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A Novel Approach to Carrying Capacity: From *a priori* Prescription to *a posteriori* Derivation Based on Underlying Mechanisms and Dynamics

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Keywords

Carrying Capacity, mechanism-based models, realistic feedbacks, logistic equation, bidirectionally coupled Earth–Human Systems, from *a priori* prescription to *a posteriori* derivation

Abstract

The Human System is within the Earth System. They should be modeled bidirectionally coupled, as they are in reality. The Human System is rapidly expanding, mostly due to consumption of fossil fuels (approximately one million times faster than Nature accumulated them) and fossil water. This threatens not only other planetary subsystems but also the Human System itself. Carrying Capacity is an important tool to measure sustainability, but there is a widespread view that Carrying Capacity is not applicable to humans. Carrying Capacity has generally been prescribed *a priori*, mostly using the logistic equation. However, the real dynamics of human population and consumption are not represented by this equation or its variants. We argue that Carrying Capacity should not be prescribed but should instead

be dynamically derived *a posteriori* from the bidirectional coupling of Earth System submodels with the Human System model. We demonstrate this approach with a minimal model of Human–Nature interaction (HANDY).

- The Human System is a subsystem of the Earth System, with inputs (resources) from Earth System sources and outputs (waste, emissions) to Earth System sinks.
- The Human System is growing rapidly due to nonrenewable stocks of fossil fuels and water and threatens the sustainability of the Human System and to overwhelm the Earth System.
- Carrying Capacity has been prescribed *a priori* and using the logistic equation, which does not represent the dynamics of the Human System.
- Our new approach to human Carrying Capacity is derived from dynamically coupled Earth System–Human System models and can be used to estimate the sustainability of the Human System.

1. INTRODUCTION

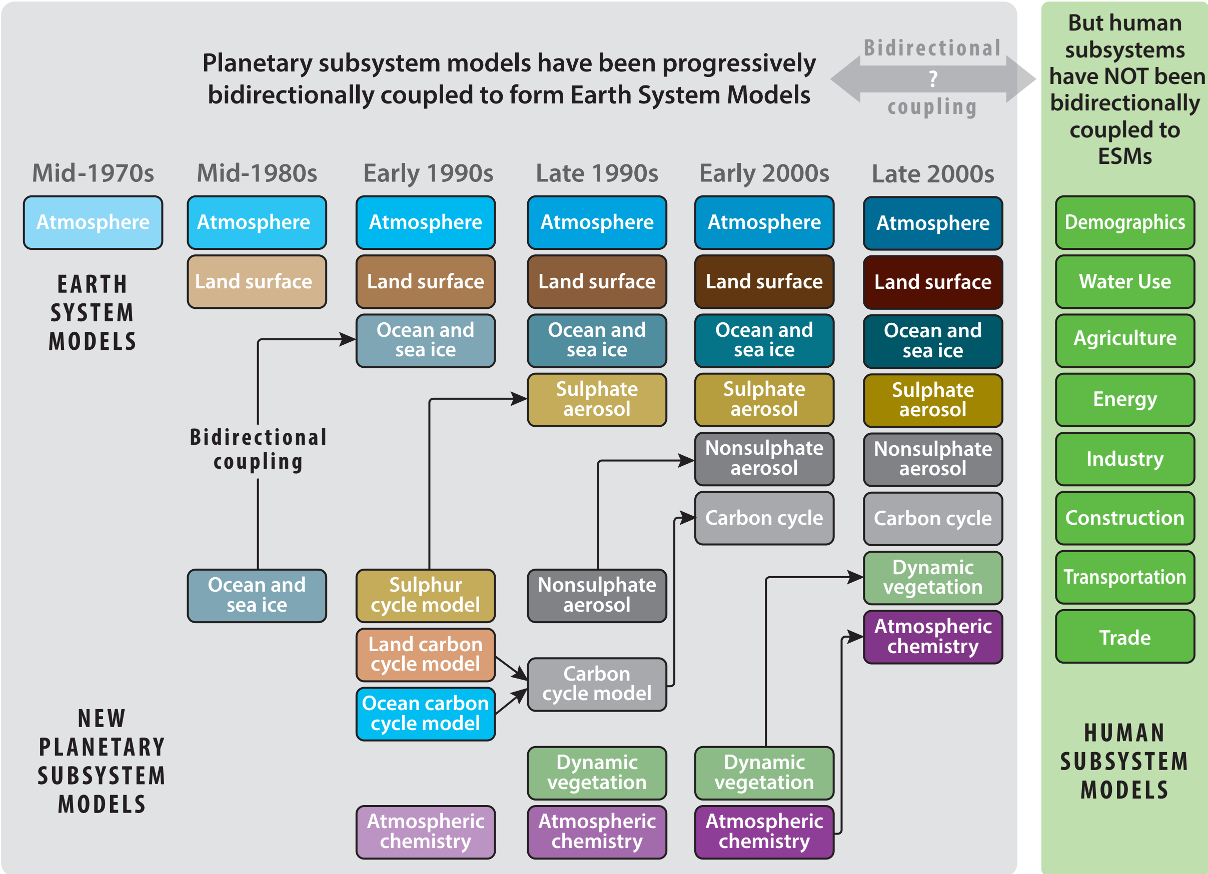
A large and rapidly growing scientific literature has emerged on the extent to which many of Earth's planetary subsystems are being driven and even overwhelmed by the rapidly expanding Human System, with potentially disastrous consequences not only for these planetary subsystems but also for the Human System itself. However, at the same time, a widespread view has emerged that the concept of Carrying Capacity, while useful in some biological and ecological systems, is not a useful measure for the Human System. Here we show that this view has resulted from the methodology of prescribing Carrying Capacity *a priori*. In particular, human population is modeled by prescribing Carrying Capacity in some variant of the logistic equation. However, the logistic equation does not represent the real mechanisms and feedbacks found in the coupled Earth–Human System. In contrast, we argue that human population change should be modeled with dynamic equations that represent real mechanisms, interactions, feedbacks, and parameters in the coupled Earth–Human System. This bidirectional coupling of Earth System models with Human System models can be used to derive human Carrying Capacity *a posteriori* from the mechanisms, variables, and parameters found in the real coupled Systems. Carrying Capacity should be determined as a product of a dynamic model, not prescribed as an *a priori* equation.

Section 2 provides a brief overview of the evolution of coupling different planetary subsystems in Earth System modeling, focusing on the critical role and nature of bidirectional feedbacks in this progressive process of coupling these subsystems. It points out that the Human System has become the primary driver of change across a range of planetary subsystems and therefore needs to be modeled and coupled with bidirectional feedbacks with the other Earth subsystems. Section 3 discusses the primary components of the Human System driving its relationship with the Earth's subsystems that need to be included in order for the combined systems to be modeled dynamically and to derive Carrying Capacity. Section 4 then turns to describing the many difficulties with earlier *a priori* conceptions of Carrying Capacity and the problems with applying it to human population. Section 5 presents our new approach to deriving, rather than prescribing, Carrying Capacity, which produces it *a posteriori*, so that it emerges as a product of the bidirectionally coupled Earth–Human System model. Thus Carrying Capacity is applicable for the Human System and is fundamentally important for measuring sustainability. In contrast, discarding the notion of a human Carrying Capacity would undermine the need to plan for long-term sustainability of the Human System and for Earth's environmental systems. Section 6 provides discussion and conclusions.

2. THE NEED FOR BIDIRECTIONAL COUPLING OF THE EARTH SYSTEM WITH THE HUMAN SYSTEM

2.1. Historical Evolution of Earth System Modeling

The historical evolution of Earth System modeling demonstrates the need for bidirectional coupling among the planetary subsystems of the model. Atmospheric scientists in the 1960s developed the first mathematical models to explain the dynamics of the planetary climate system, starting with models of the atmospheric system coupled to simple surface models (e.g., Manabe et al. 1965). Subsequently, new subsystems such as ocean, land, sea-ice, clouds, vegetation, carbon, aerosols, and other chemical constituents were coupled to make Earth System Models (ESMs) more physically complete (**Figure 1**). These couplings had to include bidirectional feedbacks (Manabe et al. 1965)



The Human System has become the main driver of change in the Earth System, but their bidirectional coupling is still required, especially to model climate and climate change (Motesharrei et al. 2016). We argue this is also necessary for modeling the Human System and Carrying Capacity. The Earth System side of this figure is adapted from the IPCC. The original figure is at https://archive.ipcc.ch/ipccreports/tar/wg1/figts-box3.htm.

Figure 1

Progressive coupling of Earth System Models and the lack of bidirectional coupling with human subsystems. The Earth System side of this figure is adapted from the Intergovernmental Panel on Climate Change (IPCC). The original figure is at **https://archive.ipcc.ch/ipccreports/tar/wg1/figts-box3.htm**.

between these subsystems. As we show in the next section, the critical importance of implementing *bidirectional coupling* is demonstrated by the modeling of the El Niño–Southern Oscillation (ENSO), which in the real climate system results from the coupled dynamics of the tropical ocean and the atmosphere subsystems.

2.2. Bidirectional Coupling in Earth System Modeling

Efforts to predict El Niño, a phenomenon produced by the interaction and feedbacks between the tropical atmosphere and the ocean, had failed until Cane et al. (1986) and Zebiak & Cane (1987) created bidirectionally coupled models of the tropical atmosphere and the ocean and succeeded in predicting the 1986 El Niño. Prior to the 1980s, atmospheric models and ocean models were only coupled unidirectionally. The atmospheric models were influenced by sea surface temperatures (SSTs) but could not, in turn, change them, while the ocean models were affected by atmospheric wind stress and surface heat fluxes but could not, in turn, change them. These simple "one-way" couplings could not represent the positive, negative, and delayed feedbacks occurring in the real climate system that produce the El Niño phenomenon. Zebiak & Cane (1987) developed the first bidirectionally coupled ocean–atmosphere model prototype. This model was able to predict, for the first time, El Niño episodes several seasons in advance (Cane et al. 1986). Similarly, advancing the modeling and prediction of droughts required bidirectional coupling of the land and atmosphere subsystems (Koster et al. 2009). Most global climate models have since implemented bidirectionally coupled atmosphere–ocean–land–ice submodels. This has been necessary to accurately model climate change. This progression of coupled models demonstrates that very important outcomes will be missed if the models fail to include the bidirectional feedbacks between the various components of the real systems that the models represent.

2.3. The Human System Is Driving Changes in the Climate System

In the same way, modeling climate change would fail (i.e., be unrealistic) without also bidirectionally coupling the Earth System with the Human System that is driving the climate change (Motesharrei et al. 2016). **Figure 2** illustrates how the growth in the Human System is driving the growth of the main greenhouse gases. Note that the population growth with the advent of the Agricultural Revolution about 10,000 years ago underwent a strong acceleration around the Industrial Revolution (~1750) when large-scale use of fossil fuels started, and an even stronger acceleration with the "Green Revolution" (~1950) when the major use of fossil fuel products was introduced in agriculture, as we discuss below.

The human impact on the climate began in the pre-Industrial Era through the processes of forest clearing, irrigation agriculture, and soil depletion by agricultural societies (Ruddiman 2003, 2005), but since the large-scale exploitation of fossil fuels during the Industrial Era, the human impact on climate has become massive from the outputs (pollution) of the Human System into the Earth System—i.e., the emissions of vast stocks of greenhouse gases [mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)] from the consumption of these fossil fuels, as evident in **Figure 2**. The overwhelming scale of these emissions for the Earth System can be understood from the fact that it took Nature hundreds of millions of years to store energy from the Sun by converting atmospheric stocks of carbon into the underground stocks of fossil fuels, but humanity is now consuming these stocks (and thus rereleasing them into the atmosphere) in just a few hundred years. So, in our current Fossil Fuel Era, humanity is putting back into the atmosphere those carbon stocks stored away by Nature at a rate on the order of one million times faster than it took Nature to store them away. This extremely rapid consumption of Nature's stores

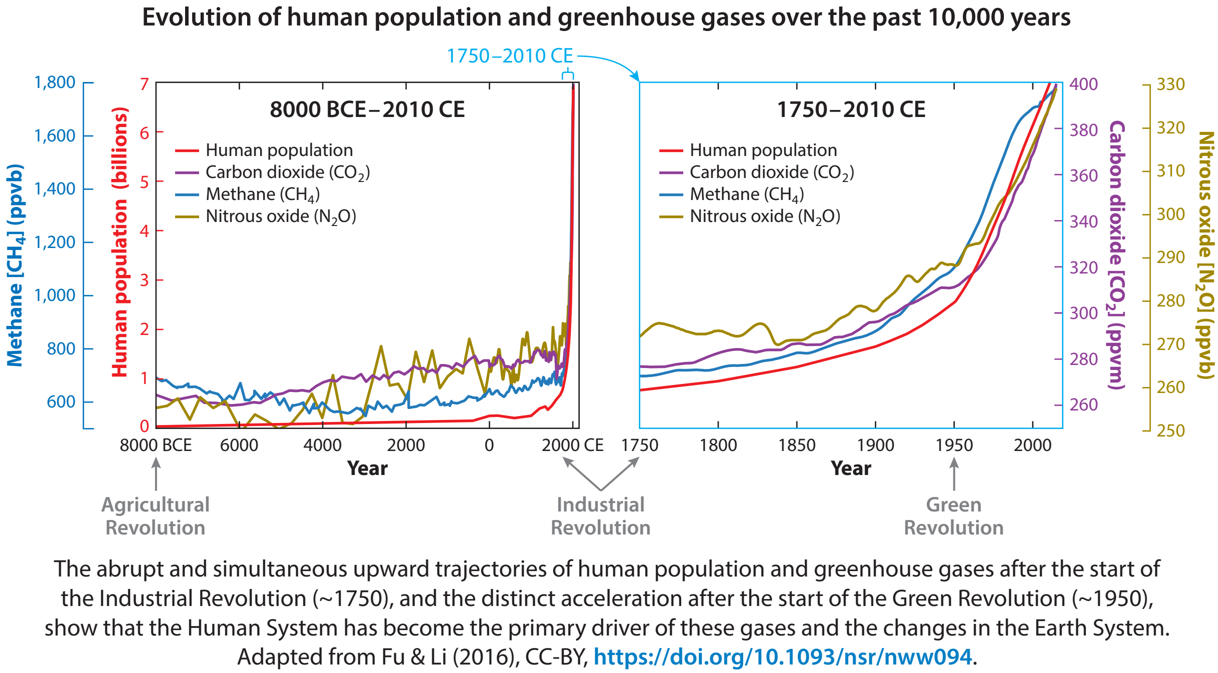


Figure 2

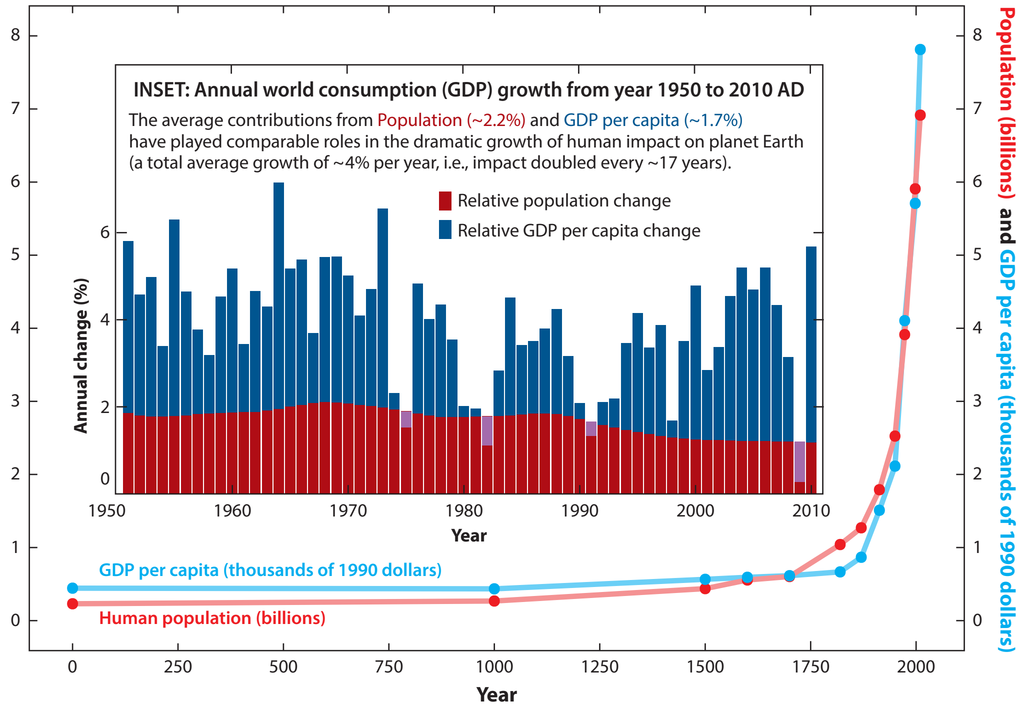
The similar evolution of world population and the atmospheric concentration of greenhouse gases over the past 10,000 years strongly suggests that human population is the driver. Adapted from Fu & Li (2016). **https://doi.org/10.1093/nsr/nww094**.

of fossil fuels is therefore causing a dramatic change in atmospheric and oceanic carbon, altering the carbon composition of the atmosphere and the oceans at rates not found in Nature prior to industrial civilization.

2.4. It's More than Just Climate Change!

This use of a vast new stock of nonrenewable energy and materials, in the form of fossil fuels, impacts the Human System in at least two major ways: First, the massive introduction of carbon into the atmosphere is causing rapid climate change, and this has myriad impacts on humanity that are widely described in the scientific literature (e.g., USGCRP 2017). But second, the rapid consumption of energy in just a few hundred years that it took Nature a few hundred million years to accumulate has allowed humanity to expand its population and its consumption per capita at rates never seen before in human history. It took humanity tens of thousands of years of very slow long-term population growth, with numerous regional cycles of rapid growth and subsequent decline, to reach approximately one billion people (∼1800) in the pre–Fossil Fuel Era (Motesharrei et al. 2014; Diamond 2005, 1994; Shennan et al. 2013; Downey et al. 2016; Goldberg et al. 2016; Turchin 2009; Turchin & Nefedov 2009; Turchin 2005; Kondratieff 1984; Tainter 1988; Yoffee & Cowgill 1988; Chase-Dunn & Hall 1997; Goldstein 1988; Modelski 1987; Meadows et al. 1972; Chu & Lee 1994; Needham & Wang 1956).

It then took humanity only about two centuries to add approximately six billion more people during the Fossil Fuel Era, and most of this growth (approximately 4.5 billion people) has occurred since the Green Revolution—i.e., in just one human lifetime. The UN projects that



MAIN GRAPH: Population and GDP per capita from year 1 to 2010 AD

Both Population and GDP per capita increased explosively following the Industrial Revolution.
The human impact is the product of both curves. Adapted from Motesharrei et al. (2016), CC-BY,
https://doi.org/10.1093/nsr/nww081.

Figure 3

MAIN GRAPH shows world population and gross domestic product (GDP) per capita from year 1 to 2010 AD. The total human impact is their product. INSET shows the relative annual change of population growth and GDP per capita growth from 1950 to 2010, demonstrating that they both played a similar role in the growth of human impact. Figure adapted from Motesharrei et al. (2016). Data from Bolt & van Zanden (2014), Maddison (2001), and United Nations (2013a).

another approximately four billion people will be added in less than a century (by ~2100)—i.e., again in just one human lifetime (United Nations 2013a).

Just as striking, consumption per capita during this period also increased by the same order of magnitude (Motesharrei et al. 2016, Maddison 2001). The size and extent of Human System impact on the Earth System are determined by the rates of extraction and the rates of pollution, which in turn are determined by the total consumption rate. Total consumption is the product of population multiplied by average consumption per capita, and both factors are recognized as primary drivers of human environmental impact. It is critical to understand that humanity's total consumption of natural resources is the product of the explosion in consumption per capita multiplied by the explosion in total population (see **Figure 3**).

Thus, until about the last two centuries, humans used renewable biomass as the primary source of energy and materials, but since then the Human System has instead become dependent on nonrenewable stocks, such as fossil fuels (coal, oil, and natural gas) and other minerals,[1] for both energy

[1]Minerals became available for large-scale exploitation because of the large-scale availability of fossil fuel energy.

and materials. The exploitation of these nonrenewable resources made possible the two revolutions that drove this regime shift in growth both in population and in consumption per capita: the Industrial Revolution and the Green Revolution (Erisman et al. 2008; Krausmann et al. 2009; Ramankutty et al. 2002; Smil 2011, 2004). Population, consumption per capita, and inequality in consumption have grown extremely rapidly, accelerating with the Industrial Revolution and especially with the Green Revolution after about 1950.

However, the Human System relationship with the planetary system is not limited to consuming resources. What is produced must return to the Earth System in some form of waste. The recent rapid consumption of fossil fuels and emissions of greenhouse gases is not only causing climate change (something that is already given considerable attention), but the resulting explosion in the Human System has meant that Human System impacts on the Earth System are occurring across a range of planetary subsystems (Barnosky et al. 2012; Crutzen 2002, 2006; Rockström et al. 2009; Steffen et al. 2015b)—i.e, it's more than just climate change! Furthermore, this explosion explains why the size of the Human System has gone from being a minor influence on these planetary subsystems to becoming the dominant driver in most of these subsystems. This also threatens to overwhelm the many critical functions and ecosystem services of the Earth System. Motesharrei et al. (2016) provide an extensive overview of examples of the Human System coming to dominate most aspects of the Earth System: appropriation of global net primary production (of vegetation) (Foley et al. 2005; Haberl et al. 2007, 2011; Imhoff et al. 2004; Krausmann et al. 2013; Lauk & Erb 2009; Liu et al. 2015; Millenn. Ecosyst. Assess. 2005; Rojstaczer et al. 2001; Zeng & Yoon 2009; Zeng et al. 2014); land use for biomass production (Kareiva et al. 2007; Tilman et al. 2002, 2011), open pit and other surface mining (Bardi 2014, Palmer et al. 2010), and urban sprawl (Imhoff et al. 2000); soils, fisheries, forests, and desertification (Aeschbach-Hertig & Gleeson 2012, Döll et al. 2014, Scholes & Scholes 2013, Vitousek et al. 1997a, D'Odorico et al. 2013); global atmospheric composition and changes to global climate (Ciais et al. 2013, Hansen et al. 2013, Tripati et al. 2009) and human impact on local climates (Li et al. 2015, 2016); sea-ice, ice sheets, glacier mass, permafrost area, snow cover, sea surface temperatures, sea level, and ocean acidification (Ciais et al. 2013); global nitrogen cycle (Canfield et al. 2010, Galloway et al. 2004, Gruber & Galloway 2008, Holtgrieve et al. 2011, Howarth et al. 2012, Rockström et al. 2009, Vitousek et al. 1997b); eutrophication, hypoxia, and dead zones in rivers, lakes, estuaries, and coastal oceans, as well as rising sea temperatures and ocean acidification (Cai et al. 2011, Canfield et al. 2010, Carstensen et al. 2014, Ekstrom et al. 2015, Melzner et al. 2012, Rabotyagov et al. 2014, Rockström et al. 2009, Tilman et al. 2001, Vaquer-Sunyer & Duarte 2008); regional hydrological cycles (Barnett et al. 2008, Gordon et al. 2008, Grasby 2004, Meybeck 2003, Molden 2007, Molle et al. 2010, Vörösmarty et al. 2000, Wagener et al. 2010, D'Odorico et al. 2010); aquifers and groundwater (Castle et al. 2014, Famiglietti 2014, Famiglietti & Rodell 2013, Famiglietti et al. 2011, Konikow 2013, Rodell et al. 2009, Scanlon et al. 2012, Voss et al. 2013); ecosystem degradation and fragmentation (Bierregaard et al. 1992; Ferraz et al. 2003; Gibson et al. 2013; Hanski et al. 2013; Laurance 2004; Laurance et al. 1997, 2000, 2002; Lewis et al. 2015; Powell et al. 2015); and biodiversity loss and species extinction (Ceballos et al. 2017, IPBES 2019, Kolbert 2014, Mace et al. 2005, Regan et al. 2001, Vitousek et al. 1997a, Isbell et al. 2017, WWF 2016, Loreau et al. 2001). Indeed, human impacts on the Earth System have accelerated synchronously since the 1950s with little sign of abatement (Steffen et al. 2006, 2015a).

3. THE EARTH SYSTEM–HUMAN SYSTEM RELATIONSHIP

3.1. Resource Inputs and Waste Outputs of the Human System

Coupling the Earth and planetary system with the Human System requires understanding the primary components of the Human System that drive its relationship with Earth's subsystems.

Figure 4

Relationship of the Human System within the Earth System. Adapted from Motesharrei et al. (2016), CC-BY, **https://doi.org/10.1093/nsr/nww081**.

These primary components (**Figure 4**) include the *Inputs* drawn from the Earth System into the Human System (human consumption of natural resources from the Earth System) and the *Outputs* from the Human System into the Earth System (human emission of waste and pollution into the Earth System). In addition, a key property of the Human System determining these inputs and outputs is the *inequality* in the consumption and the emissions within the Human System [e.g., the highly different consumption and emissions between Elites and Commoners (Motesharrei et al. 2014)]. Carrying Capacity has typically been measured in terms of the total population that can

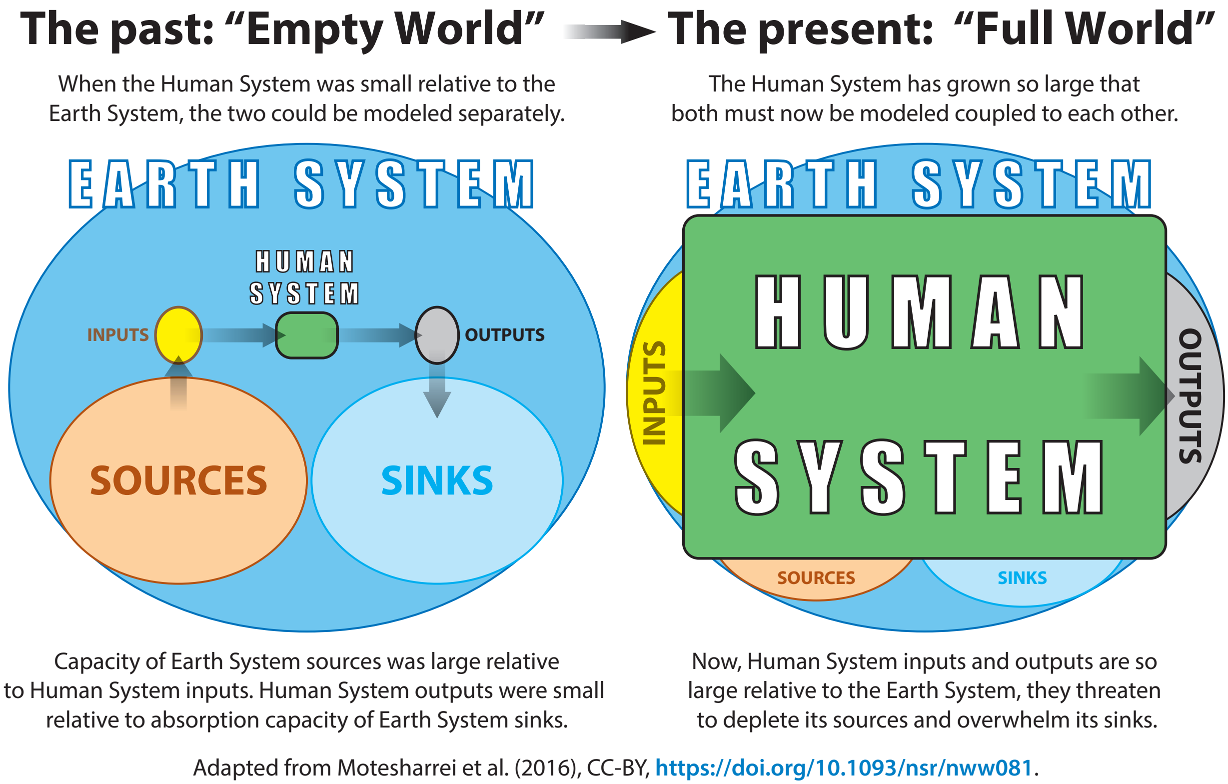


Figure 5

Growth of the Human System has changed its relationship with the Earth System, and thus both must be modeled interactively to account for their feedback on each other. Adapted from Motesharrei et al. (2016), CC-BY, **https://doi.org/10.1093/nsr/nww081**.

be sustained by a system over the long term. Since humans can have vastly different consumptions per capita (due to this inequality), the human Carrying Capacity of the Earth System has to be measured in terms of the total load the Earth System can support over the long term—i.e., total human resource use and waste generation, not just total human population. That total load is not produced equally by all humans. Thus, including this key property of inequality is necessary both for modeling the combined Earth–Human System (Motesharrei et al. 2016) and for modeling the Carrying Capacity of this combined system, as we discuss below.

Our Human And Nature DYnamics (HANDY) article (Motesharrei et al. 2014) and in more detail our Modeling Sustainability article (Motesharrei et al. 2016) describe that the human impact on Nature comes from two processes: depletion and pollution (**Figure 4**). Depletion is the consumption of natural resources from the Earth System as inputs into the Human System. Pollution is the process of dumping the outputs (waste) of the Human System back into the Earth System. However, the explosive growth of the Human System relative to the Earth System means that the Human System has come to dominate the Earth System (**Figure 5**).

3.2. Regenerating, Renewable, and Nonrenewable Resources

Understanding the inputs from the Earth System to the Human System and how they determine Carrying Capacity requires understanding that these inputs come in three distinct forms:

1. Renewable resources, e.g., solar, wind, and hydro power
2. Regenerating resources, e.g., crops, fisheries, forests, and herds
3. Nonrenewable resources, e.g., fossil fuels, metals and other minerals, and slowly recharging aquifers ("fossil water")[2]

The Environmental and Ecological literature normally distinguishes between renewable and nonrenewable resources, but we argue that in modeling the real Earth–Human System, it is critical to also distinguish between renewable and regenerating resources because they have very different properties and therefore different behaviors and impacts: Regenerating and nonrenewable resources are *stocks* that can be depleted, whereas renewable resources are *flows*.

Understanding how outputs from the Human System to the Earth System determine Carrying Capacity requires modeling how the outputs are (or at what rates can they be) absorbed and processed by the Earth System. These processes are essential Ecosystem Services provided by the Earth System to the Human System, such as clean water, clean air, absorption of carbon emissions, etc. If the Human System outputs are not absorbed and processed, then it is critical to model how they are stockpiled by the Earth System as they are emitted by the Human System (e.g., carbon emissions causing climate change) and at what levels they overwhelm the Earth System, thus changing both its natural properties and its dynamics.

3.3. Carrying Capacity: Pre–Fossil Fuel Era Versus Fossil Fuel–Driven Explosion of the Human System

In the past, regional Human Systems (which we could call "civilizations") have grown until limited by surpassing the Carrying Capacity of the (mostly regenerating) resources of their particular region. Very often this process of surpassing regional Carrying Capacity resulted in collapses. Thus, we frequently see regional cycles of growth and collapse in human history (Motesharrei et al. 2014).

In contrast, in our current Fossil Fuel Era, a vast stock of nonrenewable energy and materials has allowed the Human System to explode, both in population size and in consumption per capita (**Figure 3**), far surpassing its regenerative Carrying Capacity and thus *appearing* to be able to grow forever (Rees 1992, Wackernagel & Rees 1996, Wackernagel et al. 2002). This has led many scholars to abandon the concept of Carrying Capacity with regard to humans (Natl. Res. Counc. 2014) (see Section 4). However, we argue that this does not negate the concept of Carrying Capacity. Rather, modeling the underlying mechanisms of this dramatic *regime shift* in the Human System is necessary both to explain the radically different trajectory human society has taken during the last 200 years and to model humanity's Carrying Capacity and thus, most importantly, its trajectory in the near future.

Understanding most aspects of this Earth System–Human System relationship requires formulating a novel understanding of the planetary human Carrying Capacity of the Earth System. Attempts have been made in the past to formulate human Carrying Capacity, but they have foundered because they do not have a dynamic understanding of the factors that determine Carrying Capacity.

[2]Most aquifers are practically nonrenewable on a human timescale due to their slow recharge rate compared to current withdrawal rates.

4. "CLASSICAL" CARRYING CAPACITY

4.1. The Classical Notion of Carrying Capacity: Origins in Theoretical Biology and Ecology

The most widespread understanding of the concept of Carrying Capacity has its roots in the first mathematical appearance of this variable in the logistic growth equation (Pearl & Reed 1920, Verhulst 1838):

$$\dot{x} = rx\left(1 - \frac{x}{K}\right), \qquad 1.$$

where x is the state variable that dynamically changes, r is its free growth rate (when $x \ll K$), and K is the "classical" Carrying Capacity.[3] One may think of x as the population of an animal species on an isolated patch of land, the population of fish in a pond, or the number of trees on a patch of land. In general, x is the population or mass of any living organism or species that regenerates itself in a bounded environment. Hence, these two properties are fundamental for developing the concept of Carrying Capacity: some endogenous growth (change) mechanism and system boundaries. The second property is of extreme importance when modeling real physical, natural, or human systems.

However, the logistic equation can only represent exponential growth of a variable damped by the existence of a saturation level. Hence, applying the logistic equation to a system with different dynamics will necessarily lead to failure. Our proposed approach to deriving Carrying Capacity is, by contrast, *a posteriori*: First the dynamical model representing the real system needs to be designed, and then the Carrying Capacity is obtained by running the model or by deriving it from the model equations themselves. In contrast to prescribing Carrying Capacity *a priori*, which will necessarily fail because it is not consistent with the system that is being modeled, an *a posteriori* Carrying Capacity derived from the model will always be consistent with the model. We now show several examples of the different kinds of difficulties of prescribing *a priori* the "classical" Carrying Capacity, followed in the next section with the more appropriate *a posteriori* approach based on the model equations.

The solution to Equation 1 is the well-known sigmoid curve, i.e., almost exponential growth when $x \ll K$, followed by saturation to K. For the logistic equation, the equilibrium solution is indeed $x_{eq} = K$. This has led to the assumption that this classical notion of Carrying Capacity can be defined as the saturation or equilibrium level for the corresponding state variable, e.g., population, even if its dynamics are not necessarily well represented by the logistic equation. Therefore, various paradoxes and confusion arise by establishing this assumption (Gabriel et al. 2005).

One example is the "Ginzburg paradox" (Ginzburg 1992), where an additional mortality term is added to Equation 1:

$$\dot{x} = rx\left(1 - \frac{x}{K}\right) - \mu x. \qquad 2.$$

Because of this additional $-\mu x$ term, the equilibrium value is no longer $x_{eq} = K$ but rather $x'_{eq} = \frac{r-\mu}{r}K$. This confusion led Ginzburg to change Equation 2 itself to avoid this new level of equilibrium, x'_{eq}, that does not match the classical Carrying Capacity, K (Ginzburg 1992). Gabriel et al. (2005) and others have highlighted these paradoxes. Hui (2006) proposes to define the classical Carrying Capacity as the "environmental maximal load" to avoid such paradoxical conclusions that could arise even in such simple systems.

[3] K first became formally known as Carrying Capacity in Odum (1953).

Another major issue with this classical notion of Carrying Capacity is that, in reality, this level depends upon multiple factors, both endogenous and exogenous. For example, the fish population in a pond could depend on the water temperature, which itself could vary from year to year, or the amount of nutrients that are brought into the pond by surface water flows, which itself would be a function of multiple environmental factors including precipitation. As the complexity of the system grows, the Carrying Capacity itself becomes a function of a growing set of variables and parameters in an ad hoc way. To address this problem, Thornley & France (2005) propose to make the asymptote, i.e., K, in Equation 1 a state variable that can decrease depending on growth conditions, current population (organism mass), and a parameter that represents development. Many other authors have proposed to generalize Equation 1 to better fit the growth of various biological and ecological variables. These changes primarily modify the *a priori* prescription of Carrying Capacity, K, instead of replacing the logistic equation with a set of dynamic equations that represent the real dynamics of change in the system. A comprehensive review of these models, as well as a mathematical analysis for each, can be found in Tsoularis & Wallace (2002).

4.2. Application of Classical Carrying Capacity to Human Population

For the human population, Cohen (1995a) lists over 20 definitions of the classical Carrying Capacity from the literature, each proposing a different function with a different set of parameters and variables, based on variants of the logistic equation. In particular, Earth's human Carrying Capacity would be determined by a wide range of natural, economic, environmental, demographic, and political factors (Cohen 1995b) in both the Human System and the Earth System. Since it is believed that technology can generally increase the Carrying Capacity (Arrow et al. 1995), scientists have also tried time-dependent models of Carrying Capacity, $K(t)$—for example, a model in which $K(t)$ itself grows according to the logistic equation, i.e., following a sigmoid curve (Meyer & Ausubel 1999). (For a discussion of various types of technology and their potential impacts on Carrying Capacity, see Motesharrei et al. 2016.) Shepherd & Stojkov (2005) apply perturbation methods to find closed-form analytical solutions for Equation 1 when K varies slowly with time. Safuan et al. (2011), following an approach similar to Thornley & France's (2005), make the Carrying Capacity, K, a state variable itself and couple it to the population. This allows the population (as well as K) to oscillate around a final equilibrium value before converging to it. Al-Moqbali et al. (2018) apply this approach to the predator-prey system, resulting in a system with three state variables, including a Carrying Capacity, K, that itself grows according to the logistic model.

Hopfenberg (2003) equates Carrying Capacity to food availability and claims that world population grows according to the logistic model, with food availability as its Carrying Capacity. He then concludes that Carrying Capacity is the available food.

Another fundamental problem with using an equation that does not represent the real underlying mechanisms in the system is its failure to capture and predict the real behavior of the system. A striking example of this problem is the inherent inability of the logistic equation to produce human population collapses, a phenomenon that has occurred repeatedly in history (Motesharrei et al. 2014). The essential role of the logistic equation is to slow down the growth of the population as it approaches K, but in reality the growth can continue at the same or even a higher rate. In reality, human population can (and has many times) overshoot Carrying Capacity, whereas in the logistic equation, the rate of growth slows as the population approaches K and thus the population cannot overshoot Carrying Capacity for a significant period of time. However, as the inclusion of nonrenewable resources in the dynamics of a model clearly shows, population can overshoot Carrying Capacity for an extended period of time in a manner not represented by the logistic equation. Existing conceptions of Carrying Capacity can have a collapse of population for a significant period of time due to a collapse of Carrying Capacity, not from an extended overshoot over Carrying Capacity. We argue that human population change should be modeled with dynamic equations that represent real mechanisms, interactions, feedbacks, and parameters in the coupled Earth–Human System.

Many authors propose that these nontrivial changes in population could be reproduced using the logistic equation if an appropriate functional form for Carrying Capacity is adopted that includes the driving factors for population change (e.g., Hopfenberg 2003, Meadows et al. 1972). For example, a collapse in population could be reproduced by an arbitrarily prescribed collapse in Carrying Capacity. The fundamental problem with adopting such an approach would be the lack of derivation of the formulation from the dynamic mechanisms that modify Carrying Capacity. Therefore, the only consistent approach to derive or produce Carrying Capacity would be to build the model with basic mechanisms and key interactions and feedbacks and then allow the model to produce Carrying Capacity endogenously.

All these paradoxical outcomes and differences in definitions and functional forms, especially for the extremely complex coupled Earth–Human System, have led to deep confusions within the scientific community, to the point that some distinguished groups of scientists have recommended a rejection of the concept of Carrying Capacity for the human population (Natl. Res. Counc. 2014). This National Research Council report that began with the task of studying the planet's Carrying Capacity did reject it, stating, "Because the human species manipulates and converts its habitat and can counter the natural limits on its population. . .the conceptual basis of carrying capacity breaks down when considering people." The report states on page 11 that "carrying capacity should be only a heuristic device," and scholars are "cautioned against calculating specific values for the human–environment system." Indeed, it claims that "carrying capacity has been 'largely abandoned' in the social and policy sciences."

There are several fundamental problems with this approach of trying, at all costs, to use the same equation—i.e., Equation 1—to describe the human population dynamics and modifying its Carrying Capacity by various prescriptions. As discussed above, human population is coupled with many environmental, social, natural, and economic factors in both the Human System and the Earth System through one-way interactions and two-way feedbacks. These factors all interact dynamically to help determine the human Carrying Capacity of the whole Earth System or of a smaller regional or local system. To properly understand and model the dynamics of population change, one must model the change in other coupled variables together with human population. This will result in a dynamic system that closely represents the mechanisms in the real system. However, the logistic equation does not represent the underlying mechanisms or interactions in the real system. This necessarily results in the earlier frustrations with various failed attempts to represent the human population dynamics by modifying the logistic equation. As previously pointed out, the *a priori* approach to estimate the Carrying Capacity instead of deriving it *a posteriori* as a product of realistic dynamic models will necessarily fail.

Moreover, trying to equate Carrying Capacity to only one or a few interacting variables in the system—e.g., food as in Hopfenberg (2003)—could lead to dangerous conclusions that only one or some factors determine the sustainability of the combined, coupled systems and overlook the impact of many other factors, such as freshwater, cultivable land, energy, and climate, as well as social, political, demographic, and human health factors. A particular variable may be the critical limiting factor under some scenarios but not under other scenarios. In contrast, a dynamic model of all the interacting variables would be able to calculate *a posteriori* the dynamic Carrying Capacity under these different scenarios without having to select *a priori* which is the critical variable that sets Carrying Capacity.

Another complex problem that could be better addressed by using an appropriate dynamic model to derive Carrying Capacity is the precise specification of the system boundaries. For example, calculating Carrying Capacity requires a careful definition of spatial system boundaries. By neglecting such boundaries, one may conclude incorrectly that, for example, world population can continue to grow, whereas in certain regions it could be experiencing a catastrophic collapse due to a regionally limited critical factor, such as the collapse of freshwater resources. For example, if we investigate the sustainability of freshwater in the United States, including all available sources (e.g., the Great Lakes), one might conclude that sufficient freshwater will be available for many centuries. However, several regions, such as the Central Valley in California or the Great Plains, are already facing serious water scarcity. Coupled dynamic models of these interacting systems would allow for the calculation of Carrying Capacity on local, regional, and global scales.

The attempts to redefine and modify Carrying Capacity are not limited to studies of human population. Even in Ecology, there are more than 10 different definitions for Carrying Capacity, which makes parameterizing or measuring it very difficult, if not impossible, as Hixon (2008) notes in the entry for Carrying Capacity in the *Encyclopedia of Ecology*. This has, therefore, led scholars to consider Carrying Capacity to be "most useful as a heuristic and theoretical tool" but without much practical value (Hixon 2008, page 528).

As an example, McLeod (1997) develops a coupled model of herbivores (H) and vegetation biomass (V) based on a review of seven alternative models, with the goal of informing range managers. With this approach, McLeod (1997) first correctly develops a dynamic model for interactions of H and V without making an *a priori* prescription for Carrying Capacity. He then attempts to calculate the equilibrium levels for both a deterministic system and a stochastic system due to rainfall. He notes, on page 530, that "Although carrying capacity might seem to be a simple concept, it has had a very confusing history." In conclusion, he argues that Carrying Capacity is a helpful concept for deterministic systems but dismisses it for stochastic systems. We disagree that Carrying Capacity should be dismissed in all stochastic systems because in most systems, despite stochasticity, the variable has a fairly predictable moving average and/or the stochastic flow coexists with a deterministic flow. An example of this would be the freshwater system, where similar to the example of McLeod (1997), rainfall is a stochastic variable. However, its average trend can be predicted with appropriate climate models, and furthermore, the precipitation supplies only a part of the demand in combination with groundwater, which is a deterministic variable. We therefore believe that Carrying Capacity would still prove to be an important measure of sustainability in such systems where parts of the system are stochastic.

For example, rain is stochastic on a daily or weekly basis but not on a seasonal basis, so it is the time-averaged flow that is important in determining Carrying Capacity. And if there is any form of storage or buffer for the flow (such as groundwater or reservoirs), then this makes the stochastic nature of the short-term fluctuations in flow less important and the average flow more important in determining the Carrying Capacity. Even in the case of a large deviation of this stochastic variable from the long-term average, such as in the case of a drought or any other long-term change far out of the normal range, this does not mean Carrying Capacity cannot be calculated; rather, it means that when the major influencing stochastic variable has a trend, then the Carrying Capacity would dynamically change in the direction of that trend of that stochastic variable.

McLeod (1997) argues that if a major influencing variable in the system is highly stochastic, then you cannot calculate an equilibrium so you cannot calculate a Carrying Capacity. But we show how this is not true. If the stochastic variable has a time average value, then the model would still produce the Carrying Capacity. Even if the state variable would be constantly fluctuating, the time-smoothed average would still produce a Carrying Capacity. This is why it is so important to distinguish an equilibrium state from the Carrying Capacity.

The related concepts of "Ecological Footprint" and "Appropriated Carrying Capacity" were first introduced by Rees (1992). Ecological footprint was further developed by Wackernagel & Rees (1996) to calculate the amount of productive land and marine area that is required to produce enough food and material for human consumption and to absorb waste from human activities. Wackernagel et al. (2019, page 270) formally define ecological footprint as "a resource accounting tool that measures the amount of the Earth's regenerative capacity (or 'biocapacity') demanded by a given activity." They incorporate impacts of various sectors of the Human System such as agriculture, food processing, transportation, construction, building maintenance, and other service industries on Earth's regenerative capacity. By 1986, Vitousek et al. (1986) had estimated that about 40% of potential terrestrial net primary productivity on Earth was appropriated by humans. Wackernagel et al. (2002) estimated that humans were using 70% of Earth's biocapacity in 1961, crossed 1 Earth's biocapacity by the early 1980s, and reached 1.2 Earths by 1999. Lin et al. (2018) estimate that by 2014, humanity's ecological footprint had grown to 1.7 Earths. However, without the current use of nonrenewable stocks of fossil fuels and fossil water, the ecological footprint would be many more Earths because we are currently using the resources (especially energy and water) accumulated from past Earths. As McBain et al. (2017) explain, this overshoot trend will most likely increase in the future in the absence of appropriate policy interventions.

In summary, we do agree that the coupled Earth–Human System is enormously complex. However, complexity does not mean Carrying Capacity should be discarded or that it is impossible to calculate. Earth System scientists have been modeling very complex systems very successfully, and this can be applied to modeling coupled Earth–Human Systems, leading to the calculation of Carrying Capacity. Discarding this powerful measure of the sustainability of the system, regardless of its degree of complexity, can lead to missing important warning signals that could determine the fate of our planet and our species. This *a posteriori* approach to producing Carrying Capacity can combine many factors and parameters in the system into a single variable, hence making it a simple measure of sustainability, despite the inherent complexities of the coupled systems that it describes. In the next section we propose instead a Carrying Capacity derivation based on coupled modeling with bidirectional feedbacks.

5. CARRYING CAPACITY DERIVED FROM THE DYNAMICS OF THE REAL SYSTEM

5.1. From an *a priori* Prescribed, Classical Carrying Capacity to a Carrying Capacity Derived *a posteriori* in Bidirectionally Coupled Systems

We propose that the dynamic Carrying Capacity of the coupled human–natural systems can be derived only after a system is carefully modeled with a set of essential bidirectional feedbacks (Motesharrei et al. 2016). This new approach is in contrast to the traditional method of prescribing the classical Carrying Capacity in the models as discussed in Section 4.

We demonstrate this alternative approach in a simple example of this methodology by using a minimal dynamic model, the HANDY model (Motesharrei et al. 2014). Since its publication, this article has been the most downloaded paper of the journal *Ecological Economics*, the flagship journal of its field, and has been cited over 330 times to date.[4] The article has been translated into several languages (e.g., French, Portuguese, Spanish), and the model code for HANDY has been programmed in several computer languages [e.g., VENSIM, Python, Modelica (Castro et al. 2014), MATLAB, and R].[5]

[4]The total downloads count was measured and updated over each 90-day period.

[5]Contact the authors for a copy of the model code.

The dynamic equations of HANDY are given by

$$\begin{cases} \dot{x}_{\mathrm{C}} &= \beta_{\mathrm{C}} x_{\mathrm{C}} - \alpha_{\mathrm{C}} x_{\mathrm{C}} \\ \dot{x}_{\mathrm{E}} &= \beta_{\mathrm{E}} x_{\mathrm{E}} - \alpha_{\mathrm{E}} x_{\mathrm{E}} \\ \dot{y} &= \gamma y(\lambda - y) - \delta x_{\mathrm{C}} y \\ \dot{w} &= \delta x_{\mathrm{C}} y - C_{\mathrm{C}} - C_{\mathrm{E}} \end{cases}, \tag{3}$$

where x represents human population separated into Elites, x_{E}, and Commoners, x_{C}; y is Nature; and w is accumulated wealth. Nature, y, regenerates according to the logistic equation, with λ denoting Nature's capacity. γ is the regeneration rate of Nature, and δ is the depletion rate of nature. The four state variables of HANDY are coupled with bidirectional feedbacks between the human and natural systems.

We show that for various types of societies, a Carrying Capacity can be derived. We note that we were also able to analytically calculate this Carrying Capacity, χ, not only in HANDY but also in much more complex models, e.g., our Coupled Human-Climate-Water model, COWA (Motesharrei et al., Working Paper). For example, in an egalitarian society, the Carrying Capacity in HANDY is given by

$$\chi = \frac{\gamma}{\delta}\left(\lambda - \eta\frac{s}{\delta}\right), \tag{4}$$

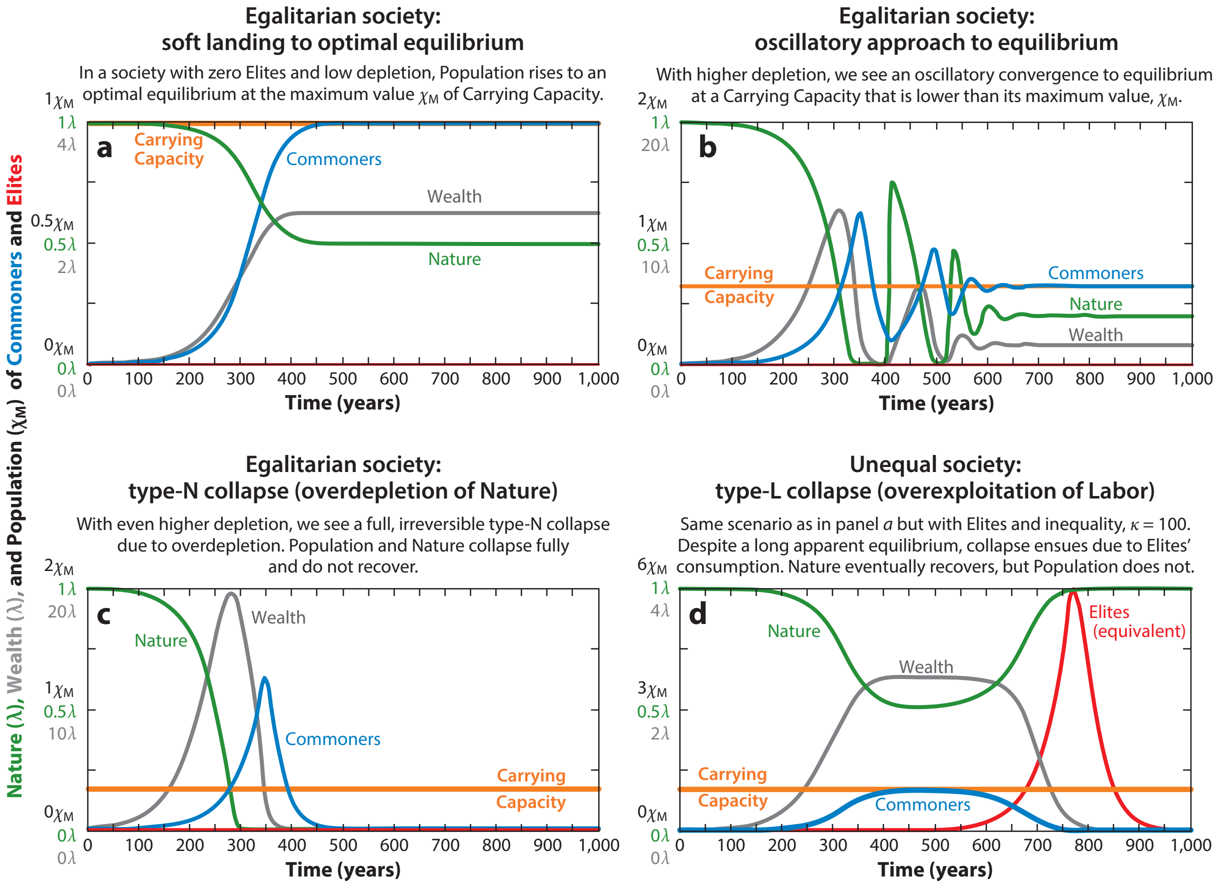
where s is the subsistence salary and η is a parameter that is determined by demographic factors (i.e., birth and death rates). We further show that by varying the per capita depletion, δ, the system can achieve a maximum level of equilibrium, χ_{M}:

$$\chi_{\mathrm{M}} = \frac{\gamma}{\delta_*}\frac{\lambda}{2} = \frac{\gamma}{\eta s}\left(\frac{\lambda}{2}\right)^2. \tag{5}$$

We should note, to avoid potential misunderstanding, that a minimal model such as HANDY cannot be used to calculate the actual Carrying Capacity of a specific society. We present this model as a simple example of how our methodology could be used to calculate Carrying Capacity. Calculating the Carrying Capacity of a specific population in a particular context or scenario would require a model that includes the multiple relevant variables, parameters, feedbacks, and associated data sets. HANDY is a minimal dynamic model, and that allowed us to derive *a posteriori* the Carrying Capacity of the system and express it in a closed, analytical formula. However, for a more complex system, with perhaps many more state variables, parameters, and feedbacks, deriving a closed-form formula might not be feasible. In such cases, a Carrying Capacity, if it exists, can still be calculated via numerical integration of the model.

Furthermore, we showed in Motesharrei et al. (2014) that even without full knowledge of the underlying mechanisms in the real system, one may still be able to estimate the time at which Carrying Capacity is exceeded by observing the approximate onset of the decrease of Accumulated Wealth (or, in other coupled human–natural systems, the equivalent variables representing stored resources). Under all scenarios of HANDY, we found that the onset of the decline of Accumulated Wealth corresponded with the onset of overshooting Carrying Capacity (see **Figures 6*b,c*** and **7**). This example shows how Carrying Capacity could provide a warning signal of overshoot and indicate the need to take preventive measures (such as discussed in the next section) (cf. Ridolfi et al. 2015).

Thus we showed that in various kinds of societies and under different scenarios, Carrying Capacity is a simple yet powerful indicator and measure for the sustainability of the system. When



Adapted from Motesharrei et al. (2014), CC-BY, **https://doi.org/10.1016/j.ecolecon.2014.02.014**.

Figure 6

Example experiment results from Human And Nature DYnamics (HANDY) demonstrate the key role of Carrying Capacity in measuring sustainability of various types of societies. Adapted from Motesharrei et al. (2014), CC-BY, **https://doi.org/10.1016/j.ecolecon.2014.02.014**.

there is a small overshoot above Carrying Capacity, the system undergoes small partial collapses but eventually converges to Carrying Capacity (see **Figure 6*b***). By reducing δ to an "optimal" value, even those partial collapses can be avoided, and a smooth landing on the Carrying Capacity could be achieved (see **Figure 6*a***). However, with a large overshoot, the system could undergo an irreversible, full collapse (see **Figures 6*c*** and **7**). In contrast, as mentioned earlier, if one uses a logistic model for population change, then neither a large overshoot nor a long-lasting collapse can be produced.

We used here the HANDY model as an example because it specifically demonstrates the calculation of dynamic Carrying Capacity in different scenarios based on changing underlying dynamics. There are many other recent examples of excellent studies using dynamic modeling to couple human and environmental systems that cite the HANDY article and highlight the importance of this approach.

For example, Roman et al. (2017), using an approach similar to that used in Motesharrei et al. (2014), developed a model of societal dynamics with a population that extracts regenerating

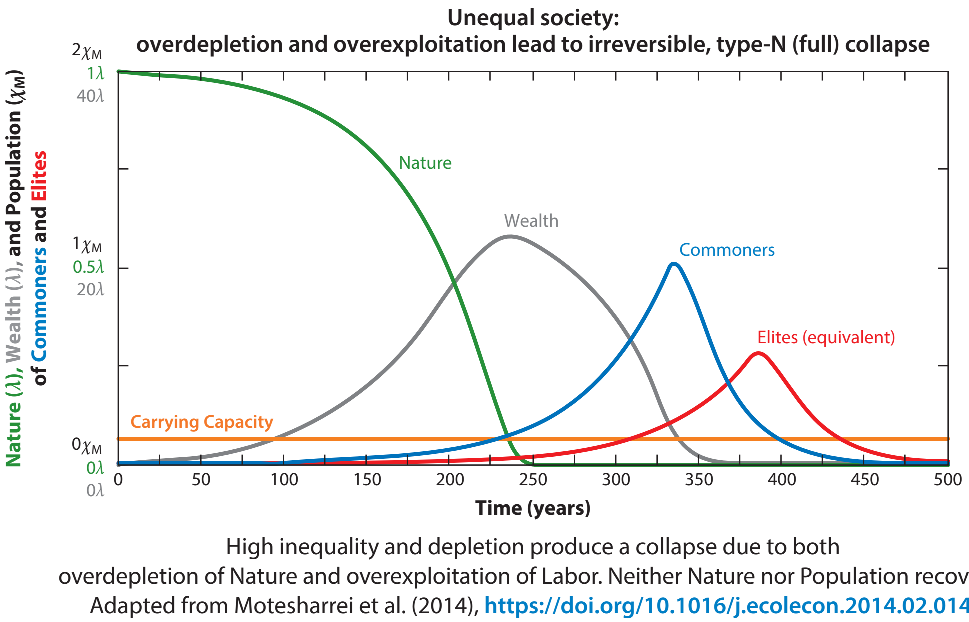


Figure 7

A typical collapse due to both overdepletion of Nature and high inequality. Adapted from Motesharrei et al. (2014), **https://doi.org/10.1016/j.ecolecon.2014.02.014**.

resources (termed "renewable" in their article) and produces goods that then feed back on population. Quite parallel to our findings in the HANDY model, they find that system collapse is forced by a critical transition that takes place when the rate of resource depletion exceeds a particular level for which they present numerical and analytical results. Importantly, the application of their model to Easter Island provides a good fit to the available archaeological data and evidence. Interestingly, the model is then used to explore the dynamics that can emerge from coupling two societies by allowing the movement of natural resources, products, and populations between these societies, with the results suggesting that the region of parameter space in which societies can avoid collapse is significantly enlarged (Roman et al. 2017).

In another recent approach similar to HANDY, Dockstader et al. (2019) apply a single-population model, used to study persistence and collapse in human populations, to multiple discrete population groups and show that when populations are allowed to extract resources from other groups' resource bases after their own resource bases become scarce, the total population reaches a higher peak size, but importantly, the ensuing population collapse is significantly accelerated and across a broader parameter regime. They find that as the number of population groups increases, the "collapse is more sudden, more severe, and occurs sooner." Thus, their findings parallel those of HANDY in that the greater the overshoot of Carrying Capacity, the steeper and sooner the collapse. Very importantly, their findings persist under scenarios of asymmetry and inequality between population groups, thus also corroborating HANDY's findings of the effects of inequality on sustainability and collapse. They conclude that the robustness of the model predictions suggests the need for more complex and complete models of human–environment system sustainability to guide current thinking and policy making (Dockstader et al. 2019).

More recently, Navarro & Tapiador (2019) developed RUSEM (RUral SocioEconomic Model), which models many of the variables and primary feedbacks that underlie population dynamics and sustainability (such as economics, demography, labor market, and essential services) for rural areas of Europe in order to provide policy makers with advice on the long-term dynamic effects of different policy choices under varying scenarios. In addition, RUSEM provides a set of indicators (e.g., economic development index, unemployment rate, and population structure) reflecting the structural features of rural dynamics that could then be used as inputs to Earth System models. For example, population density and the economic development index could be used to calculate anthropogenic emissions at the grid cell level (Navarro & Tapiador 2019).

Other important recent papers using similar approaches include Bauch et al. (2016), Brandt & Merico (2015), Henderson & Loreau (2018, 2019), King (2020), Kuil et al. (2019), Lafuite et al. (2017, 2018), Navarro et al. (2018), Roman et al. (2018), Tenza et al. (2019), and Warren (2015).

5.2. Summary: Carrying Capacity Can Be Properly Derived and Provides Essential Information on Sustainability

In summary, there are dozens of different definitions of Carrying Capacity both for human population and in theoretical and applied ecology. These differences have led to deep confusion of scientists and mathematicians over the concept of Carrying Capacity, to the point that many consider it a purely theoretical, heuristic concept of little practical value. Some distinguished groups of scientists have even proposed discarding Carrying Capacity altogether, particularly for human populations (Natl. Res. Counc. 2014).

We explain that this general confusion is a result of the attempt to prescribe Carrying Capacity as an *a priori* variable in the model, usually based on the logistic equation. We propose that models should instead be built with known variables, mechanisms, interactions, and bidirectional feedbacks (Motesharrei et al. 2016). Carrying Capacity then emerges as a fundamental property of the coupled system, i.e., as a variable derived *a posteriori* for the system. This emerging variable proves to be a simple, yet powerful, practical measure to determine the sustainability of the system.

6. DISCUSSION AND CONCLUSIONS

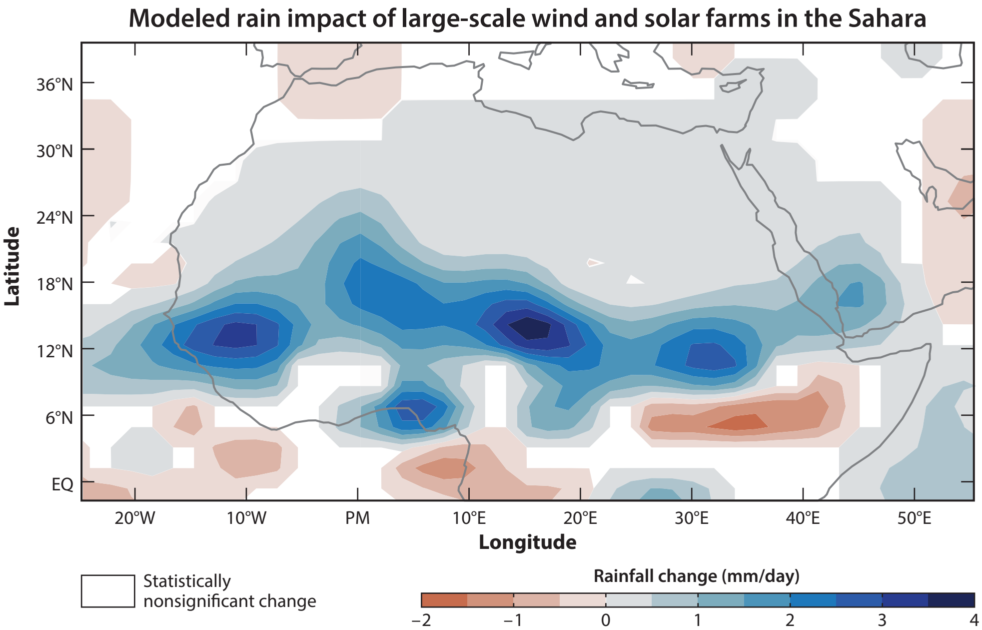
Many of Earth's planetary subsystems are being overwhelmed by the Human System, with potentially disastrous consequences not only for these planetary subsystems but also for the Human System itself. As Ceballos et al. (2017, page E6095) conclude, "...the ultimate drivers of those immediate causes of biotic destruction, [are] namely, human overpopulation and continued population growth, and overconsumption, especially by the rich. These drivers, all of which trace to the fiction that perpetual growth can occur on a finite planet, are themselves increasing rapidly." If a transition to renewable forms of energy and the reuse and recycling of materials is not achieved in time, a rapid decline in both human population and consumption per capita will follow (i.e., a collapse) (Catton 1980, Ehrlich & Ehrlich 2013, Warren 2015). The HANDY model shows not only that the inequality in the Human System increases the overdepletion of these planetary subsystems but also that the associated overexploitation of common people is itself an independent threat to the future trajectory of the Human System. These two processes (overexploitation of Nature and overexploitation of Labor) combine and magnify the threat of societal collapse (Motesharrei et al. 2014).

Modeling with HANDY also tells us that the poorest people will be the first impacted by the overexploitation of natural resources and the collapse of society. There are examples of this already across the world—for example, in cases of the so-called "failed states" (Hsiang et al. 2011, 2013; Kelley et al. 2015).

One warning signal is observed when humanity's consumption has surpassed the Carrying Capacity of the system. Numerous other institutions and scientists have estimated that we are already past (or several times past) the planet's Carrying Capacity. HANDY shows that when population overshoots Carrying Capacity, Accumulated Wealth starts to decline, and it will be only a matter of time before the collapse happens, as shown in **Figures 6*c*** and **7**.

The explosive growth of the Human System relative to the Earth System means that the Human System has come to dominate the Earth System (**Figure 5**). Thus, the Human System needs to change the trajectory that it is on, in order to avoid catastrophic outcomes. However, this is not a case of inevitable doom. It is certainly possible to rectify this trajectory. Changing this trajectory is feasible both from a technological point of view and from a policy point of view (e.g., Jacobson et al. 2015, 2018). Coupled Earth–Human System modeling tells us that there are three broad strategies that humanity has to follow to change the trajectory and avoid collapse:

1. Reduce depletion per capita and pollution per capita. By contrast, currently both are continuing to increase on a planetary level. In order to achieve this reduction, it is necessary to transition from nonrenewable resources to renewable resources and to reuse and recycle the outputs of the Human System as new inputs to the Human System.
2. Stabilize population. By contrast, currently the planet's population continues to increase, and the yearly increases in absolute numbers continue to be relatively stable (~80 million) and near the all-time high, which is equivalent to adding the population of about 1 Germany every year (United Nations 2013a, 2015).
3. Reduce inequality in the consumption of resources and production of waste, emissions, and pollution. By contrast, inequality continues to increase globally, both within most countries



Average precipitation in the Sahara increases from 0.24 to 0.59 mm/day, and in the Sahel increases from 2.23 to 3.57 mm/day. Licensed under CC-BY 4.0. To reuse, link to: Li et al. 2018, https://doi.org/10.1126/science.aar5629.

Figure 8

Summary of beneficial rain impacts of large-scale wind and solar farms in the Sahara. Licensed under CC-BY 4.0. To reuse, link to: Li et al. (2018), **https://doi.org/10.1126/science.aar5629**.

(Milanovic 2013, 2016; Piketty 2014), and between most countries (Bolt & van Zanden 2014, Maddison 2001).

These three strategies could be carried out. As an example, Li et al. (2018) show that it is possible to produce far more renewable energy just from the Sahara than humanity uses with already existing technology, and that would have both economic and environmental benefits—in this case, increased precipitation in the Sahara and especially in the Sahel (**Figure 8**).

This is just one example of the kinds of visionary solutions to these problems that are already available to us. So, the question is not whether we *can* make these changes, but rather whether we *will* make these changes, and whether we will make them *in time*. Estimating the Carrying Capacity scientifically would play a critical role in informing these necessary policy changes, at both regional and global scales.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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