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Society as a complex system: can we find a safe and just operating space for humanity?

John J. Finnigan

Australian National University, Research School of Biology; CSIRO Oceans and Atmosphere

Corresponding author.
Email: john.finnigan@csiro.au

Abstract

The concept of "planetary boundaries" that surround a "safe and just operating space" for humankind is a powerful framing of the problems of global sustainability but implies that we can describe the dynamics of the human-earth system. After defining complex systems in general and introducing the idea of system attractors, we assert that the human-earth system can be understood as a complex system with a set of societal attractors. We show that at a high level its dynamics have been controlled by a powerful 'Malthusian' attractor through most of history but that it left that state in the Industrial Revolution. We go on to model the post-industrial world as a dynamical system with population, economic output, societal state and impact on the biosphere as state variables. A novel aspect of this model is its overt incorporation of political dynamics. Finally, we ask whether this system has an attractor that constitutes a safe and just space for humanity in the future.

Introduction

As we head towards levels of human population and economic activity that the world has never before seen, understanding what is required to ensure the sustainability of human society is now recognized as the most pressing scientific and social issue of our time. In this paper we approach this issue by conceptualizing the human-earth system, that is, the intersection of society and the biophysical workings of the planet, as a complex, globally connected system. This approach assumes that questions of global sustainability require global answers. The United Nations recognized this basic fact over three decades ago and the UN's Sustainable Development Goals (SDGs), which are intended to be achieved by 2030, are the latest set of targets to which member nations have committed in the quest for a socially, economically and environmentally sustainable world. Achieving the SDGs will be challenging for two reasons. First, while the SDGs address individual areas of concern such as poverty, hunger, education and health (and 13 others), these are all reflections of an underlying dynamical system and are connected at a deep level so that achieving one goal may aid or thwart another; and, second, because the current trajectory of the human-earth system seems to be heading in a different direction to some of the most important of these goals.

A different more 'scientific' approach to the question of global sustainability was proposed in 2009 when Johann Rockström and colleagues proposed a framing of global sustainability through a set of Planetary Boundaries (Rockström et al., 2009; Steffen et al., 2015). They defined the extremely stable late Holocene climate of the last 10,000 years as demonstrably a safe operating space for humanity, because all human civilizations arose in this period. They catalogued biophysical processes that could tip the planet out of this state and defined safe, uncertain and high-risk levels for a minimal set of nine controlling variables. Transgressing the high-risk boundaries poses clear and present dangers for the biospheric services that society depends upon. In their 2015 update they calculated that two indicators, namely loss of genetic diversity and perturbations to the global phosphorus and nitrogen cycles, had entered the high-risk zone while climate and land system change were heading inexorably towards it (see Figure 3 in Steffen et al. 2015).

While controversial, the Planetary Boundaries approach had its intended effect of reframing the debate on biophysical sustainability. However, in an influential paper for Oxfam in 2012, Kate Raworth pointed out that a Safe Operating Space for humanity must have social dimensions also, and that for a safe and *just* operating space (SJOS), we need to respect both sets of boundaries (Raworth, 2012). Raworth insisted that we must live on the 'doughnut' bounded on one side by the biophysical boundaries and on the other by her social boundaries (see Figure 1 in Raworth, 2012). Raworth's eleven boundaries included qualities like gender equality, social equity, jobs, voice and resilience. The problem of using such attributes in the same way as the physical boundaries of Rockström et al. soon becomes apparent, however. The physical boundaries corresponded to variables in a mathematical description of the coupled biophysical dynamics of the planet. Raworth's social boundaries in contrast were not related to any underlying mathematical description of social wellbeing and, furthermore, they were incommensurate in the sense of a hierarchy of needs, such as that of Maslow (Maslow, 1943), which starts from the basic physiological requirements of life but moves up through safety, love and belonging, esteem and self-actualization. Raworth's boundaries were notional threshold values of quantities that belonged to different levels of Maslow's hierarchy.

Nevertheless, the point that a SJOS for humanity has both social and biophysical dimensions is well taken, as is the need to describe the human-earth system mathematically as a dynamical system, if we are to apply the planetary boundaries approach in a rational way. So let's start again and see what a dynamical systems description of the human-earth system would look like. The theme of this symposium is society as a complex system so the first question we need to ask is why we would describe the human-earth system as a complex system, but even before that we need to understand what we mean by a complex system.

Complex Systems

The literature abounds with definitions of complex systems, for example, that they have many interacting parts, feedback loops, strongly nonlinear behaviour, exhibit learning, and so on. However, when forced to decide what separates a complex system from one that is 'merely' fiendishly complicated, we find that complex systems have just two essential attributes. One is emergence: the behaviour of the whole system is qualitatively different from the sum of its parts. The second is self-organization: the system tends spontaneously to some level of ordered behaviour.

Emergent properties and emergent behaviour means that many underlying micro-states of the system correspond to the same emergent macro-state. We see this in physics, where atoms can arrange themselves in many different ways to form crystals, such as in the crystal patterns of snowflakes, or in the biological world, where termite or ant colonies or bees in hives, for example, have many interacting units (the insects), whose behaviour is much simpler than that of the whole colony. Bees, of course are complex organisms in themselves, but the bee colony behaves as it does because many worker bees, a few drones and the queen act in interchangeable ways to produce the emergent property of the beehive. The hive is a super organism that can construct a home, seek food, reproduce the next generation, feed the queen and swarm.

Now move up some levels to human society. As humans evolved from earlier primates, basic social systems such as family groups and bands emerged to exploit the evolutionary advantages of cooperation. More complex organizations such as tribes achieved the added advantages of larger groups and then, as society developed, we saw the creation of even more complex political arrangements such as kingdoms and empires. The social technologies necessary to enable these larger groupings to have a stable existence, such as money, economies, religions, patriarchal and matriarchal traditions and systems of government, were all emergent properties of the interaction of many people living as a society.

Self-organization is somewhat different. At one level it has a whiff of Bergson's 'elan vital' but really it just means that there are some preferred states that the system would like to be in and that its internal workings will drive it towards these configurations. Physical systems often seek configurations with the lowest potential energy. In the previous example of snowflakes, it takes extra energy to move the system of interacting water molecules out of their low-energy crystal configurations. Add heat to the snowflakes though and they become just a bunch of disordered colliding water molecules.

Considering human society again, physical infrastructure such as villages, towns and cities are attractors in the case of groups of people producing a surplus of food, which describes humankind after the Neolithic revolution, the invention of farming and pastoralism. Villages, towns and cities solve the problem of how to live optimally on a landscape. They provide human society with clear advantages, such as defence against predation, cooperation for tasks that are beyond the capacity of small groups and development of and access to specialists. We can think of what might be called 'the great paired experiment', the development of civilization in the old and new worlds. Humans went to the Americas in Palaeolithic times, 12,000 years ago at the latest, when human society consisted only of hunter gatherer bands. They then developed societies on both sides of the Atlantic completely independently. But when Europeans went to the Americas in the 15th century, they found political systems, tribes, empires, cities, economies and religions, which were exact parallels of what they had left behind in Europe. These societal arrangements developed completely independently and so are evidently fundamental properties of human society once people start to interact in larger and larger groups. They are attractors for human society.

The concept of attractors is an important complement to that of emergence and self-organisation. If many microstates of a system correspond to just a few emergent macro states, we can infer that these macro states are attractors. We could start the system off in many different initial configurations and it will self-organize or 'be attracted' to one or another of the limited number of macrostates. Many different arrangements of atoms organize themselves in just a few snowflake patterns as the temperature drops below freezing. Different numbers of individual bees arrange themselves in functioning hives, and different races of humans eventually develop cities, religions, economies and so on from scratch.

Attractors can be illustrated most directly using the state space visualization of system behaviour. The state space is defined by axes that reflect the defining properties of the system so that every point in the space is a potential state of the system. As time progresses, the actual system behaviour traces a trajectory through this space and, when an attractor exists, the trajectory is drawn to this restricted region of the state space and thereafter cannot escape it. For a more detailed treatment of this important point as well as an illustration of the power of the geometric approach to analysing complex systems, the reader is referred to Appendix 1.

Understanding human history using the concept of attractors

If one had to describe the history of the world from the emergence of farming until now, it is possible to do so succinctly (or glibly) in two statements: for the first twelve thousand years nothing happened and then, in the last 200 years everything happened. Figure 1 illustrates these statements by indicating the emergence of physical and social technologies on a graph of global population for the last 11,000 years. Clearly evident on this graph is the very slow change in population over most of this period and the concomitant slow emergence of different physical and social technologies and then, suddenly, with the arrival of the Industrial Revolution[1] 200 years ago, we see a step change in the growth rate of population and a similar quantum leap in the emergence of advanced technologies.

Looking at population and wealth together in Figure 2 confirms the existence of two different behavioural domains. Global population and GDP grow almost in lockstep and at a very slow rate until the Industrial Revolution and then increasingly rapidly up to today. Global wealth (approximated by estimated GDP) grows even faster than population so, if we divide the two and look at wealth per person, (approximated by GDP per-capita), we see that in the last 200 years it has grown even faster than the population.

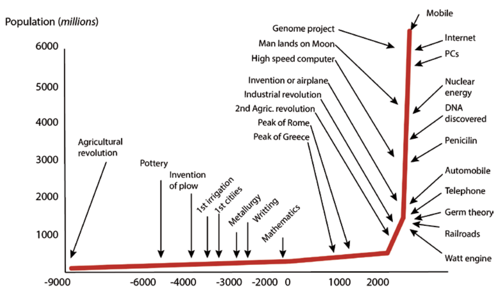

Figure 1. Growth of world population and the history of technology. Source: Milken Institute, Robert Fogel, Univ. of Chicago.

Contrast this with earlier millennia. A peasant in China in 1000 BC was just as well off as a peasant in Europe in 1000 AD. Basically, for the mass of humanity, things stayed the same for most of those past twelve thousand years. To be sure, great empires emerged,

[1] We use the familiar term Industrial Revolution as a generic label for the rapid transformation not only in industrial activity but in food production, population, urbanisation and international inequality that began 200 years ago in Western Europe (Clark, 2007).

great art was made, great cities rose and fell and a very few people were extremely wealthy. For the majority of people, life didn't change.

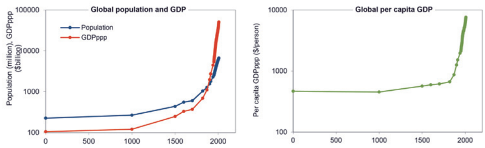

Figure 2. Left panel: estimates of global population and global aggregate gross domestic product (GDP) from AD 1 to 2008. GDP is in International Gheary-Khamis dollars, a time-independent unit that approximates the purchasing power of $US1 dollar in 2000. Right panel: per-capita GDP over the same period. Source: Figures from Raupach et al. (2012); data from Maddison (2010).

Adopting the geometric description of system state (Appendix 1) and choosing axes of population and per-capita wealth to define the state space of the human-earth system, through most of these past millennia its trajectory stayed on an attractor with low values of both. If we extend the state space by adding an axis to denote human impact on the global biosphere, the trajectory stayed close to the origin of that axis too. In Figure 3 we illustrate this state of affairs schematically but also show that, starting at the Industrial Revolution, the trajectory has moved rapidly away from the origin, reaching by 2015 a global population around 7Bn, globally averaged per-capita income of around U$15,000 pa and major impact on the biosphere, denoted in Figure 3 through the exceeding of several biophysical planetary boundaries. This figure prompts the obvious question: what was the nature of the attractor that kept human population, wealth and biospheric impact so small for so very long and what eventually allowed them to escape this attractor?

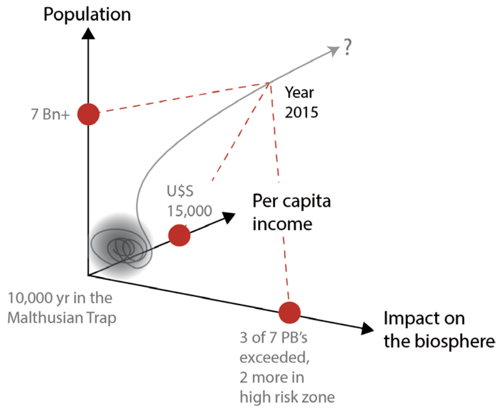

Figure 3. Trajectory of the human-earth system in a 3D state space of population, income per-capita and biospheric impact.

The Malthusian Attractor

Thomas Robert Malthus was an English clergyman of the 18th century. His famous book, *An Essay on the Principle of Population*, ironically written in the opening years of the Industrial Revolution, explained why people actually stayed poor — basically, why the many remained trapped in poverty while the rich few remained rich (Malthus, 1798). In its simplest form, the elements of the Malthusian attractor (sometimes called the Malthusian Trap) are threefold: first, that the birth rate, or fertility, increases with per-capita material income[2]; second, that the death rate, mortality, decreases with per-capita material income; and, third, that per-capita material income decreases with population. This third principle implies that everyone is effectively sharing a fixed amount of resources, so the more people there are, the less any one person has. More fundamentally, it is a consequence of the law of diminishing returns which was introduced into economics by David Ricardo at about

[2] The *material income* refers to the total amount of goods and services that a person consumes.

the same time as Malthus was writing. The Malthusian economy is also the economy of the natural world and applies equally to pre-industrial humanity in the large or to a herd of wildebeest grazing the savannah. These three principles are illustrated schematically in Figure 4 after Clark (2007).

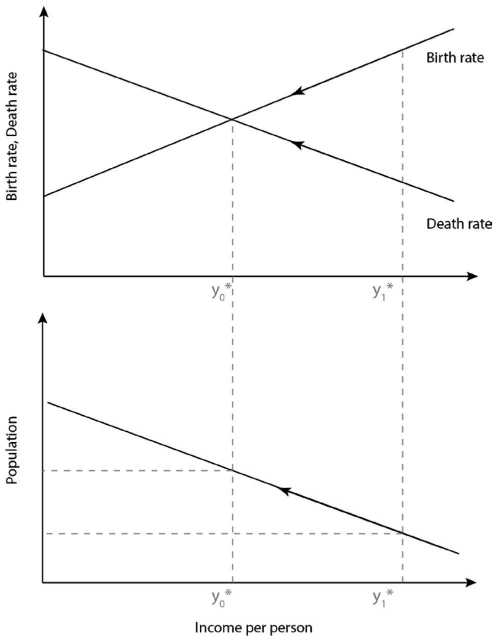

Figure 4. The Malthusian attractor.

When the population is in steady state, which on a global scale it roughly was through the 12 millennia between the agricultural and industrial revolutions (10,000BCE–1800AD), at least compared with the two centuries since then, the birth rate must equal the death rate. The point, where the birth and death rate curves intersect, defines the 'subsistence income'. The actual relationships between birth and death rates were different for different societies with different norms, expectations and practices as well as material environments but together, the birth and death rate 'schedules' define the subsistence income. At any subsistence income the curve relating income to population defines the population that can be supported at that income. This is a function of the technology available, so this third curve is called the technology schedule.

As explained by Clark (2007) or Lee and Schofield (1981) this attractor always draws the population back to the subsistence income point. An increase in the birth rate over the death rate for whatever reason will increase population in the short term but then the resulting fall in income will reduce births and increase deaths until the two are in balance again. A few important points need to be made here. First, the subsistence income is not necessarily a starvation income; it can support a healthy and relatively comfortable (by pre- industrial standards) lifestyle. Second, the subsistence income is entirely determined by the birth and death rate schedules. For example, the result of increasing the birth rate at a given income level while leaving the death rate-income relationship the same is that the population grows and everyone gets poorer. Third, improvements in technology, which shift the technology schedule to the right, are entirely swallowed up by increased population without changing the subsistence income. As a consequence, in pre-industrial times the only way the income of the mass of the population could be improved was by increasing the death rate and reducing population. This proposition is illustrated in Figure 10.1 in Clark (2007, page 194) by the almost doubling of the income of English workers between 1340 and 1450. In 1348, the arrival of bubonic plague killed up to 30% of the population and, with essentially stagnant technological change, the result was a major improvement in the material income of the survivors. The reader is referred to Clark (2007) or Lee and Schofield (1981) for a fuller discussion of the dynamics of the Malthusian attractor.

As is indicated in Figure 1, the effectiveness of material and social technologies that controlled how much impact society could have on the biosphere increased only very slowly for most of the long millennia after the invention of farming and pastoralism. As a result, while societies locally could destroy the ecosystems upon which they depended, for example, by salinizing soil through irrigation, which was a major cause of the demise of early city states in southern Mesopotamia, in total humanity's impact on the earth was slight. Hence in Figure 3, we show the trajectory moving on an attractor close to the origin of a state space defined by population, income and biospheric impact. However, in Figure 10.1 of Clark (2007 page 194) we see that something profound happened in the mid 1700s, which broke the inverse relationship between population and income. This change, as we shall see, involved rapid synergistic development in both material and social technologies, leading to a transformation not only of humanity's material condition but critically and essentially, to its social organization.

Towards a dynamical systems description of the industrial and post-industrial world

We are going to propose here that we need a minimum of four variables to describe the state space of the post-industrial human-earth system in a way that allows us to understand the basic dynamics that control the system trajectory. These variables are population, economic output, the state of the biosphere, and societal state. One of these, population, is as we have just seen an essential variable in the Malthusian attractor. Economic output is related to material income and in pre-industrial times was practically the same thing. The state of the biosphere is interchangeable with biospheric impact. But the new variable: societal state, refers to the social and political organizing principles, which, before 1800, saw most of humanity ruled by autocratic elites in large tribes, kingdoms, empires, or city states. The changes in societal state, which began with the Industrial Revolution, have shaped the modern world as profoundly as the other three state variables. Let us unpick the interdependencies of these four state variables to see what a dynamical system description of the modern world looks like.

Population

World population seems set to stabilize at levels of 9–11Bn by the end of this century (UN, Department of Economic and Social Affairs, Population Division, 2013). The mechanism of stabilization is the 'demographic transition', a process whereby an increase in life expectancy, particularly a drop in child mortality, is followed in a generation or two by a fall in birth rates (Livi-Bacci, 2012). A range of factors links these two processes. As the Industrial Revolution progressed, by the mid to late 1800s improved sanitation and other advances in cities reduced the likelihood of early death, so that the need for living children as social security for aging parents did not depend on having a large family. At the same time, there was an extra financial burden associated with raising children in an urban industrial setting, where they could not contribute to family incomes until they were much older than in rural settings. These factors provided strong Darwinian forces driving smaller families and population stabilization, which are clearly evident in the developing world today (Dye, 2008). Other factors such as female emancipation, education and contraception all played roles later in the demographic transition. Since WWII, as globalization has caused worldwide dissemination of medical and social advances originally confined to the developed nations, we are now seeing a demographic transition in the developing world while the population of the developed world is now stabilized or declining.

The mechanisms that enable the demographic transition implicitly require significant increases in per-capita wealth or income, and a robust relationship appears to exist between per-capita income and fertility and mortality and has done so over the last 200 years and across different cultures and countries today (Figures 5 & 6). At incomes around U$200 per annum, TFR values are as high as 7 or 8 but at incomes around U$5000, TFR has dropped to the replacement value of 2.1, with some cultural variations around this. Complementary to this, life expectancy reaches around 70 years at incomes of U$5000 and flattens thereafter. Globally, TFR values have now reached about 2.3-2.4 but are still strongly skewed to higher values in the poorest countries, particularly sub-Saharan Africa (UN, Department of Economic and Social Affairs, Population Division, 2013). Nevertheless, global population growth in the future is projected to be primarily due to population momentum, the fact that more generations will be alive and childbearing simultaneously as longevity increases.

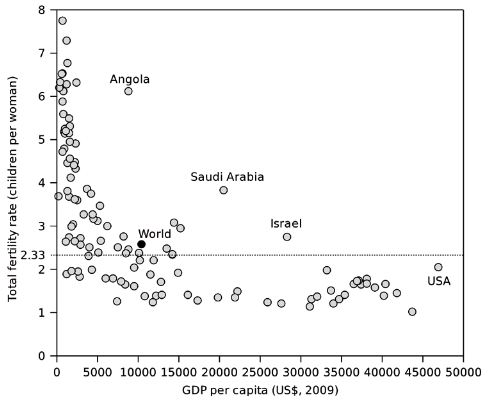

Figure 5. Total fertility rate (TFR) vs GDP per capita. Source: World Bank 2010.

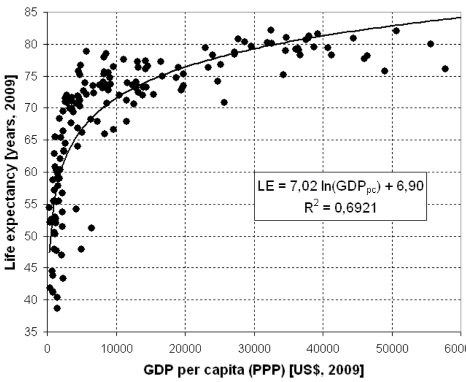

Figure 6. Life expectancy at birth vs GPD per-capita. Source: index mundi website.

Although the relationship between per-capita income (usually approximated by GDP/capita) and TFR or mortality is clear, the underlying mechanisms are complex and involve processes that include education (especially education for females), improved health services and urbanization. Urbanization in turn is correlated with economic growth and higher incomes but then exerts the Darwinian pressures for smaller families discussed earlier. Completing the demographic transition to stabilize and then reduce population thus implies an increase in global GDP, continuing urbanisation and a reduction in within-country income inequality so that the GDP rise can affect choices of family size.

Economic output

Global economic growth is required both to effect the demographic transition and also to set up the conditions for the political evolution of nations from states where basic human rights are not guaranteed to those where they are: in effect to allow them to make a transition to what Karl Popper, in his landmark book, called 'The Open Society' (Popper et al., 1945). We make the normative assumption here that to meet the kind of desiderata that Raworth (2012) suggests are necessary to have a safe and just operating space for humanity, a political structure corresponding to Popper's Open Society is necessary. In the next section, we will describe such societies as Open Access Orders. A certain minimum level of economic output is required to make this transition. Unlike the Malthusian economy described earlier, where per-capita economic growth is primarily limited by inputs of land and capital, in an industrial and post-industrial economy, three quarters of per-capita economic output devolves from gains in the efficiency with which inputs are converted to outputs (Clark, 2007). In modern societies, economic growth is a synergistic process, as wealth creation occurs much more rapidly in open societies where all can participate productively in the economy and the power of innovation and competition of ideas can be freely exerted (North et al., 2009).

Although we cannot develop this theme here, it is important to note that the second law of thermodynamics implies that increasingly complex social, economic and industrial structures require greater throughput (dissipation) of energy than simpler systems. Some recent work has strongly suggested that the industrial and post-industrial world system that was sparked by the Industrial Revolution, would have remained stillborn without access to fossil fuel energy, which exceeded earlier energy sources (wind, water and muscle) by orders of magnitude (Liska and Heier, 2013). This new energy source together with increased rates of innovation during the Industrial Revolution was critical in breaking the inverse relationship between population and material income per-capita. A third critical factor in leaving the Malthusian technology schedule was the concentration of human capital in cities. This catalysed innovation as well as increasing manufacturing efficiency, and it also played a crucial role in social transformation, as we see next.

Societal dynamics

North et al. (2009) describe three phases or 'orders' in the development of human social organization. The first, called the 'foraging order', describes the organization of hunter-gatherer bands and has little relevance today. The second they term 'the natural state' or 'limited access order', which has existed since the Neolithic revolution and still persists in most countries today. Fukayama (2012, 2015) refers to the natural state as the patrimonial state. The third is 'the open access order', a mode of social organization that characterizes the kind of advanced developed countries where Raworth's desiderata are generally obeyed and corresponds to Popper's Open Society. Fukayama calls these liberal democracies.

The distinguishing characteristic of the natural state is that all power, influence, access to legal recourse, and ability to take part in political or economic life depends on personal relationships and status — who is related to whom, who supports whom — or on one's personal prowess, reputation or popularity. No institutions that operate in society or economy are admitted except those allowed by a ruling elite. In contrast, in open access orders, recourse to law and political power is completely depersonalized — all are equal before the law. Similarly, any group of citizens can form organizations to contest political power, to promote causes or to operate in the economy.

Obviously, the natural state has evolved considerably through the long Malthusian twilight into modern times and North et al. (2009) distinguish three main levels of natural state: the fragile, the basic, and the mature, and within these levels exist still finer gradations. Mature natural states emerged in Britain, some other European countries and the USA in the 18th and 19th centuries and many (most?) countries in the world are still organized along this model. To paraphrase North et al. (2009), natural states are distinguished by:

1. Slowly growing economies, vulnerable to shocks;
2. Government without the general consent of the governed;
3. Relatively small numbers of organizations;
4. Smaller and more centralized governments;
5. Social relationships organized predominantly along personal lines, including privileges, social hierarchies, laws enforced unequally, insecure property rights, and a pervasive sense that not all individuals were created or are equal.

The transition from mature natural states to open access orders occurred in a few countries such as Britain, France and the USA in the mid to late 19th century. Paraphrasing North et al. (2009) again, open access orders are characterized by:

1. Political and economic development;
2. Economies that experience positive growth on average;
3. Rich and vibrant civil societies with lots of organizations;
4. Bigger, more decentralized governments;
5. Widespread impersonal social relationships, including rule of law, secure property rights, fairness and equality.

As intimated above, stark differences in the number of organizations and size of government as a fraction of national income serve to distinguish the twenty or so countries that today clearly exhibit open access orders from those that remain natural states (North et al., 2009).

An essential link between the growth of per-capita economic productivity and consequent national wealth that occurred in the Industrial Revolution and the transition to open access societies has been highlighted by Fukayama (2015). Prior to the industrial age, society could be broadly divided into land-owning elites and a much larger agrarian servile class. In the Industrial Revolution, centralization of manufacturing saw a step increase in urbanization and relative depopulation of the countryside, while the economic explosion created new classes: the middle classes or bourgeoisie and the industrial working class. Relaxation of the ties of the older social order in the new cities allowed these new classes to organize themselves and to demand participation in the political process. In particular, acceptance of new ideas about individual rights and what was acceptable in social organization, such as the 'Declaration of the Rights of Man and the Citizen' by Jefferson and Lafayette became widely shared in the new urban societies and informed these demands.

In this paper, we will take the existence of an open access order in society as the signifier of a social safe operating space. Based on the characteristics of this order that are listed above, this allows us to make direct links between social organization and economic output, which in turn is linked to impacts on the biosphere. Similarly, social organization can be linked formally to innovation and the technology schedule and also to population dynamics, particularly the dynamics of post-Malthusian demographic transitions.

However, if we want to use social order as a variable in a dynamical systems description (presumably as a coarsely resolved ordinal variable with the foraging order denoted as, say 1, the fragile, basic and mature limited access orders as 2, 3, 4, respectively and the open access order as 5), we need a model of how societies transition from natural states to open access orders, a model that is driven by the other state variables. For this we adopt the theory of Acemoglu and Robinson (2007), who showed that intolerance of excessive income or wealth inequality by the majority can force ruling elites to concede *de jure* power so as to avoid violent revolution. This indeed was the key mechanism of transition from mature natural states to open access orders in early adaptors like Britain and the USA. However, if de jure power is not transferred in the face of the rejection of inequality by the mass of society, the result is violent revolution or the maintenance of repressive mature natural orders. This treatment of societal state as a progression from the most primitive levels of organization to modern liberal democracies — and which depends on other state variables, particularly the absolute level of wealth and its distribution — is perhaps the most novel aspect of our approach to conceptualizing the human-earth system.

Impact on the biosphere

The impact of economic activity on the biosphere is now clear and profound. Climate change is the most prominent manifestation of this, but other factors such as ocean acidification, over-extraction from terrestrial aquifers, loss of biodiversity and the altering of oceanic and terrestrial trophic structures will have irreversible impacts on the provision of the ecosystem services that we rely on for food and water. These problems are encapsulated in the biophysical Planetary Boundaries analyses of Rockström et al. (2009) and Steffen et al. (2015) but they also play immediately into the provision of safe and just operating spaces, as the impacts of environmental degradation are greatest on the poorest people and countries.

Producing energy to drive the economy and the impact of this on the climate and biosphere poses a serious challenge. Maintaining the required societal complexity to bring a world population of 9–11Bn to a safe and just operating space requires increased energy flows. Provision of this through fossil fuels is impossible, if we are to avoid grave biophysical consequences. Fortunately, alternative renewable energy technologies exist at the price of economic transitions, which may be politically difficult but could accelerate rather than reduce economic growth rates, at least as measured by GDP and employment. Provision of food and water for 9–11Bn is possible but may require a global reassessment of what is meant by sustainability. Some things we see as valuable parts of our planetary estate may have to be abandoned to bring humanity through the population bulge safely. Making the choices that will keep us on a safe trajectory depend on social dynamics.

A model of the Human-Earth System

In this section we will illustrate the links and feedbacks between the four state variables: population, economic output, societal state, and biospheric impact. As we do so, the important role played by the linking processes, energy production, urbanization and wealth inequality will become apparent. We begin with the key processes controlling population illustrated in Figure 7.

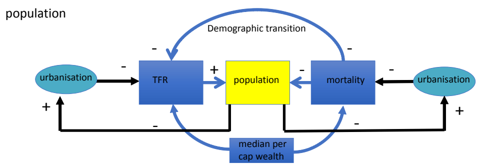

Figure 7. Population subsystem.

In all of the following diagrams the arrows indicate the direction of influence and the plus (or minus) sign by the arrowhead tells us whether an increase in the variable or process from which the arrow starts leads to an increase (or decrease) in the target variable. Population is the result of the balance between TFR and mortality integrated back through time. The demographic transition is the dominant feedback, so that a decrease in mortality leads to a decrease in TFR. An increase in per-capita wealth, transmitted down to family level either directly or through increased state services, is approximated by median GDP per-capita and decreases both TFR and mortality. Finally, an increase in population eventually can be assumed to increase urbanization, which has a damping influence on both TFR and mortality (Dye, 2008).

In Figure 8 we look at economic output. At the most basic level, population increases economic output, Y through the fundamental relationship,

$$Y = A^* \boldsymbol{F}\,[P, K, L] \qquad (1)$$

where L is land (or resources), K is capital and P is labour, while A is the efficiency with which these three inputs are transformed into output through the functional interrelationship denoted by $\boldsymbol{F}$.

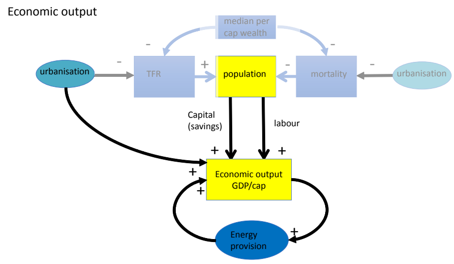

Figure 8. Economic subsystem.

As well as its labour, the savings of the population are also available to be invested into the economy so population increases output both directly and indirectly. As we stated above, concentration of manufacturing in cities increased efficiency and also innovation, while the transition to an open access order also unleashes the power of innovation and novelty on economic activity. Finally, an economy requires power, so a part of economic activity is power generation, which forms a positive feedback loop in the system.

The key links in the societal state subsystem are shown in Figure 9. As well as the positive influence of an improvement in societal state on economic output, we have seen that a certain level of wealth must be generated to first kick society out of the Malthusian attractor and then to maintain a transition towards an Open Access Order.

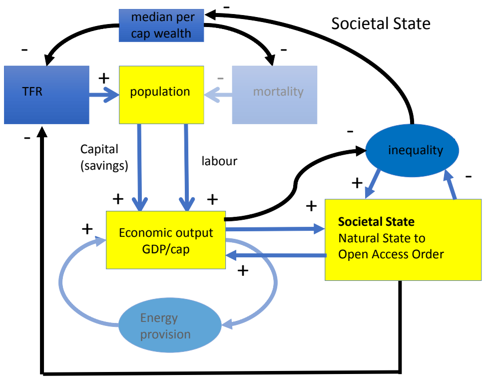

Figure 9. Social subsystem.

We have described the mechanism by which an increase in inequality can paradoxically, trigger a transition towards more democracy, and correspondingly an improvement in societal state reduces inequality. Inequality is a critical filter through which economic output passes to be converted to our measure of wealth inequality — median GDP per-capita — which then influences TFR and mortality directly. Finally, societal state affects TFR directly via cultural norms and expectations, with less developed societies having higher TFR's when corrected for all other influences (Livi Bacca, 2012).

Links and feedbacks for the last state variable, biospheric impact are diagrammed in Figure 10. The experience of the last 12,000 years is that the processes of economic output and energy provision generally degrade the environment.

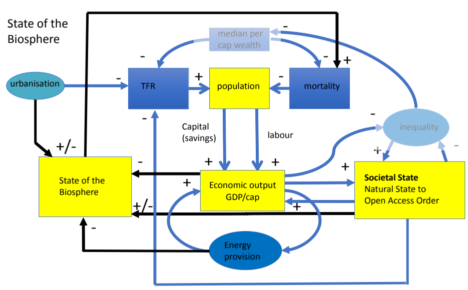

Figure 10. Biospheric subsystem.

Societal state can have either a positive or a negative influence on the biosphere, depending on whether the ruling ideas of society privilege exploitation or nurturing of the environment. Urbanization too can have either negative and positive consequences. Negative impacts come through appropriating often productive land or introducing concentrated effluent streams into the local environments of cities, for example, the dead zone extending from the mouth of the Mississippi into Gulf of Mexico. Positive impacts come because concentrating human habitation vastly reduces the amount of land the same number of people would require, if they were rural dwellers. Finally, a degraded environment will necessarily increase mortality, particularly of the poorest and most vulnerable.

These four systems are brought together in Figure 11, which prompts the immediate observation that the processes we know least about, to the extent that most models of the human-earth system do not even try to include them, are the socially determined ones. Their links are coloured red in Figure 11. Parameterizing the functional relationships between the state variables and the intermediate processes and factors illustrated in Figure 11 will be the subject of a further paper, which will focus on detailed analysis of the system properties, especially the possibility and nature of stable attractors for some parameter values.

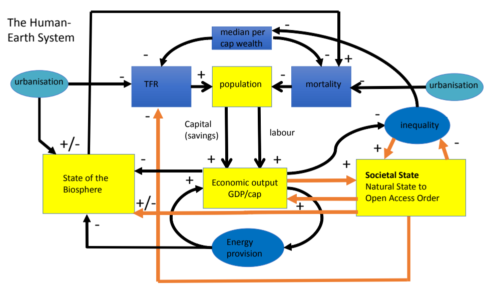

Figure 11. Human-earth system.

Discussion: is arriving at a safe and just operating space possible?

Even without the formal analysis just alluded to, exposing the dominant interrelationships of the processes controlling evolution of the four state variables suggests some conclusions that are not so obvious, if the variables are considered separately. First, there is a direct relationship between per-capita wealth and the drivers of population. As we have seen, this has existed throughout history even in Malthusian times but today it means that projections of a stabilizing then declining global population — a *sine qua non* for a sustainable world — imply very large increases in wealth generation. Generating this wealth requires economic growth, but this will have substantial negative impacts on the biosphere and thence onto mortality and other factors affecting the social dimensions of a safe and just operating space unless serious efforts are made to decouple economic activity and impact. We are seeing currently how difficult this is in the context of climate change, where, despite the fact that decarbonizing energy generation is not only possible but brings with it enormous side benefits, social forces are mounting strong opposition to this transformation.

Unless substantial within- and between-country inequality is also addressed, the amount of wealth generation required to stabilize population will be prohibitive. We have seen that inequality is a driver and reduced inequality a consequence of movement to a higher social order but that the mechanism by which this happens, involving as it does conflict and possible revolution, militates, at least temporarily, against provision of a safe and just operating space for those involved. North et al. (2009) have listed the essential doorstep conditions required so that a transformative social revolution, initiated by inequality, doesn't collapse into anarchy then the re-imposition of autocracy (*vide* the Arab Spring or the collapse of western institutions after the precipitate withdrawal of colonial powers in Africa post WWII). Our analysis together with these (and many other) examples suggests that much more effort needs to put into building institutions in developing countries, if they are to attain the goal of open access societies.

We could detail more of these links but in the spirit of this meeting it is proper instead to close with a more important question: is a safe and just operating space for human society an attractor, given current geopolitical settings, and, if not, what needs to change to make it so? A corollary of this question is whether there are other attractors that human society can end up on that are clearly not safe and just operating spaces and that, once on, would be difficult to escape from?

Conclusion

The human-earth system displays the defining characteristics of a complex system: emergence and self-organization. This implies that its dynamics should have attractors and we can point to a series of social attractors that humanity has been drawn to through most of human history. Once on an attractor, it is difficult to shift the the trajectory of a complex system to a different, more desirable, region of state space without addressing the fundamental relationships governing the system's dynamics. In the case of the human-earth system, many uncoordinated efforts to address separate features of the system, for example, those involved in addressing the UN's SDGs piecemeal, may have little long-term effect or even be self-defeating, if the nature of the major interacting forces governing the trajectory are not understood and policy actions framed with this knowledge.

Acknowledgements

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Appendix 1 Geometrical representation of complex systems

Along with the properties of emergence and self-organization around attractors, a third important thing to understand about complex systems is that they live somewhere between simplicity and chaos. If we were to plot the complexity of such a system on a graph with "simple" at one side of the *x* axis and "chaotic" at the other, complex systems live somewhere in the middle (Fig A1). Furthermore, it is the actual nature of self-organization around an attractor in a complex system that allows this balance between order and chaos.

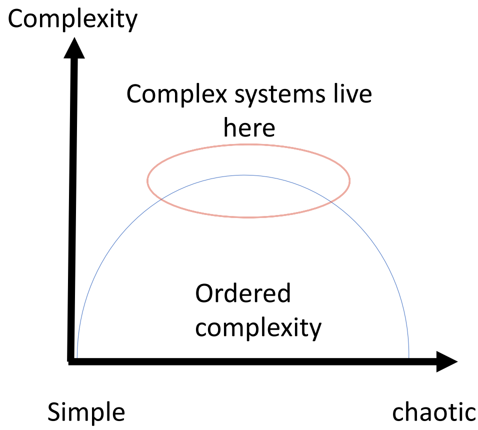

Figure A1. Simplicity vs chaos

In Fig A2 we see a plot of perhaps the most iconic complex attractor, the Lorentz Attractor, which describes convection in a thin layer of fluid (see Tabor, 1989). The Lorentz Attractor can be taken as simple model of the lower atmosphere. It lives in a 3 dimensional 'state' space with axes, *X*, *Y* and *Z*.

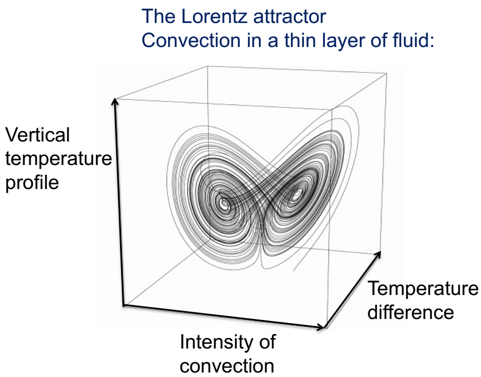

Figure A2. The Lorentz attractor.

Simplifying greatly, *X* is a measure of the way air temperature changes with height. *Y* is the intensity of convection, that is, how much movement there is in the atmosphere. *Z* is the temperature difference between ascending and descending air currents. The 'state' of this simplified model of convection in the atmosphere at any instant of time *t* is given by the location of a point in the 'state space' spanned by *X*, *Y*, *Z*. As time goes on, the system's state evolves and describes a trajectory which is confined to the surface of the attractor. So the atmospheric state is restricted to a small region of the total 'state space'.

We know from the fact that long-range weather forecasts have high uncertainty that starting a forecast from two close but slightly different atmospheric states will lead to quite different predictions of the weather a week or more hence. The equations governing air movement (of which the Lorentz equations are a simplified version) tell us that our predictions must diverge exponentially with time. Yet we also know that the atmosphere won't spontaneously boil or freeze, so, paradoxically, although the system trajectory must remain in a bounded region of state space, two trajectories that start nearby today must get exponentially far apart if we wait long enough. This paradox is resolved because the Lorentz Attractor is a 'Strange Attractor' with a dimension that isn't an integer. In fact, the Lorentz attractor has a dimension about 2.06. In other words, the surface of the attractor isn't a real surface, it's like millions (actually an infinite number of) onion skins, so two trajectories that started close together can pass each other on different onion skins such that in the 3D state space of the system they are close together but if we were to trace their trajectories back through time, we find they have been diverging continuously.

The geometrical visualization of a system's behaviour as a trajectory, tracing a path through a state space, whose axes define the key attributes of the system, makes the concept of an attractor, a restricted region of state space that the system trajectory is drawn to, easy to visualize. Indeed, the geometrical treatment of non-linear systems in general and complex systems in particular has been a powerful tool in advancing our understanding of their behaviour and it is the lens through which societal dynamics has been viewed in this paper. For a more rigorous mathematical treatment of these ideas see for example, Tabor (1989) or many other readily available books and papers.

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