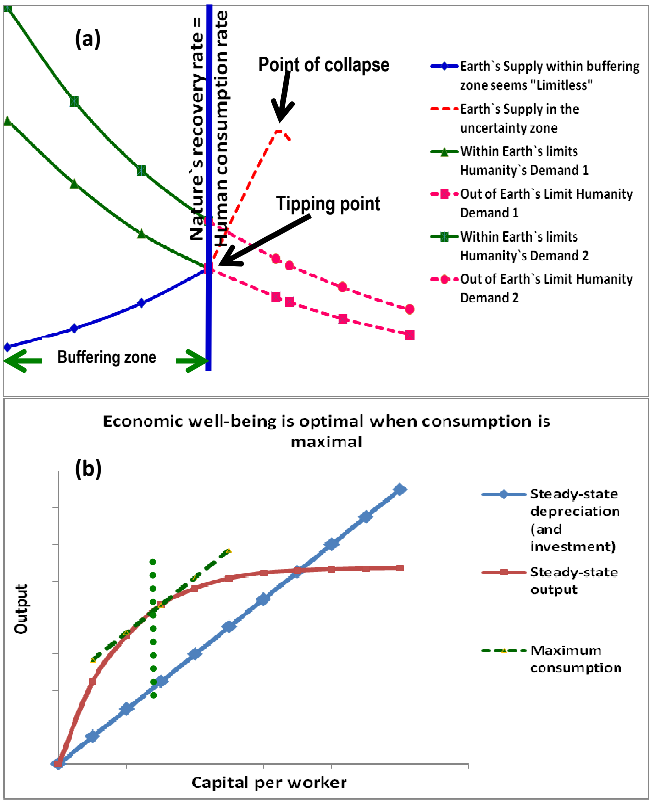

Fig. 7: Conceptual presentation: (a) human demand for critical renewable resources, Earth`s supply to humanity, and the recommended limit of resource consumption (b) one of the neoclassical economics postulates: golden rule level of capital assumes that economic well being is optimal when consumption is maximal.

5. Concluding thoughts

From the biological point of view human society is made of individual living organisms which may survive if some crucial conditions for life existence are created by nature. Some of these conditions are: food, oxygen, water, and optimal temperature. Present time scientific data show that some of the above mentioned basic conditions for life existence are threatened by humans themselves through the consumption of natural resources at faster rates than Earth can provide them. It seems that human population growth is the main driver of the increased pressure on vital natural resources. The economic theories of our time consider the economic growth as the main solution to the problems of well being for a population that is in continuous increase. Growth in economic terms means more natural resources appropriated from nature per unit of time, which consequenly leads to a further degradation of the natural resources that are critical for the existence of life on Earth. In these circumstances, a new economic paradigm designed according to the scientific principles of systems ecology and other pure and applied sciencies might contribute to solving the problems society is facing now and will very probably face in the near and far future.

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