AC 2009-2452: THERMODYNAMIC CONSIDERATIONS IN DETERMINING WORLD CARRYING CAPACITY

Scott Morton, University of Wyoming
Scott Morton received his Bachelor and Master degrees in Agricultural Engineering from the University of Wyoming in 1972 and 1978 respectively. He worked as an engineering consultant, a self-employed business owner, and a plant engineer before joining the University of Wyoming Mechanical Engineering faculty as a Research Scientist in 1999. He holds four patents and has two pending. Current research activities are in the areas of wind and solar renewable energy and computer aided laboratory instruction. Some of his many projects include radial flow and augmented flow small wind turbines, an electric car, and restoring his home, which was built prior to 1894.

M.P. Sharma, University of Wyoming
M.P. Sharma is Professor of Chemical and Petroleum Engineering at the University of Wyoming. He received Ph.D. in Mechanical Engineering from the Washington State University in 1977. His current areas of teaching/research interest are thermodynamics, drilling/production of oil and gas, enhanced and thermal oil recover, air pollution control and emissions from coal fired power plants. He has published and taught courses in pollution prevention, life cycle analysis and sustainability including complex interaction between energy, entropy and environment. He has published and given ASEE short courses on how to develop and teach online courses and active learning courses.
Thermodynamic Considerations in Determining World Carrying Capacity

Abstract

Applying knowledge of thermodynamic systems and laws (laws of mass, energy, and entropy) to the overall the earth system and to individual human systems, leads to the concept of a minimum-sized control volume (called “transition control volume”). Such a control volume is the minimal control volume that is theoretically needed to cycle all mass, energy and entropy flows required by the open system of an individual human. Such processes and fluxes are necessary for an individual human to exist without environmental limitations on life.

Using simplified assumptions of just two out of many necessary components, energy fluxes, the carbon cycle, and heat rejection, this thermodynamic model analysis is used to estimate the human carrying capacity of the earth with current non-renewable energy usage. If all the earth’s inhabitants were to use non-renewable energy at the same rate as the average Unite States citizen, the carrying capacity of the world would be about 770 million people. If the average energy consumption is limited to around 40 gigajoules per year (1200 watts) and is derived primarily from renewable energy sources and if natural background heat flux from the core of the earth is supplemented by 5%, the carrying capacity is estimated to be 3.8 billion. These estimates are based on using very simplified assumptions and limited input data (like using just three fluxes mentioned above) for performing the calculations using the thermodynamic model proposed. The model, however, is capable of more accurate and comprehensive calculations and predictions, if the quality and extent of input data is improved.

Observations of problems related to energy sources and sinks in human societies show more chronic sink-related problems than source-related problems. To think that energy sink-related problems can be solved by the increased use of supplemental, non-renewable energy is erroneous. If the entropy and temperature of the earth system are to remain at reasonably low level (natural level), the thermodynamic analysis presented in this paper, shows that use of supplemental non-renewable energy increases the entropy production, making the energy sink-related problems worse. Analyses of energy fluxes through the environment from this standpoint lead to the conclusion that the human carrying capacity is more likely limited by the transport of energy and entropy to single sink for the earth system and ultimately by the sink itself than it is by energy sources.

Introduction

Many authors have addressed the question of the human carrying capacity of the world, proposing various bases to estimate carrying capacity. Most rely on energy source or resource limitations, mainly food production, to establish maximums as illustrated by the following eight estimates.

1. 5.994 Billion E. G. Ravenstein, 1891, food production limitations,
2. 15.634 Billion Albrecht Penck, 1924, food production limitations,
3. 146 Billion C. T. De Wit, 1967, non-agricultural land use limitations,
4. < 1 Billion H. R. Hulett, 1970, production of essential materials at United States consumption rates,
5. 40 Billion Roger Revelle, 1976, agricultural production limitations,
6. 157 Billion Colin Clark, 1977, agricultural production limitations,
7. 32.799 Billion Higgin et al., IIASA, 1983, agricultural production limitations, and
8. 5.9 Billion Robert Kates, 1991, vegetarian diet, food production limitations.

World carrying capacity estimates actually date back to at least the 1600s with the number of estimates increasing with time. Cohen graphs between 60 and 70 carrying capacity estimates by date and notes that “A second striking feature of the graph is that the scatter among the estimates seems to increase with the passage of time, as more and more extreme (both high and low) estimates are proposed, challenged and defended.”\(^1\). Cohen’s data is reproduced in Figure 1.

![Figure 1](image)

**Figure 1** Estimates of how many people the Earth can support, by date at which the estimate was made.

Methodologies that have been used for carrying capacity calculations include:

- categorical assertion,
- curve fitting and extrapolation,
- generalizations from observed population densities,
- constraint by resources, either single or multiple,
- system models, and, more recently,
- ecological footprint analysis.

While the scatter of previous efforts at estimating the carrying capacity of the world suggests that carrying capacity can be significantly influenced by purely human factors such as the exploitation of supplemental, non-renewable, energy sources; agricultural practices; and international trade, thermodynamic considerations suggest that sink capacities and entropy transport requirements may, in fact, be limiting. The purpose of this study is to investigate how thermodynamic principles can be applied to the question of the carrying capacity of the world and to suggest areas of study that might shed additional light upon these issues.
**Thermodynamic Systems**

A thermodynamic system is a collection of matter and energy that exists in some configuration within an imaginary boundary called a control surface. The volume within the control surface is called the control volume. Such systems can be subdivided into three categories: 1) isolated systems that exchange neither energy nor mass with their environment across the imaginary boundary, 2) closed systems that exchange energy but not mass with their environment across the control surface, and 3) open systems that exchange both mass and energy with their environment across the control surface.

**The Concepts of Energy and Entropy**

Early investigators into thermodynamic systems of single substances found that the substances had certain properties, some independent of the mass of the substances such as temperature, pressure, and density and some dependent on the mass of the substance such as volume and heat. When the investigators considered changes in the state of the substance in a system, they observed that when closed systems go through a series of states, returning ultimately to equilibrium at the initial state, the cyclical integral of work is proportional to the cyclic integral of heat crossing the control surface. These observations led to the First Law of Thermodynamics, from which it can be inferred that all the energy in the system is a property of the system dependent upon the mass of the system, but not dependent on how the state was achieved. The energy can be subdivided into kinetic and potential energy with the remainder lumped into a quantity defined as internal energy. Further considerations show internal energy is a property of a system, so the conservation of energy can be quantitatively determined for processes as well as for cycles.

When open systems were observed, investigators found that mass is conserved, where the flow of mass into and out of the control volume equals the net increase or decrease in mass inside the control volume, and the mass transports energy across the control surface. Relativistic effects from Einstein’s famous equation for the equivalence of energy and mass, \( E = mc^2 \), where \( E \) is energy, \( m \) is mass, and \( c \) is the speed of light, on mass flows can be neglected for systems at ordinary conditions, since the ordinary effects are many orders of magnitude larger than the relativistic effects. Studies of these open systems found that energy is conserved across the control surface for open systems as well as closed systems. The equation for the rate of energy change for a control volume is:

\[
\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left( h_i + \frac{V_i^2}{2} + g z_i \right) - \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + g z_e \right)
\]

(1)

where \( \frac{dE_{cv}}{dt} \) is the rate of energy change within the control volume, \( \dot{Q}_{cv} \) is the rate of heat flow across the control surface, \( \dot{W}_{cv} \) is the rate of work crossing the control surface, \( \sum_i \dot{m}_i \left( h_i + \frac{V_i^2}{2} + g z_i \right) \) is the transport of energy into the control volume by the mass flowing in, and \( \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + g z_e \right) \) is the transport of energy out of the control volume by the mass flowing.
out. The energies associated with the mass flows are composed of the internal energy, \( h_i \), the kinetic energy, \( \frac{V_i^2}{2} \), and the potential energy, \( g\xi_i \), with \( g \) being the acceleration of gravity. For a closed system, the last two terms of Equation 1, representing the energy associated with the mass flows into and out of the control volume, are zero. Hence, the energy rate equation reduces to the net heat and work flows into and out of the control volume for a closed system. This equation is

\[
\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} \quad (2)
\]

Further observations were made that not all cycles are possible. For example, one can heat a rubber band by vigorously stretching and relaxing the band for many cycles, but heating the band will not generate cycles of stretching and relaxing. The fact that processes proceed in specific directions and not in the opposite direction led to the formulation of the Second Law of Thermodynamics which states that it is impossible to have a heat engine that receives a quantity of heat from a high temperature reservoir and produces an equivalent amount of work, and it is impossible to transfer heat from a low temperature body to a higher temperature body without an input of work.

The second law leads to another property, entropy, which allows quantifiable determination of entropy changes for processes as well as cycles. Entropy can be said to be a measure of the lost work or low-temperature, unavailable energy in a system. For example, the work needed to overcome bearing friction in a flywheel is converted to heat and the entropy of the flywheel system increases as the flywheel slows. Ultimately, the heat from bearing friction is transferred to the environment of the flywheel and the entropy of the flywheel system decreases to near its original value, but the total entropy of the flywheel system and its environment has increased.

The equation for the conservation of entropy flow for a control volume is

\[
\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{\sigma}_{cv} \quad (3)
\]

where \( \frac{dS_{cv}}{dt} \) is the rate of entropy change within the control volume, \( \sum_j \frac{\dot{Q}_j}{T_j} \) is the rate of entropy flow in the form of low-level heat across the control surface, \( \sum_i \dot{m}_i s_i \) is the rate of entropy change associated with mass flow into the control volume, \( \sum_e \dot{m}_e s_e \) is the rate of entropy change associated with mass flow out of the control volume, and \( \dot{\sigma}_{cv} \) is the rate of entropy production within the control volume. For a closed system the two terms of entropy transfer associated with the mass flows into and out of the control volume are zero. Hence, the entropy rate equation reduces to the rate of entropy transfer from radiant energy and the rate of entropy production within the control volume as shown in Equation 4:

\[
\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \dot{\sigma}_{cv} \quad (4)
\]
When applied to substances in a system, entropy can be considered an inverse measure of the capacity of the substances to perform particular functions in the system. An example to illustrate this concept is the irreversible mixing of various salts or other substances with water within a system, thereby increasing the entropy of the substance and making the water less useful or even totally unsuitable for some purposes, such as drinking water. The term “quality” is used to describe in broad terms the suitability of substances for the particular purposes to which they apply. The term “quality” will be used in this sense in the remainder of this paper and not in the thermodynamic definition of the ratio of the mass of vapor to the total mass of the system in a two-phase liquid-vapor mixture.

Classification of the Earth as a Thermodynamic System

Assuming that the earth and its near environs, to the outer edge of the atmosphere, is considered a thermodynamic system with a control surface at the outer edge of the atmosphere, the mass within the earth system is approximately $10^{24}$ kilograms. About $1.5 \times 10^8$ kilograms of dust and debris from space will enter the earth system during a typical year\(^3\). Over the 4.5 billion years of the world’s existence\(^4\) this amounts to about 66 centimeters of loose dust over the face of the entire globe. The escape of atmospheric constituents into outer space appears to be smaller than the influx of dust and debris. An average of $3.4 \times 10^7$ kilograms of atmosphere\(^5\) may escape into space annually, giving a net gain of mass of slightly less than $1 \times 10^8$ kilograms per year. Since these mass flows amount to less than 1 part in $10^{16}$ and the net mass gained is only about 1 part in $10^{16}$, the effects of the annual mass flow across the earth control surface can be considered insignificant.

Significant energy fluxes do cross the boundaries of the defined earth thermodynamic system. Approximately 177,500 terawatts (terawatts = $10^{12}$ Watts) of short wave radiation, predominately solar radiation from a black body of about 6,000 degrees centigrade\(^6\), enters the upper atmosphere. About 50,000 terawatts is reflected back into space\(^7\) as described by Equation 5\(^8\).

$$\dot{E}_r = a\dot{E}_i$$

where $\dot{E}_r$ is the rate of reflected energy flux, $a$ is the albedo or reflectivity of the earth, and $\dot{E}_i$ is the rate of incident energy impinging on the earth. The average net albedo of the earth is about $0.29$\(^7\). The remainder of the energy flux entering the earth system, 122,500 terawatts\(^7\), is circulated within the upper lithosphere and the earth’s atmosphere.

The bulk of the short-wave radiation entering the earth’s atmosphere is absorbed at the surface of the earth. A very small portion of this, approximately 133 terawatts\(^7\), enters the biosphere and is the basis of life. Plants utilize about half of this amount in plant respiration, generating about 67 terawatts\(^7\) of Net Photosynthetic Production (NPP) in phytomass.

The Second Law of Thermodynamics, i.e. heat cannot be drawn from a high-temperature reservoir and produce an equivalent amount of work, leads to the conclusion that the earth must also have at least one low temperature sink for the various thermodynamic processes on the earth, such as the weather patterns, ocean currents, and even life processes. This is, indeed, the
case with outer space at a background temperature of 2.7 degrees Kelvin being the only sink available and heat being transferred into it by long-wave radiation. On average the entire 122,500 terawatts of power circulating through the earth system is re-radiated into outer space as long-wave radiation and transporting about 43,300 terajoules per degree Kelvin per second of entropy produced within the earth system into outer space.

The amount of radiant energy flux that is transferred from the earth to outer space can be quantified by a modified form of the Stephan-Boltzmann equation:

\[ \dot{Q}_r = \varepsilon \sigma A T_b^4 \]  \( \text{(6)} \)

where \( \dot{Q}_r \) is the rate of heat flow, \( \varepsilon \) is the emissivity of the emitting body, \( \sigma \) is the Stephan-Boltzmann constant equal to \(5.6703 \times 10^{-8} \) W/m\(^2\)-K\(^4\) in the SI system of units\(^{10}\), \( A \) is the area of the emitting surface, and \( T_b \) is the absolute temperature of the emitting surface. The earth has an average surface temperature of 288 degrees Kelvin and radiates some 122,500 terawatts into outer space at 2.7 degrees Kelvin. Assuming the outer edge of the atmosphere is the emitting surface and is 200 kilometers above the earth’s surface\(^{11}\), the area of the emitting surface is \(5.43 \times 10^{14}\) square meters. The average emissivity of the earth is then 0.58. Since the amount of energy that can be radiated into outer space is proportional to the temperature of the earth raised to the fourth power, significant changes in energy flux can occur with small changes in absolute temperature of the earth, assuming the emissivity remains constant. This makes the temperatures of the earth system relatively immune to significant variability in the amount of energy rejected. Radiating an additional 100 terawatts of power would raise the temperature of the earth by less than 0.1 degrees Kelvin.

However, the radiant energy flux is directly proportional to the emissivity of the earth, so small changes in the emissivity can make significant changes in the average temperature of the earth system. A 5% reduction in emissivity would increase the average temperature by about 4 degrees Kelvin. Also, small changes to the albedo of the earth results in large changes to the energy flux within the earth system. A 5% change in albedo inversely changes the energy flux in the earth system by about 2500 terawatts, requiring about a 2.5 degree Kelvin compensating change in the temperature of the earth assuming emissivity remains constant.

A small amount of work crosses the control surface of the earth in the form of tidal energy. The tidal energy is about 0.002% of the radiant energy\(^7\) and is eventually re-radiated into outer space.

The fact that significant energy and work flows do cross the thermodynamic boundary of the earth while negligible amounts of mass cross the boundary, classifies the earth as a closed thermodynamic system. Therefore, the energy and entropy rate equations, Equation 2 and Equation 4 respectively, for closed systems apply to the earth as a whole. The amount of work crossing the control surface of the earth is very small compared with the radiant energy and could be considered negligible. In this case, the work term in the energy rate equation is also zero, reducing the energy rate equation to:

\[ \frac{dE_w}{dt} = \dot{Q}_r \]  \( \text{(7)} \)
Figure 2 on the following page (derived from Sørensen⁷) is a diagram of the energy fluxes for the earth. Tidal and anthropogenic energy flows are included.

**Classification of Humans as Thermodynamic Systems**

If a human is considered as a thermodynamic system, with a control surface covering the human in the manner of an outer skin, significant mass does cross the control surface. The human breathes, drinks, eats, sweats, urinates, defecates, and sheds hair, skin, tears, mucus, and other bodily substances. Energy also crosses the control surface of a human being in the forms of radiant, mechanical, electrical, and chemical energy. Since both mass and energy cross the control surface of a human being, they are classified as open thermodynamic systems. But humans and all other living organisms do live within the larger closed system of the earth, so ultimately all mass flows to and from the open systems of living organisms are contained within the closed earth system.

**The Implications of the Open Systems of Humans**

While there will be fluctuations in the entropy of a human system, the average must remain within fairly narrow limits for life to proceed without harm. Although entropy is produced within the human system through any number of processes, the overall entropy of the human system is kept reasonably constant by the transfer of low entropy mass into and the transfer of higher entropy mass out of the open human system in accordance with Equation 3.

Even when mass flows into and out of a human system are allowed to proceed uninhibited, the quality of the mass flows is significant. Some degree of harm will occur if the composition,
Figure 2  Schematic energy cycle of the earth with anthropogenic interference. Energy flows are in terawatts (10^{12} \text{ Watts}). Numbers in parentheses are uncertain or rounded off. (Adapted from Sørensen, 2004)
energy content, and entropy of the various mass streams vary from some optimum, i.e. if the “quality” of the mass flows is reduced. Furthermore, for a defined open thermodynamic system, such as a human, to operate continuously, sources of high quality mass must be available from the environment, and sinks must exist for the lower quality mass that flows from the system into the environment. For the processes within the open thermodynamic system of a human to be maintained, the qualities of the sources and sinks cannot change significantly over time.

The various mass flows across the control surface for a human being are critical to varying degrees. Some, such as air for breathing, can cause death if interrupted for more than a few minutes or if the composition changes even slightly, such as including 1,000 parts per million of hydrogen sulfide. If the open system of the human is changed to a closed system by shutting off all mass flows across the control surface, the entropy within the human system will rise dramatically in a very short time and the human will die. This is not only true for humans, but also for all living creatures.

The external sources and sinks, from which a living system extracts and rejects mass, exist entirely within the closed thermodynamic system of the earth. Since no mass exchange takes place across the control surface of the earth, as shown by Equation 7, these sources and sinks can only maintain adequate quality if they are reconstituted through processes within the earth system. Otherwise the entropy of these various sources and sinks increases over time and eventually they become unsuitable for supporting life. Equation 4 shows that the reconstitution cycles for these sources and sinks must ultimately be driven only by energy crossing the control surface of the earth to avoid increasing the entropy of the entire earth system. Any use of internal stored energy, i.e. fossil fuels, nuclear energy, or geothermal energy results in entropy production, which must either be transported out of the earth system by added long-wave radiation or isolated from the biosphere for long time periods, perhaps geologic time, within the earth system. Two examples of proposals to isolate entropy within the earth system for geologic time periods are geologic carbon sequestration and nuclear waste storage. Both of these isolation schemes are controversial and as yet unproven. Indeed, their very nature makes them difficult to prove. For purposes of this discussion, significant, long term storage of entropy within the earth system will not be considered.

**Defining the Minimal, Sustainable Human System**

The reconstitution processes, whereby the quantity and quality of the sources and sinks necessary to support the open systems of living creatures are maintained, include various biologic, geologic, and hydrologic cycles. One of the most important of these is the phytomass cycle which exists in the biosphere and generates NPP. In this cycle solar energy is captured through photosynthesis, the captured energy propagates through various food chains and is ultimately converted to low-level heat through decay processes, and finally the heat radiates into outer space via long-wave radiation, transporting entropy out of the earth system. The decay process returns vital materials to the photosynthetic process, whereby this cycle has been maintained over relatively long, i.e. geologic, time scales. This cycle is obviously a limiting cycle on most all life, including human life.
If the previously defined control volume of an open human system is enlarged so that the control surface encloses a small measure of the biosphere of the earth in addition to the human, the mass flows across the control surface that are necessary to sustain life will be reduced, since some of the required mass flows now cycle within the control volume. The required energy flows and entropy rejection across the control surface are correspondingly increased to operate the reconstitution cycles within the control volume. As the control volume is further enlarged, the required mass flows continue to decline until a point is reached where no mass flow is required and the system could theoretically be a closed system, exchanging only energy and entropy with the environment. This transition from an open thermodynamic system to a closed thermodynamic system marks the minimum environmental volume necessary for keeping the average entropy of the closed system constant while sustaining one individual human life. However, the actual size of such a control volume is highly dependent upon many factors, which include the entropy production activities engaged in by the human, the nature of the phytomass cycles within the control volume, and the energy and entropy fluxes across the boundary.

**Estimating Minimal Human Transition Volumes**

Since the overwhelming majority of the phytomass cycle occurs in a very thin film on the surface of the earth, the size of a transitional control volume may be defined by the required surface area on the earth to achieve transition phytomass cycles for individual humans. The associated control volumes are then prismatic solids extending from their apex at center of the earth to their bases at the outer reaches of the atmosphere.

A further simplification and idealization of these prismatic, closed, control volumes is that they be isolated from neighboring control volumes. In this case not only does no mass flow across their adjacent sides, but no net energy or entropy flows across their common boundaries. This simplification ignores natural processes that enhance some control volumes at the expense of others, but it is a valid simplification given long term averages over time and space. With this simplification, the only surface of the control volume through which significant energy and entropy flux can occur is the base of the prism at the outer edges of the atmosphere. Obviously, limitations on energy and entropy fluxes through the biosphere and ultimately through the base surface of these prisms will limit how small these control volumes can be made, and consequently, how many humans the earth can support. In addition, internal reconstitution cycles may further limit how small these control volumes can be made.

**Estimating the Carrying Capacity of the Earth from Transition Volumes**

Using averaged, idealized, transition volumes, the carrying capacity of the earth can be estimated. While many processes contribute to the size requirement of any particular transition volume, an individual process is likely to dominate in determining the minimal transition volume size. On average two processes appear to be candidates for limiting, critical, processes. These processes are both biological and are NPP generation and carbon cycling. Since the bulk of all biological processes on the earth take place in the very narrow region where solar energy is captured by plants, the portion of the prismatic transition control volumes of most interest is then the essentially planer area where the control volume intersects the earth’s surface. Therefore, an estimate of the number of transition volumes possible on the earth, and, hence the world carrying
capacity can be made by estimating the area on the surface of the earth required for NPP generation or carbon cycling for individual humans.

Additional research and studies are needed to verify the selection of these two processes and establish the priority ranking among the many possible averaged processes, but calculating the areas required for NPP generation and carbon cycling will at least demonstrate the application of transition control volumes to estimating world carrying capacity for humans.

—NPP Generation

In the biologic food chain considerable reduction occurs in energy transmitted between each trophic level from the primary producers through the various levels of consumers. In a relatively lush environment the average transmission percentage may be about $16\%^{12}$, but generally it is thought to average about $10\%^{13}$. This implies that over geologic time biologic systems have evolved to tolerate approximately $10\%$ predation without deleterious effects. Therefore, the maximum appropriation of the base trophic level, i.e. NPP, by humans should be no more than $10\%$ assuming humans to be the only trophic level above the primary producers. This is, of course, not possible, since NPP is utilized by a majority of organisms in the animal kingdom. There are estimated to be between 5 and 10 million animal species$^{14}$. Humans are only one of these, but they may be currently appropriating as much as $41\%$ of the total NPP, or over 28 terawatts$^{14}$. The World Conservation Union reports the extinction rate as “between 1,000 and 10,000 times greater than would naturally be,”$^{15}$ and this is likely can be traced to the appropriation of NPP by humans. While arguments can be made that some level of increase in the extinction rate can be tolerated, it is safer to bring that value as near the natural extinction rate as possible for humans to avoid joining the extinction roster. However, as a point of departure, assuming humans are allowed $10\%$ of the NPP will provide an upper limit to the human carrying capacity of the earth based on NPP. For a conservative estimate of the human carrying capacity of the earth this value should probably be significantly reduced, perhaps to a tenth of this value, or $1\%$ of NPP.

Humans require an average of about 105 Watts of metabolic power input$^{16}$, but metabolic power is not the only human power requirement. Additional draws on the NPP are required for fiber, recreation, and other uses. The amount of NPP required for metabolic and other activities is currently averaging about 4,300 Watts globally$^{14}$. Dividing the 67 terawatts of NPP by 10 and then by 4,300 Watt per person, gives a carrying capacity of approximately 1.6 billion persons using current NPP consumption values. The conservative NPP based estimate reduces this value by an order of magnitude to 160 million. The world population is currently about 6.5 billion.

—The Carbon Cycle

The above analysis assumes that life sustaining energy conversions take place with no effects on intermediate sinks within a transition control volume, but in fact such conversions also change mass reservoirs within the system. For example, the respiration process is vital for most animals, including humans. For this process to proceed, oxygen must enter respiring animals’ control volumes from the atmosphere, and carbon dioxide must exit to the atmosphere. Thus the earth’s atmosphere is both the source for oxygen and the sink for carbon dioxide and the entropy...
produced by the oxidation of carbon. If no carbon cycle existed in the larger earth system to
strip carbon from carbon dioxide, release oxygen, sequester the carbon in organic hydrocarbon
compounds and transport the produced entropy to outer space, the low entropy oxygen source
and the carbon dioxide sink would both eventually degrade and the animal life would cease.
However, carbon dioxide is removed from the atmosphere, oxygen is reconstituted through the
photosynthesis process, and the produced entropy from carbon oxidation is transported out of the
earth system through the phytomass process. Photosynthesis extracts about $5.7 \times 10^{13}$ kilograms
of carbon from the atmosphere annually, but about $2.8 \times 10^{13}$ kilograms of that is returned
directly to the atmosphere in the form of carbon dioxide through plant respiration. $2.9 \times 10^{13}$
kilograms of carbon remain in fixed photosynthetic plant material, i.e. NPP, giving an average
annual carbon conversion per unit area of $5.7 \times 10^2$ kilograms per square meter over the entire
surface area of the earth, about $5.1 \times 10^{14}$ square meters.

Humans respire and excrete about 127 kilograms of carbon per year, so every human needs an
average of 0.22 hectares of the earth’s surface area to cycle their metabolic carbon dioxide
production back to oxygen and organic hydrocarbon compounds. With the present world
population, about 2.8% of the surface of the earth is required to cycle humans’ metabolic carbon
dioxide production.

Humans also use significant amounts of bio-mass for fuels. This generates carbon dioxide that
contains about $1.5 \times 10^{12}$ kilograms of carbon. In addition, humans burn fossil fuels, which add
about $5.5 \times 10^{12}$ kilograms of carbon in the form of carbon dioxide. Together these sources
average about 1,080 kilograms of carbon per person, requiring about 2 hectares per person for
cycling bio-mass and fossil fuel carbon production. The total area needed is then about 2.2
hectares. Dividing this value by 0.10 to allow for other animal species, and dividing the total
area of the earth by this result gives a maximum world population of about 2.3 billion.

**Effect of Supplemental Energy Use on Transition Control Volume Size**

Humans are also augmenting the natural heat flux arising from the mantle by accelerating
nuclear decay processes, mining geothermal energy, and transforming energy stored within the
earth’s crust in the form of fossil fuels. These supplemental energy fluxes are used in food
production, shelter, clothing, transportation, entertainment, and a host of other human activities.
In 2001, citizens in the United States had an average individual supplemental flux over 100 times
greater than the metabolic level, about 11,300 Watts. Worldwide an average flux of 12.9
terawatts of supplemental energy, a per capita value of nearly 2,000 Watts, is currently
released, essentially on the surface of the earth and in the lower atmosphere. Food, food
processing, and food distribution appear to be the largest single component of this supplemental
energy. In Sweden the per capita energy cost of food is about 10,000 kilowatt hours per year,
almost ten times the approximate 1,200 kilowatt hour energy content of the food. The annual per
capita energy usage in Sweden was around 45,000 kilowatt hours per year, or over 5,100
Watts.

The question then is what effect this supplemental, stored energy has on the minimum transition
area required for a single human. Prior investigators into the carrying capacity of the earth
assume that the supplemental energy flux will reduce the transition area by supplying additional
resources, primarily food. However, the requirement that all energy and entropy fluxes into and out of the transition volume must pass through the base of the prism in the form of radiant energy, forces the transition area to be larger to accommodate not only the additional long-wave radiant heat energy produced in the supplemental energy conversions, but also the additional energy required to reconstitute all of the byproducts of the supplemental energy transformations and transport the associated entropy production into outer space. Some of the by-products of supplemental energy transformations (unavailable energy) include unburned hydrocarbons, carbon monoxide, petrochemical smog, particulates, and radio isotopes. Ultimately, the amount of low-grade heat rejected to space must equal the amount of supplemental energy being utilized in the system.

The massive use of supplemental energy is also altering both the emissivity and reflectivity of the earth by altering the color, texture, and surface coating. This is being done by altering the vegetative cover, terraforming the earth to a greater degree than any other natural agency, and altering the composition of the coating, i.e. the atmosphere, in ways that generally lower the emissivity. Greenhouse gases are an example of substances the lower the emissivity by changing the coating of the earth. Making the surface darker or decreasing the cloud cover are examples of changes that increase the emissivity. The biosphere plays a disproportionately large role in establishing the emissivity of the earth, so gross changes in the biosphere will significantly affect the emissivity. Without the atmosphere and the biosphere, the theoretical equilibrium temperature of the earth would be 394 degrees Kelvin as is illustrated by the average day side temperature of the moon, 365 degrees Kelvin. The conversion of non-renewable supplemental energy sources within the biosphere is making other observable changes today. It is clear is that the 43% increase in heat rejection from the core of the earth by the burning of fossil and nuclear fuels creates heat islands in and around cities. This is a well known and documented phenomenon. Some of these heat islands are of such magnitude as to alter weather patterns. Changes induced by humans in the thermal balances of bodies of water are also known and documented to have had profound effects on the aquatic biotic systems. It is likely that human induced changes play at least some part in thermal alterations that affect large scale weather patterns such as the El Niño and La Niña cycles.

**Societal Changes to Increase the Carrying Capacity**

There is a large variation in both the per capita energy consumption and the energy consumption per unit of Gross Domestic Product (GDP) among developed nations in the world. Even when other factors are considered, such as the climate of the nations, energy consumption can vary by more than a factor of seven without accompanying increases in the quality of life. Smil plotted infant mortality, food availability, life expectancy, and literacy rates against per capita supplemental energy consumption. A reproduction of Smil’s graphs are shown in Figure 3. All graphs show curves with a distinct knee around 50 gigajoules per year per person with diminishing returns for additional energy consumption above the knee. The implication is that an acceptable quality life can be maintained on an energy budget considerably lower than the approximately 350 gigajoules per year (11,300 Watts) of the average United States citizen. The world wide average of supplemental energy usage at the present time is about 70 gigajoules per capita per year, but large inequalities exist.
With the application of conservation measures and planning, it should be possible to reduce the per capita energy consumption into the 40 gigajoules per year range without any loss of quality of life. Under these conditions, about 1,200 Watts of power per capita, most if not all of the energy could be supplied from renewable sources. If humans appropriated 5% of NPP and were allowed to supplement that by another 1.7 terawatts from other renewable energy streams, about 4.2 billion people could be supplied with energy and the energy sinks could accommodate about 3.8 billion people.

The Limits of Energy Sources and Sinks

The current emphasis is finding additional energy sources for human activities. However, within the past few decades, there are actually few examples of human activities or quality of life being reduced by the lack of energy sources other than some 15 million persons who die annually from starvation. Some notable examples are the great Irish famine of the 1840s, the 1973 oil embargo and the Northeastern United States blackouts of 1965 and 2003. In these cases the problems resulted not so much from the lack of energy sources, but instead from socio-political, distribution, and other similar problems.

Less recognized are the limitations of the sinks required for rejecting low grade energy and entropy. Most of the “pollution” problems that exist are examples of the rejection of energy.

Figure 3  Four physical quality of life indicators plotted against the consumption of primary energy in gigajoules. Data from United Nations Organization (1980) and World Bank (1988).
transformation byproducts and entropy into intermediate sinks where they must undergo additional transformations or reconstitution processes driven by solar energy to be completely transformed into heat and radiated into outer space. Even heat itself can be a problem as evidenced by recent heat waves such as the 2003 heat wave in France that is reported to have killed around 3,000 individuals. Deaths from sink issues, such as air and water pollution, while not clearly documented, appear to be at least as numerous as source related deaths. Probably, if awareness of sink related deaths was increased, these numbers would far outstrip source related deaths. The problems associated with sinks also tend to be more intractable than energy source problems. While energy supplies can be redistributed, energy sinks, as evidenced by the European heat wave, are so diffuse that redistribution is nearly impossible by human actions. This fact suggests that the earth may be more energy-sink limited than energy-source limited.

Conclusions

Applying knowledge of thermodynamic systems to the overall closed system of the earth and to the open systems of individual humans, leads to the concept of minimum-sized closed control volumes. Such control volumes, called here transition control volumes, are the minimal, closed control volumes that are theoretically needed to cycle all the mass flows required by the open system of individual humans, to receive the solar energy necessary to run these cycles, and to reject the necessary heat energy and entropy produced into outer space. Such closed systems are necessary for individual humans to exist without environmental limitations on life.

Estimating such transition control volumes using just two out of the many necessary components, the phytomass cycle and the carbon cycle, gives a high human carrying capacity of the earth with current non-renewable energy usage of approximately 2.4 billion people. If all the earth’s inhabitants were to use non-renewable energy at the same rate as the average United States citizen, the carrying capacity of the world would probably be much lower, perhaps as low as 160 million people. If the average energy consumption is limited to around 40 gigajoules per year (1200 Watts) and is derived primarily from renewable energy sources and if natural background heat flux from the core of the earth were allowed to be supplemented by 5%, a world population of around 3.8 billion could be supported.

Observations of problems related to energy sources and sinks in human societies show more chronic sink-related problems than source-related problems. Analysis of the energy fluxes through the environment from this standpoint leads to the conclusion that the human carrying capacity is more likely limited by sinks for the cycles within the earth system and ultimately by the sink for the earth system, i.e. re-radiation of energy to outer space, than it is by energy sources.

Acronyms

\( a \) = the albedo or reflectivity of the earth  
\( E \) = total energy  
\( \dot{E}_r \) = the rate of reflected energy flux
\( \dot{E}_i \) = the rate of incident energy impinging on the earth

\( g \) = acceleration of gravity

\( h \) = specific enthalpy

\( m \) = mass flow across the control volume boundary

\( \text{NPP} \) = Net Photosynthetic Production in phytomass

\( Q_{cv} \) = heat interaction across the control volume boundary

\( S, s \) = total and specific entropy respectively

\( T \) = temperature

\( W_{cv} \) = work interaction across the control volume boundary

\( V \) = velocity

\( z \) = height measured from a datum

\( \dot{\sigma}_{cv} \) = entropy production rate

Subscripts:

\( i \) = inlet

\( e \) = exit

**Bibliography**


http://outreach.ecology.uga.edu/watershed/thermal.html, Institute of Ecology, University of Georgia, Athens, Georgia.