



"Earthrise" taken on 24 December 1968 by Apollo astronauts. NASA

Thematic Focus: Environmental Governance, Resource Efficiency

One Planet, How Many People? A Review of Earth's Carrying Capacity

A discussion paper for the year of RIO+20

We travel together, passengers on a little spaceship, dependent on its vulnerable reserves of air and soil; all committed, for our safety, to its security and peace; preserved from annihilation only by the care, the work and the love we give our fragile craft. We cannot maintain it half fortunate, half miserable, half confident, half despairing, half slave — to the ancient enemies of man — half free in a liberation of resources undreamed of until this day. No craft, no crew can travel safely with such vast contradictions. On their resolution depends the survival of us all.

~Adlai Stevenson, Speech to the UN Economic and Social Council, Geneva, Switzerland (9 July 1965)(1)

The size of Earth is enormous from the perspective of a single individual. Standing at the edge of an ocean or the top of a mountain, looking across the vast expanse of Earth's water, forests, grasslands, lakes or deserts, it is hard to conceive of limits to the planet's natural resources. But we are not a single person; we are now seven billion people and we are adding one million more people roughly every 4.8 days (2). Before 1950 no one on Earth had lived through a doubling of the human population but now some people have experienced a tripling in their lifetime (3). So many people now inhabit the planet with so much impact that scientists have coined a new word to describe our time, the Anthropocene Epoch (4). Unlike previous epochs,

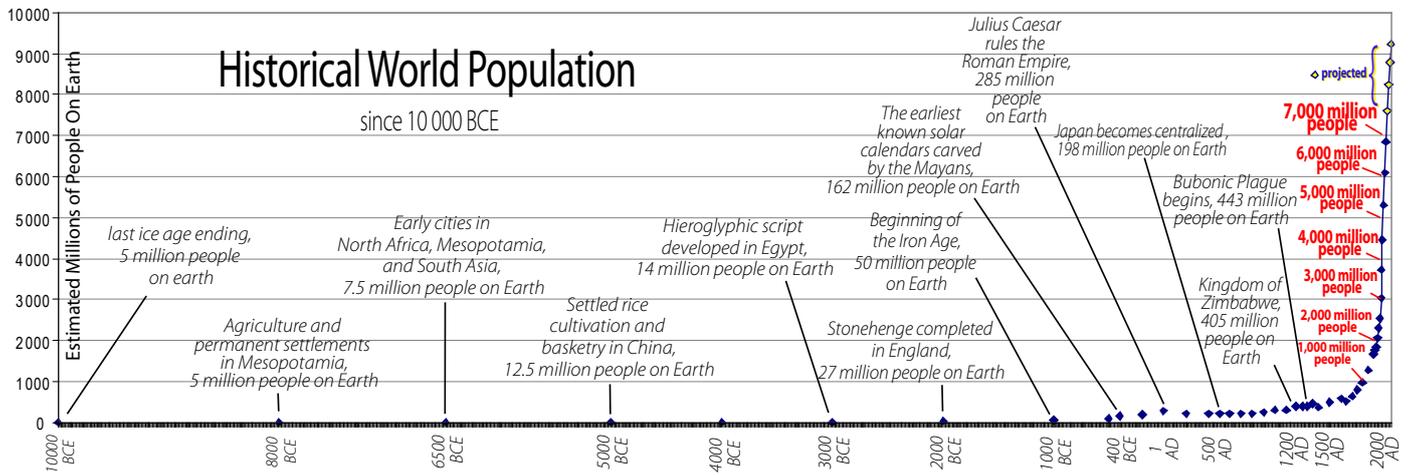


Figure 1: World population began accelerating about 4 000 years ago and has “exploded” in the past 1 000 years. Source: UNEP-GRID Sioux Falls; population data – US Census Bureau 2011.

where various natural regimes of geological processes defined the time periods, the Anthropocene is named for escalating human influence on the environment. The release of CO₂ into the atmosphere is beginning to alter the global climate. Species are going extinct at a rate 100 to 1 000 times above the natural rate. The scale of human appropriation of the products of photosynthesis—the most fundamental process of the biosphere—has reached around one-quarter to one-third of all global Net Primary Production (see box 1). We have become a major “global geophysical force” (5).

After roughly 100 000 to 200 000 years of modern humans remaining at very low numbers (and with a very minimal impact on the planet), our numbers began to grow around 4 000 years ago. That growth began to accelerate over the following centuries until we were adding more people each year than had ever lived on Earth at one time prior to 500 BCE (87 million added in 1989) (2). While the rate of population growth in percentage terms is estimated to have peaked in the 1960s, the absolute number of people added each year continues to be staggering (2). The most recent billion arrivals were added in about 13 years; it took 12 years for the billion before that and 13 years for the billion before that. Even though the global growth rate peaked more than 40 years ago, it is estimated that there will be another billion added over the next 15 years and yet another billion before mid-century (6). The UN Population Division’s “medium-variant” projection for the end of the century is now 10.1 billion (6)!

Increasing Per Capita Impact

While global population has doubled since the 1960s, per capita GDP has grown to more than 10 times what it was then (7). Per capita income for millions in the developing world including India and China is growing rapidly, creating enormous demand for material goods

and services (7). Life expectancy has also increased globally —by almost 20 years (8). That puts twice as many people on the planet, living about 40 per cent longer and each person consuming many times what the average person in the 1960s did. Most developing economies are striving to close the gap between their living standards and those of developed economies. However, it has been estimated that “if everyone lived the lifestyle of the average American we would need five planet Earths” to provide the needed land and ecosystem goods and services (9). Living standards and consumption need not be directly equivalent to environmental impact (10). While population is a multiplier of per capita impact, technological advances in efficiency can be a divisor of per capita impact. However, so far development of technologies that can deliver goods and services efficiently enough to stabilize environmental impact in the face of rapidly growing population remains a profound challenge (10). In other words, population growth is multiplying per capita impacts faster than technology (the divisor) is mitigating environmental impacts. It is not surprising that concerns about the number of people the Earth can support have re-emerged in the past decade.

How Many People Can We Fit On Spaceship Earth?

Speculation about the ultimate carrying capacity of the planet dates back at least to the 17th century. Dutch scientist Antoni van Leeuwenhoek (1632-1723) estimated that if the population of Holland in his day (one million people) were extrapolated across the estimated area of inhabitable land around the globe, it would equal 13 billion people (11). Since then many more estimates have been made as to how many people the Earth could support (11,12). The range of these estimates is enormous,

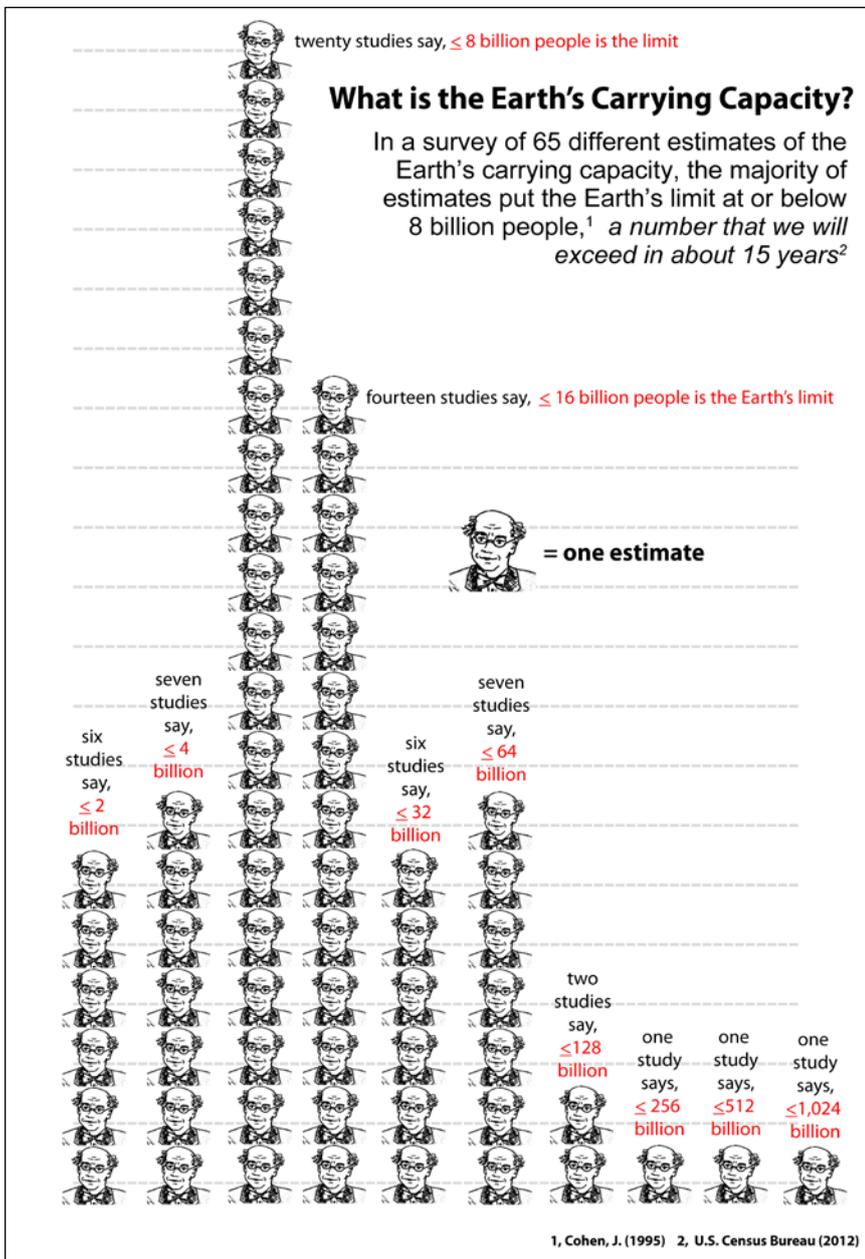


Figure 2: Estimates of Earth's carrying capacity vary dramatically as this survey of 65 different estimates shows.

and rather than converging toward a narrower range over time, they have if anything, become more wide ranging in recent decades (13). A study looking at 94 different estimates of the upper bounds of Earth's population found estimates ranging from a low of 500 000 000 to a high of 1 000 000 000 000 000 000 (11).

Why do these estimates vary so dramatically? Part of the variation comes from the differences in methods used (at least six) to estimate the limits of human population on Earth (11). One method was the above mentioned approach used by Leeuwenhoek. A problem with this method is that it must assume the initial populated area to be a valid example of a population which has reached the limits of its environment. This approach also assumes that the factors and dynamics constraining population in this sample area would apply for other areas.

Many other studies have assumed a single constraining factor to estimate population limits (11), such as the maximum population that could be supported by the available food. These estimates could only be as valid (or invalid) as that assumption of a single constraining factor and the method of calculating limits of that assumed constraint (e.g. food supply).

A more sophisticated variation of this method assumed a set of multiple possible constraints (say food, water and fuel), and whichever of these was in shortest supply would set the limit of population (11). This allowed for different constraints to be limiting in different locations, as in water in deserts or land area on an island.

A still more sophisticated approach identifies several constraining factors and also takes account of the interdependence of these variables (11). This is the approach of dynamic systems modeling which develops a set of defined relationships for multiple factors reflecting their influence on each other and ultimately on the limits of population (11). The degree to which humankind can change its interaction with the environment through technology cannot be foreseen. For example, availability of fossil fuels impacts food production through fertilizer production, pumping of irrigation water, use of farm machinery, and so on. Current manufacturing methods for fertilizer production rely

heavily on natural gas. Guesses about future availability and cost of natural gas depend on assumptions about future technological advances in efficiency. Alternatively, if an economically viable substitute for natural gas in the production of fertilizer could be found, then natural gas as a constraint on food production would be diminished or eliminated. These uncertainties must be incorporated into estimating future agricultural land use efficiency and by extension affect whether or not available farmland is ultimately an important constraint on population.

As methods of estimating an upper limit for human population have become more sophisticated they have had to incorporate more factors, which often can only be estimated or have uncertain values. Natural limits, such as those imposed by the climate system, are not fully understood and must be estimated from imperfect

models. We do not know how much CO₂ can be released into the atmosphere before it may cause an abrupt change in the environment, for example. And, it is not yet possible to say with certainty how much rise in surface temperature there could be before the Antarctic Ice sheets would be at risk of collapse.

Individual and societal choices as to the level of material that is “necessary” for well being and the deprivations that would be tolerated in the future can be estimated within some plausible range, but cannot be known for certain. How much food, medicine, heat, clothing, shelter and water do we assume is required for each future inhabitant? How evenly can these be distributed?

In the end, the outcome of attempts to define a static ceiling for sustainable human population seems destined to uncertainty. However, rather than estimating a static upper limit of human population, it might be more important to understand the dynamics of the complex system upon which the survival of that population depends. Models that capture the key dynamics of the Earth system can serve as a map for choices that will impact our collective future (however many of us there ultimately are).

Modeling Our Future On Earth

In the early 1970s a group of computer scientists at the Massachusetts Institute of Technology (MIT) developed just such a model to help use define safe limits to our impact on the Earth system. Jay Wright Forrester was a computer engineer at MIT and the founder of “System Dynamics,” a modeling approach for studying complex systems. Forrester realized that advances in computers he used for modeling of economic systems might

enable modeling of the global economy and the global ecosystem as a single complex system (14). At the same time, a set of Forrester’s colleagues at MIT, headed by Dennis Meadows, also began working on the same type of global models (14). The teams worked independently publishing their work in 1971 (Forrester’s “World Dynamics”) and 1972 (Meadows and others’ “The Limits to Growth”).

The authors had simulated the relationships of several of the Earth System’s key processes over time, and both teams came to similar conclusions. They found that Earth’s economic system tends to stop growing and collapse from reduced availability of resources, overpopulation, and pollution at some point in the future. Various scenarios of technological innovation, population control, and resource availability could delay the collapse, but only a “carefully chosen set of world policies designed to stop population growth and stabilize material consumption could avoid collapse” (14).

The books were quite successful, particularly Meadows’ book “The Limits to Growth,” which was written for the layperson and translated into several languages (14). Many in the sciences responded enthusiastically and many tried to adapt the groundbreaking technical approach to their own fields of study (14). But in spite of their popularity, criticism came from several directions as well. Many critics saw a political meaning in the works (15), many dismissed it as alarmist (16), but the most enduring push-back came from mainstream economists (16).

In the past decade, however, many have begun to revisit the Limits to Growth and “world modeling” of Forrester and Meadows (14,16,17,18,19). Several have pointed out that the projections of the Meadows’ World3 model’s “business as usual” scenario are proving to be remarkably close to reality for the 40 years since they were first published (14,17,19). New science, including advances in modeling dynamic systems such as the Earth System, is trying again to see what might lie in the future (14).

Living in the Anthropocene

The past 10 000 years, a period known as the Holocene to geologists, has given humankind a relatively stable environment during which human civilization and population have flourished. Human activity is now having important influence on the Earth’s climate (20) and ecosystems (5,21). To most of the scientists studying the planet it has become increasingly evident that there are limits to the human impact that our Earth System can absorb and still remain in that Holocene-like state. Several crucial processes are believed to have thresholds which, once passed, could trigger abrupt and/or irreversible environmental changes at a global scale (22).

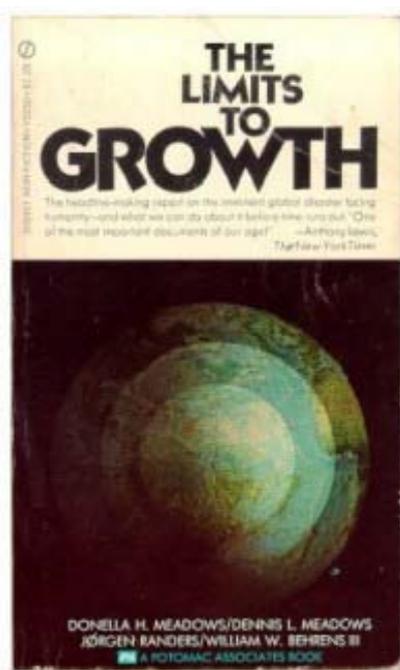


Figure 3: The Limits to Growth was released in 1972 selling millions of copies and drawing both accolades and criticism.

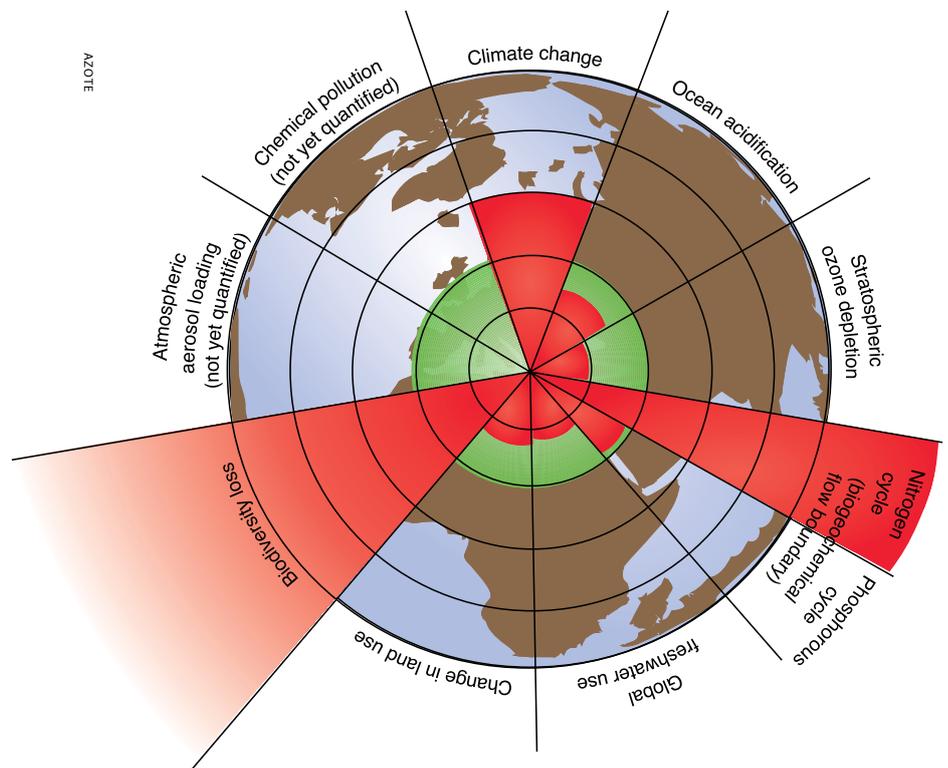
The Club of Rome

It is feared that these changes could cause the stable environment of the Holocene to transition to a new state which could be detrimental or even catastrophic to humankind (23).

Climate change, caused by increasing atmospheric CO₂, is the most widely known of these limits. However it is not the only limit that scientists are concerned about. In particular one group of scientists working together through the Stockholm Resilience Centre has identified nine such key processes in the global ecosystem which they feel are being altered enough by human activity to put the stability of the Earth System at risk (23). The graphic (Figure 4) shows those nine Earth System processes. Several of these are global in scale, such as climate change, ocean acidification, and stratospheric ozone. These can be understood as “top-down” in their impact. Others among the nine are local or regional processes which likewise have local and regional thresholds, but whose aggregate influence is important at the global scale. These could be understood as “bottom-up” in their global impact.

One of the ideas most emphasized by the Stockholm Resilience Centre is the susceptibility of key Earth System processes to “tipping points.” They believe that exceeding these thresholds risks triggering abrupt environmental change. Think of the Earth System as a bus that is overloaded (Figure 5). Up to a point each new rider has a “linear” impact—causing the bus to tilt a little more when it turns. No one pays much attention when another and then another rider climb on the bus. After all it just seems to cause the bus to tilt a little more each time. Then at some point, just one more added rider causes the bus to overturn as it rounds a corner. What had up to that point had a linear impact—one passenger equals a little more tilt—reaches a tipping point—one passenger equals an overturned bus. Continuing with the metaphor, several factors can influence the tipping, such as speed, weight of the passengers, condition of the suspension, sharpness of the turn, and so on. Some of these are contributing factors to the stress on the bus (e.g. weight of passengers) and others are factors which reduce the busses ability to handle that stress (e.g. the condition of the suspension).

In a similar way some of the nine processes that are identified by the Stockholm Resilience Centre’s work



Planetary Boundaries: the nine red wedges represent an estimate of the current position of each boundary. The inner green shading represents the proposed safe operating space.

Figure 4: The Stockholm Resilience Centre’s Planetary Boundaries Framework identifies nine key Earth processes which serve as a sort of set of safety gauges for the Earth System.

are primarily contributing factors in the sense of added stress—for example, climate change. On the other hand, some processes may also diminish the system’s ability to absorb change, such as land use change. All of the processes are interconnected and the uncertainty about change in one process then introduces uncertainty into the whole system model. Because of this it is not possible to pinpoint exact thresholds where change in these processes would trigger a change in the state of the system. To return to the bus metaphor, we would have to know the weight of each passenger, the speed that the bus will travel in the future, the degree of turns the bus will make in the future, the condition of the



Shayan/Flickr (Modified)

Figure 5: Like an overloaded bus, the Earth System is subject to tipping points where linear additions of stress can lead to non-linear outcomes.

suspension, and many other factors to know precisely when the bus will tip over. However, we can see that the bus is approaching that threshold as it tilts farther and farther with each added passenger.

The point where the risk becomes intolerable, for either the bus or the Earth System, is not a clear black line. For the Earth System, we do not know the future state of several of the interconnected processes, such as land cover change and future CO₂ emissions. This makes it impossible to give that precise number of passengers where the “bus will tip over” but it may allow us to set a limit on passengers that minimizes the risk that it will.

That there are some unsustainable possibilities which must be avoided is an emphasis of the Stockholm Resiliency framework. It could be said that they have devised and continue to refine a set of “safety gauges” for the planet. Three of those gauges are already in the danger zone and others are approaching it.

Another emphasis of the Stockholm Resiliency Framework is (not surprisingly) resilience. In this context they mean the Earth System’s capacity to withstand perturbations without transitioning from the current Holocene-like state to an alternate state (24). Resorting again to a metaphor, think of the Earth System as an airplane (Figure 6). It is flying along at a good speed, at a good altitude, at the correct angle, and with a manageable load on board. As long as all of these parameters are within the design tolerances, the airplane has a fair “margin for error”—it has resilience. If an engine fails, the altitude allows our airplane to glide to

a safe place for an emergency landing. If the nose of the airplane gets too high, there is enough speed so that the airplane will not immediately stall. Each parameter has a point that if crossed will be enough to cause serious trouble on its own (e.g. too much weight, too steep a climb angle, too close to the ground, or moving too slowly). In systems dynamics parlance this resilience of a specific parameter as it relates to one or more controlling factors is called specified resilience.

General resilience, on the other hand, is the overall ability of a system to absorb shocks and remain within its current state or “basin of attraction” (more dynamical systems parlance). With a system as complex as the Earth System, the shocks include those from all known factors (e.g. the nine planetary boundaries) as well as novel ones (the proverbial “black swans”). In a sense, maintaining general resilience is a sort of insurance, a means of hedging our bets. It is an implicit acknowledgement that the problems of the whole Earth System are “simply too complex and contingent for scientists to make definitive predictions” about (25).

Planetary Boundaries

The Planetary Boundaries framework seeks to define safe limits for human impact on key Earth System processes that will keep us from crossing the thresholds of tipping points and to help us maintain the overall resilience of the Earth System. The roughly 50 scientists of the Stockholm Resilience Centre come from 19 organizations around the world and have published their work to, “lay the groundwork for shifting our approach to governance and management . . . toward the estimation of the safe space for human development. Planetary boundaries define, as it were, the boundaries of the ‘planetary playing field’ for humanity if we want to be sure of avoiding major human-induced environmental change on a global scale” (23). They propose that boundaries be set at the lower limit of the zone of uncertainty for key Earth System processes. Going beyond this line would take us into the zone of uncertainty where surprises in the state of one of the key Earth System processes could push us over a threshold to an abrupt change in the whole Earth system.

Staying within these limits, on the other hand, should ensure continued stability of Holocene-like conditions for thousands of years (22).

Unfortunately, scientists at the Stockholm Resilience Centre believe that three of these safe boundaries have already been passed: climate change, rate of biodiversity loss, and changes to the global nitrogen cycle (22). The climate change boundary established by the group is 350 ppm atmospheric CO₂. Concentrations above this “increase the risk of



Paul Friel/Flickr

Figure 6: The stability and margin of error that an airplane gets by maintaining proper speed, altitude and weight is a sort of general resilience. In a similar way, maintaining the Earth System’s resilience gives it a greater ability to withstand shocks and continue operating in its current Holocene-like state.

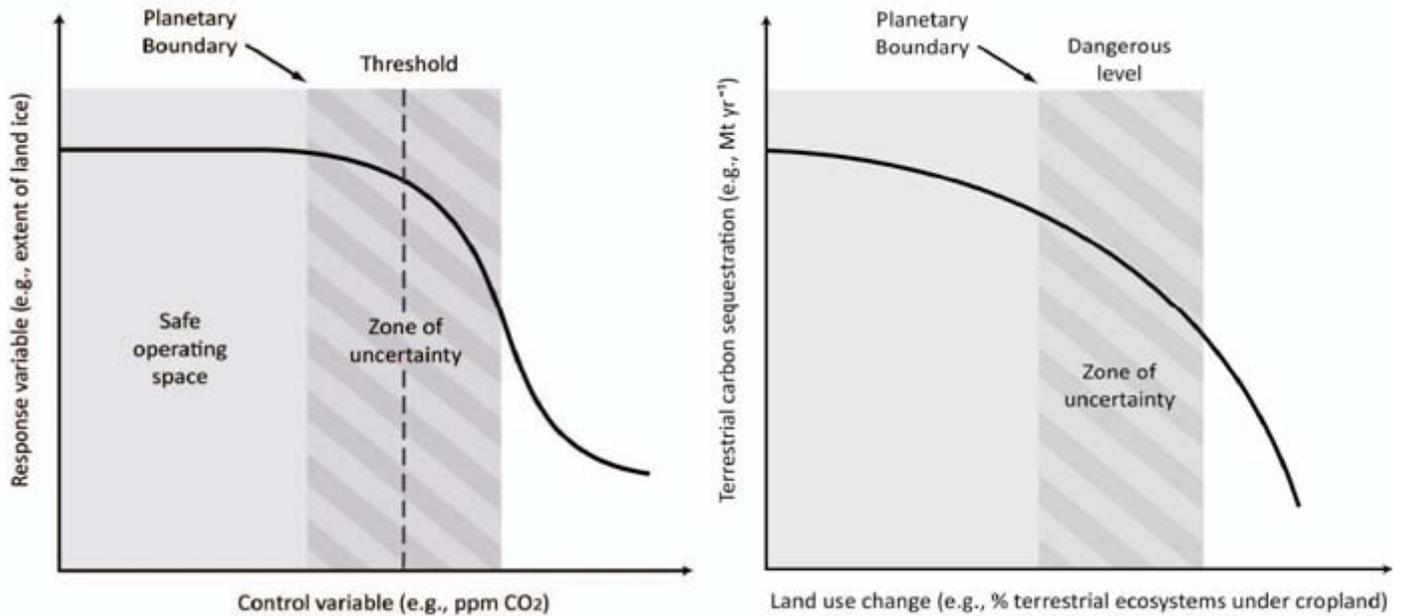


Figure 7: The Resilience Centre’s “planetary boundaries” are not clear black lines but rather zones where the risk of reaching a tipping point must be avoided.

irreversible climate change, such as the loss of major ice sheets, accelerated sea level rise and abrupt shifts in forest and agricultural systems.” Current atmospheric CO₂ concentration has recently reached 400 ppm (26) and is rising nearly 20 ppm per decade (27).

A second boundary already passed is loss of biodiversity. While it is clear that biodiversity is an important component of ecosystem resilience, the authors suggest that more research is needed to define a more certain boundary. As a provisional boundary they propose 10 times the natural rate of extinction. However, they are confident that the current rate of extinction is unsustainable at between 100 to 1 000 times the natural rate.

The third boundary that is estimated to have already been exceeded is for the nitrogen cycle and more generally for the nitrogen and phosphorus cycles. These are important nutrients with central roles in both natural and agricultural productivity. The authors estimate that human activities currently convert around 120 million tonnes of nitrogen from the atmosphere each year into reactive forms (for fertilizer and from cultivation of leguminous crops) exceeding the conversion by all land based natural processes. An estimated 20 million tonnes of phosphorus is mined for agricultural and industrial use. Much of this agricultural pollution ends up in the environment. Nitrogen pollutes “waterways and the coastal zone, accumulating in land systems and adding a number of gases to the atmosphere [and] . . . slowly erodes the resilience of important Earth subsystems” (22). As much as 45 per cent of the mined phosphorus ends up in our oceans (22).

The Stockholm Alliance acknowledges that their proposed framework is in many ways an extension of

past work such as the Limits to Growth systems modeling (28), the Precautionary Principle (29), and the Tolerable Windows Approach (30), to name a few (22). However, they point out several ways in which the Planetary Boundaries Framework advances from these earlier works (23). In contrast and perhaps to some degree in response to the criticism of non-specificity of the Limits to Growth, the Planetary Boundaries framework has identified the specific processes which they believe must be kept within defined safe limits for humanity to operate safely on planet Earth (23). Also in contrast with the Limits to Growth, the Planetary Boundaries framework recognizes the threat posed by non-linear changes that could result from crossing thresholds (23). Limits to Growth did not foresee this type of abrupt change or non-linear system response (23).

The Stockholm Resilience Centre is not the only organization addressing environmental limits. Another widely known approach to conceptualizing human pressure on the Earth System is the Global Footprint Network. Its “Ecological Footprint” is a measure of human impact on the planet. It is expressed as a budget where resources consumed and waste generated are balanced against nature’s capacity to generate new resources and absorb waste (9). While it has many similarities to the concept of carrying capacity, Ecological Footprint accounting approaches the question from a different angle. Ecological Footprints are not speculative estimates about a potential state, but rather are an accounting of the past. Instead of asking how many people could be supported on the planet, the Ecological Footprint asks the question in reverse and considers only present and past years, using historical data sets (see Box 2). This makes the Ecological Footprint less uncertain

than dynamical systems modeling; however, it avoids that uncertainty by not trying to predict the future. Wherever humanity chooses to look at what might lay ahead there will be uncertainty.

The dynamical systems modeling of climate and other natural processes which Meadows and Forester developed and which the Planetary Boundaries approach relies on, includes uncertainties and at best is able to recognize and define the range and nature of those uncertainties. Nevertheless, by understanding these uncertainties and the appropriate applications for models and simulations we can begin to take a qualified look into the future. Among the greatest values of these models is their ability to explore many ways which the future may unfold and to develop insights into the dynamics which affect that unfolding. Models can help us prepare for those possible futures by testing various responses to what they suggest and by avoiding responses (or lack of responses) which are indicated to have high risks.

Future Role of Technology?

One of the greatest sources of uncertainty, and a focus of considerable disagreement, is the development of future technologies. Many, including most mainstream economists, are quite optimistic about human ingenuity and technological advances to overcome challenges posed by population growth (16,31). According to this view, the “invisible hand” of the market system will spur any innovations necessary to substitute for natural capital such as land, sources of energy, minerals and so on (32). They acknowledge that resources are limited but assume that technology will continue to increase our efficiency in utilizing those resources (and in finding substitutions) such that production could keep growing even in the presence of declining mineral resources and other constraints (14). In the 1970s, one of the key advocates of this point of view, Robert Solow of MIT, stated that, “There really is no reason why we should not think of the productivity of natural resources as increasing more or less exponentially over time” (32).

Several environmental economists find fault with this blind faith in innovation and technological development (16,31,33,34). They contend that mainstream economics tends to ignore the laws of biophysics in its formulation of production (35). In a growth model with environmental constraints, clean technological development needs to be directed and encouraged while “dirty innovation” should be discouraged (36). Globally, there are large disparities in capacities to both generate technology and absorb new technologies. Building local capacity must be a central aspect of technological development (37). Government support is essential to

create national systems of innovation (37). Thus, the invisible hand is a merely theoretical concept. In reality, markets are regulated by visible hands. Governments have a role to play in designing the legal frameworks within which competition takes place; setting product standards, taxes and subsidies; and encouraging green technology development. Nevertheless, while many contemporary academic economists accept and address these issues in their work, environmental constraints continue to remain largely absent in the thinking of much of applied economics used in formulating policy (38).

Future Demographic Transitions?

In the past, people have also argued that concerns over world population will dissipate as countries undergo the demographic transition. Peak global population growth rates of 2.1 per cent occurred in the 1960s followed by a peak in the absolute number of people being added each year at 87 million 25 years later (2). This slowing in global average population growth was the outcome of a dramatic drop in birth rates among the world’s most developed countries; many dropping to replacement level or even below (39). It is very widely accepted that this phenomenon, part of something demographers call the demographic transition, reliably occurs in countries as they become developed (Figure 8) (40,41). This assumption is incorporated into estimates that project world population leveling off just above nine billion by the middle of this century (39,40). In general, projections of future population also assume that the economic and social development which is an important dimension of demographic transition, can and will occur in many of the world’s poorer countries (39,40).

This suggests a crucial dilemma for policy makers. The prevailing assumption about population growth rates is that as the developing countries achieve greater development their population growth rate will slow (the demographic transition described in Figure 8). This would mean an easing in the number of people putting pressure on the Earth System. So far, so good. However, developed countries also have larger ecological footprints and elevated levels of consumption. Thus while population growth will decline during demographic transition, the reduced number of consumers may have an equally large impact on the Earth System. A further problem is that the steady progress of global GDP, which is taken as evidence that development will eventually reach the entire world, has so far been built on cheap energy—primarily oil.

Several researchers studying population dynamics have begun to question the inevitability of these development trends continuing and leading most countries through demographic transition

Demographic Transition Model

schematic representation

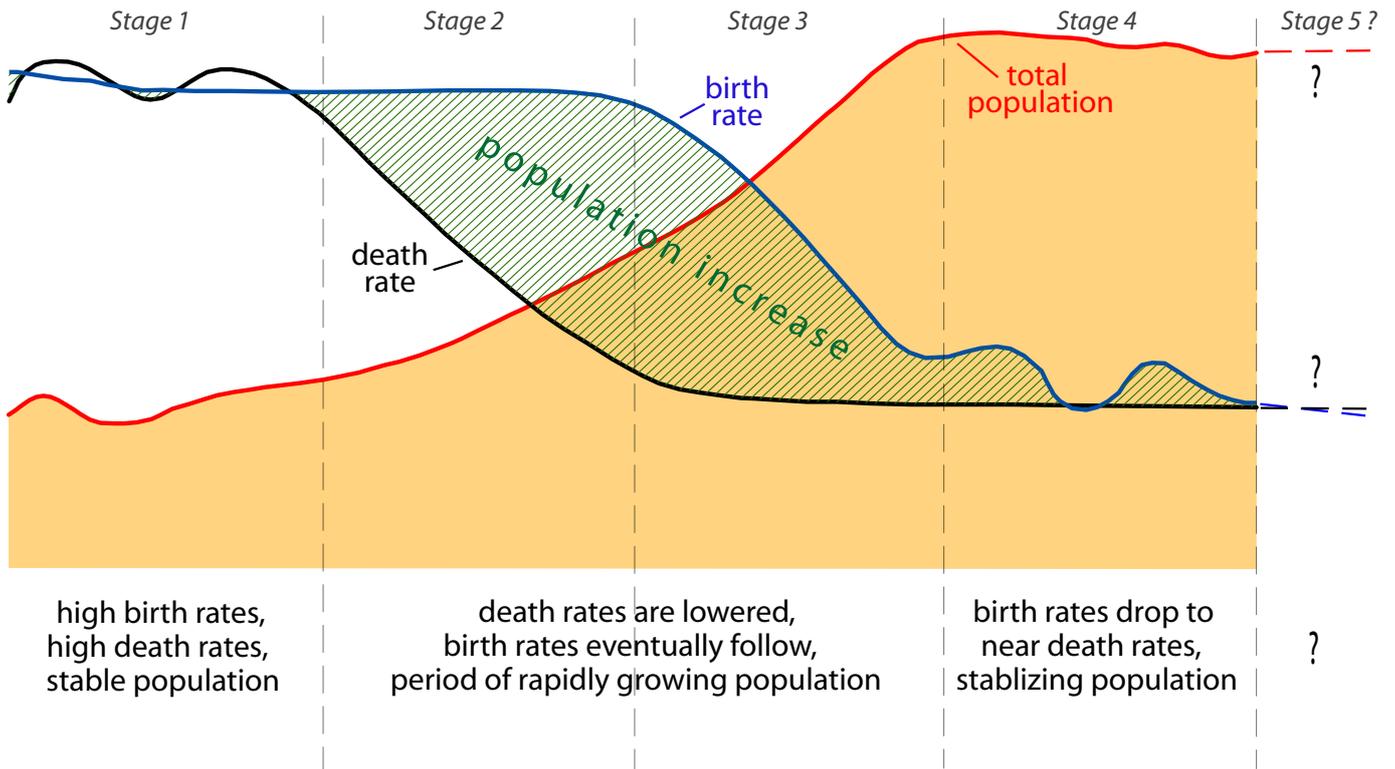


Figure 8: Demographic transition has occurred in parallel with (and presumably because of) social and economic development in the world's most developed countries. Most population projections assume it will occur in many currently developing nations. *Source: UNEP-GRID Sioux Falls – generalized from multiple sources.*

(40,41,42,43,44,45,47). In some countries, population growth itself is serious challenge to economic and social development, as an ever-increasing number of employment opportunities and services are needed to meet the needs of the population. A further problem

is that as the world's supply of cheap oil declines, increasing energy costs will hinder economic and social development, which are presumed to be important drivers of demographic transition (40,45,46,47). Researchers warn that large amounts of cheap energy are needed to

Oil Production, Global Per Capita GDP and Population Growth Rates

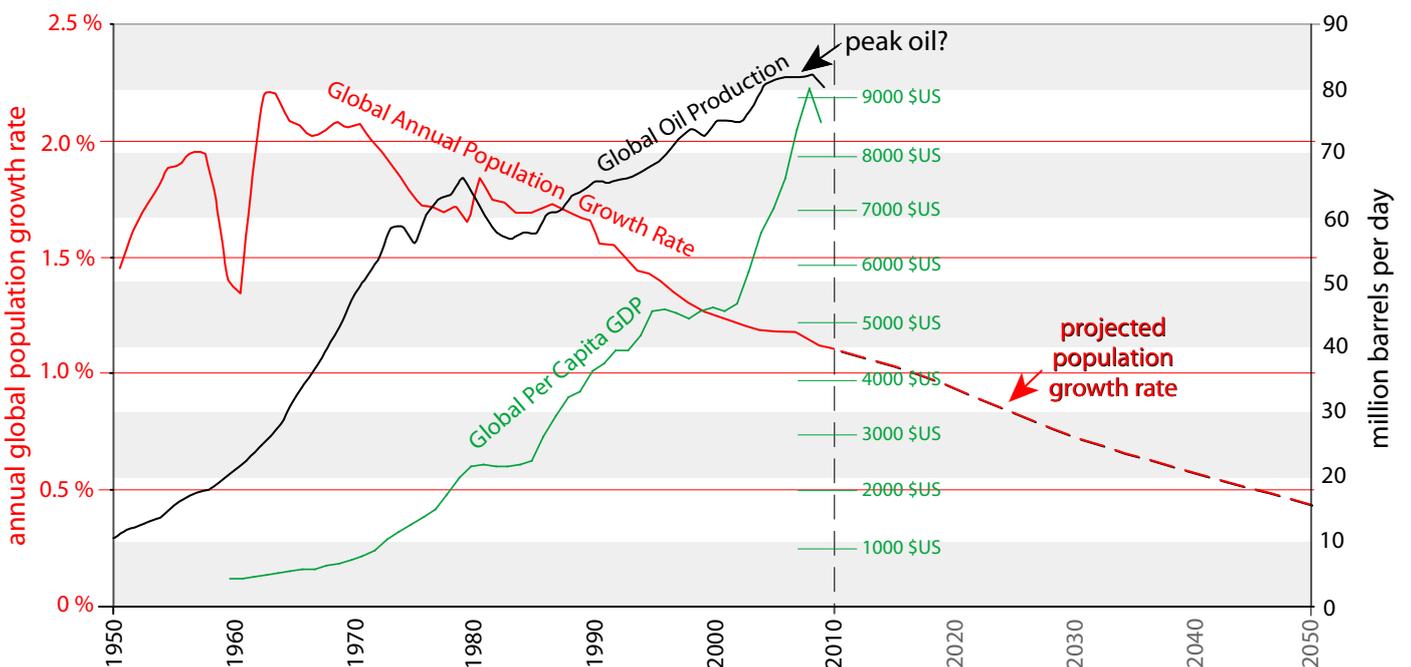


Figure 9: Global GDP has risen with global oil production. The global economic development reflected in per capita GDP is linked to lower birth rates and population growth by the demographic transition concept.

drive development (35,40,47,48). The historical reality of the relationship between per capita energy consumption and per capita GDP is illustrated in the graph above. As we reach (or have reached) “peak oil” (49), there is good reason to question the sustainability of the current trend of rising global per capita GDP, barring the emergence of a cheap and abundant alternative energy source (40,45).

All of this suggests that demographic transition may not be inevitable and that population growth and the question of carrying capacity may still be important concerns. Complacent reliance on demographic transition, however politically acceptable it might be, is highly problematic. The current population is believed by many to overshoot the Earth’s capacity to sustainably support it already (9,18). To bring developing countries up to consumption levels of developed countries—and thereby trigger demographic transition—would magnify per capita impact on top of an increasing number of consumers.

Prediction is Difficult, Especially About the Future

Certainty about what the future will bring is beyond the reach of dynamical systems modeling or economics. With the exception of fortune tellers, most people accept that predictions all fall along a continuum between guesses and educated guesses. Perhaps then the best that can be hoped for is to make well educated guesses and to understand that that is what they are.

History teaches us that predictions are uncertain and that they become increasingly so the further into the future they are made. Perhaps just as importantly, solutions extending forward to those predicted futures are uncertain as well. Committing to those uncertain solutions often requires trade offs and sacrifices between haves and have-nots, between current and future generations. As the highly respected ecologist Edward O. Wilson, pointed out, “The human brain evidently evolved to commit itself emotionally only to a small piece of geography, a limited band of kinsmen, and two or three generations into the future . . . We are innately inclined to ignore any distant possibility not yet requiring examination” (50).

A strategy to overcome paralysis that can prevent addressing long-term problems has been suggested by the analysis of an economist, a physicist, and a computer scientist at the Rand Corporation (25). Referring to work by Herbert A Simon, Popper suggests that rather than choose the solution which would be optimal under the scenario which we consider to be most likely, most human beings tend to choose solutions which will be sub-optimal but acceptable under several conceivable scenarios.

Popper and colleagues suggest applying this insight as we try to arrive at practical solutions to environmental problems (25). Each side in this argument has committed to a paradigm which at least in broad terms predicts a distant future. Concomitant with that paradigm is an implied range of solutions which are optimal for the respective paradigm’s accepted scenarios of the future, but which take no account of the outcome under the countervailing scenario. Ironically the more detailed (and thus actionable) these predictions are the more likely that they will be wrong. The uncertainty of each paradigm’s projected future and the political difficulty of committing to either “all-in” solution paralyzes policy makers and as a consequence “the world’s long-term threats often get ignored altogether or are even made worse by shortsighted decisions” (25). Popper and his colleagues suggest a strategy which they say better suits real-world uncertainty. They suggest a robust decision making strategy which seeks the solution that will stand up under most imaginable scenarios, even if it is not the ideal solution under any single scenario. In their own words:

Traditional predict-then-act methods treat the computer as a glorified calculator. Analysts select the model and specify the assumptions; the computer then calculates the optimal strategy implied by these inputs.

In contrast, for robust decision making the computer is integral to the reasoning process. It stress-tests candidate strategies, searching for plausible scenarios that could defeat them. No strategy is completely immune to uncertainty, but the computer helps decision makers exploit whatever information they do have to make choices that can endure a wide range of trends and surprises.

Experience tells us there is a good chance that most predictions about the future will be wrong. However, choosing policy that is robust for all of the plausible scenarios we can imagine may offer our best chance of making decisions that can “meet the challenges presented by what actually comes to pass” (25).

Can We Work It Out?

In summary, it could be said that solutions from three different paradigms have been put forward to resolve the collision of population growth with resource limitations (11). Mathematician and author Joel Cohen characterized them as follows:

1) “a bigger pie”

This is the technological solutions approach, which finds alternative sources of energy and materials and greater



Figure 10: How do we share the “pie”?

efficiencies to provide for a larger number people on Earth.

2) “fewer forks”

This approach is based on the demographic transition, the slowing or stopping of population growth to have fewer people dividing the metaphorical pie.

3) “better manners”

This approach is to rationalize and improve the connection between the decisions and actions taken by people and the consequences of those actions, so we remain within key planetary boundaries. This approach includes such things as defining property rights to open-access resources, elimination of economic irrationalities, improving governance and perhaps even imposing some of the “externalized” costs of having children on the people making the decision to have more children, to create a downward bias on the decision (11).

Cohen suggests that none of the solutions are adequate in themselves and that likely all of them must be a part of any sort of sustainable future. To arrive at pragmatic “robust decision” strategies, we should test solutions against the range of scenarios and find ones that would be well suited to several possible futures. For example, among the many factors which drive demographic transition, increased education, particularly for young girls, is a strategy that seems to be robust across all three paradigms of the resources/population issue. The “bigger pie” paradigm, which counts on innovation and technology, would presumably be agreeable to educating future innovators. The “fewer forks” paradigm, which seeks to limit population, would be on board because of the established association between increased levels of education and lowered birth rates. The “better manners” paradigm (or some portion of it) would likely be open to schooling for children in developing countries that would presumably be accomplished by and contribute to a more

equitable distribution of global resources while encouraging a lower birthrate. Pragmatic strategies such as Poppers’s robust decision making approach may allow us to make decisions that—while not ideal for any one future scenario—will yield an acceptable outcome regardless of which predictions about the future are closest to correct.

In fact, it may be the case that most approaches to slowing population growth are well suited to pragmatic compromises, acceptable among the three “pie sharing” paradigms. Cohen summarizes the six principal approaches to slowing population growth as: “promoting contraceptives, developing economies, saving children, empowering women, educating men, and doing everything at once” (13). These approaches would seem to offer many opportunities for action that could meet a variety of goals and be acceptable to a range of possible futures. As Oxford economist Robert Cassen says, “Virtually everything that needs doing from a population point of view needs doing anyway” (13). Perhaps in the end, reconciling the paradigms is not as important as accepting the limits of our ability to predict the future with certainty, and then making robust, pragmatic decisions that will hold up under a variety of futures. Adopting a more humble idea of our ability to predict the future, we can still work to build and maintain resilient natural and social systems well suited to whatever the future brings.

So, One Planet, How Many People?

The human footprint has grown to such a scale that it has become a major geophysical force. While there are many ways we might reduce our per capita footprint on the planet, the collective impact of those footprints will always be multiplied by global population. This makes population an issue which cannot be ignored. While there is an incredible range to the estimates of Earth’s carrying capacity, the greatest concentration of estimates falls between 8 and 16 billion people (3). Global population is fast approaching the low end of that range and is expected to get well into it at around 10 billion by the end of the century. Many of us alive today will be alive when the planet is carrying (or not carrying) nine billion people.

Speculation about global population and carrying capacity has existed since at least the 17th century. This century has seen the establishment of the UN Economic and Social Council Population Commission, established in 1946, and the creation of the World Population Plan of Action (51). Dennis Meadows and his

colleagues at Massachusetts Institute of Technology sparked discussion about the finite nature of the planet's resources (28). Critics accused the authors of "Malthusian reasoning," failing to allow for the social and economic feedback mechanisms that could overcome scarcity and environmental constraints (52,53). Polarized debates continued until the Brundtland Report, *Our Common Future*, argued that environment and development were linked (54).

So where do we go from here? Scientists and policy-makers are working together to develop reduction targets for pollutants to our air, water, and soil to keep our planet below critical tipping points. However, these international policies need to be combined with implementable solutions at regional, local, and individual scales (55). Continued monitoring of changes in biotic communities and reduction of per capita human impact are needed to avert current trajectories (56). "The plausibility of a planetary-scale 'tipping point' highlights the need to improve biological forecasting by detecting early warning signs of critical transitions on global as well as local scales, and by detecting feedbacks that promote such transitions" (56). Future projections from current trends might not account for threshold-induced state shifts due to human-induced forcings (56).

Today, in 2012, a variety of things are clear:

1) Population growth remains a major concern for future well-being. There are many who feel that if humankind cannot limit the number of people weighing on the Earth System on humanity's terms, then the Earth System itself will set that limit on its own terms (18,57,58). Raising the issue of population limits directly, however, is often met with criticism and concern that any policy directly aimed at reducing population may be coercive and unfair (59,60,61). Not only are there significant political barriers to addressing human population control directly, but according to some it may even be counterproductive (59). However, even among those who argue that a direct approach to population does not belong in the environmental policy discussion (59,62), there is general acknowledgment that, "stabilizing the global population is, and will remain, necessary" (62).

2) Material consumption is a major concern. Humans are consuming resources and producing waste at a greater scale than ever before and per capita consumption levels are projected to increase with continued development. As reported by the Royal Society (2012)(63), "Population and consumption are both important: what matters is the combination of increasing population and increasing per capita consumption." They also recommend "developing socio-economic systems and institutions that are not dependent on continued material consumption growth" (63).

3) Demography is not destiny. While the UN medium variant projection is 9.3 billion people by mid century, high and low variant projections, based on plausible scenarios, are 10.6 billion and 8.1 billion. Future trends depend on today's policies.

4) We must all play a role in finding human-centered, rights-based policies: These policies must "respectfully the principles agreed upon at the 1992 United Nations Conference on Environment and Development (UNCED) and, particularly, the principle of common but differentiated responsibilities."

5) This requires a three-pronged approach: Developed countries have to take the lead in changing their production and consumption patterns. Developing countries should maintain their development goals but do so while adopting sustainable practices and slowing population growth. Developed countries should commit to enable and support the developing countries' sustainable development through finance, technology transfer and appropriate reforms to the global economic and financial structures.

6) We cannot simply rely on technological innovation (the "bigger pie") and demographic transition ("fewer forks") to eliminate or solve the population problem: However, technological innovation and the demographic transition, when supported by the dissemination of green technologies and the creation of green economies, can help achieve a sustainable future. Active development strategies must be put in place to drive the transformation towards new dynamic green activities.

7) We have existing methods that have proven to be effective sustainable development tools: These include providing access to sexual and reproductive healthcare and contraception; investment in education beyond the primary level for all genders; empowering women to participate in economic, social and political life; and reducing infant mortality. These measures enable families to better decide on the number, timing and spacing of children. Demographic change is the result of individual choices and opportunities, and best addressed by enlarging, not restricting, these choices and opportunities.

8) We also have new tools and better models that can be used to help us develop policies: However, in order to become effective and implementable solutions, these models need to be further refined and elaborated. Additional research is needed.

Box 1

1 000 Tonnes of Grass x 7 Billion People

Three hundred trout are needed to support one man for a year. The trout, in turn, must consume 90 000 frogs, that must consume 27 million grasshoppers that live off of 1 000 tons of grass.

— G. Tyler Miller, Jr., American Chemist (1971)(63)

Net Primary Production (NPP) is one way of measuring that grass. Scientifically speaking, NPP is the amount plant material produced on Earth—the net amount of solar energy converted to plant organic matter through photosynthesis. It is the primary fuel for Earth’s food web, and in terms of carbon can be measured via the photosynthesis process (i.e. CO₂ exchange between atmosphere and biosphere). The NPP has been called the “common currency” for climate change, ecological, and economic assessments. The rate at which humans consume NPP is a powerful aggregate measure of human impact on biosphere function.

Various studies have estimated that humans now appropriate between 24 and 32 per cent of global NPP for our own use (65,66,67,68). That means less NPP is available in the form of grass and other vegetation at the bottom of the food web, but it also changes the composition of the atmosphere, the level of biodiversity, and alters the provision of important ecosystem services (68).

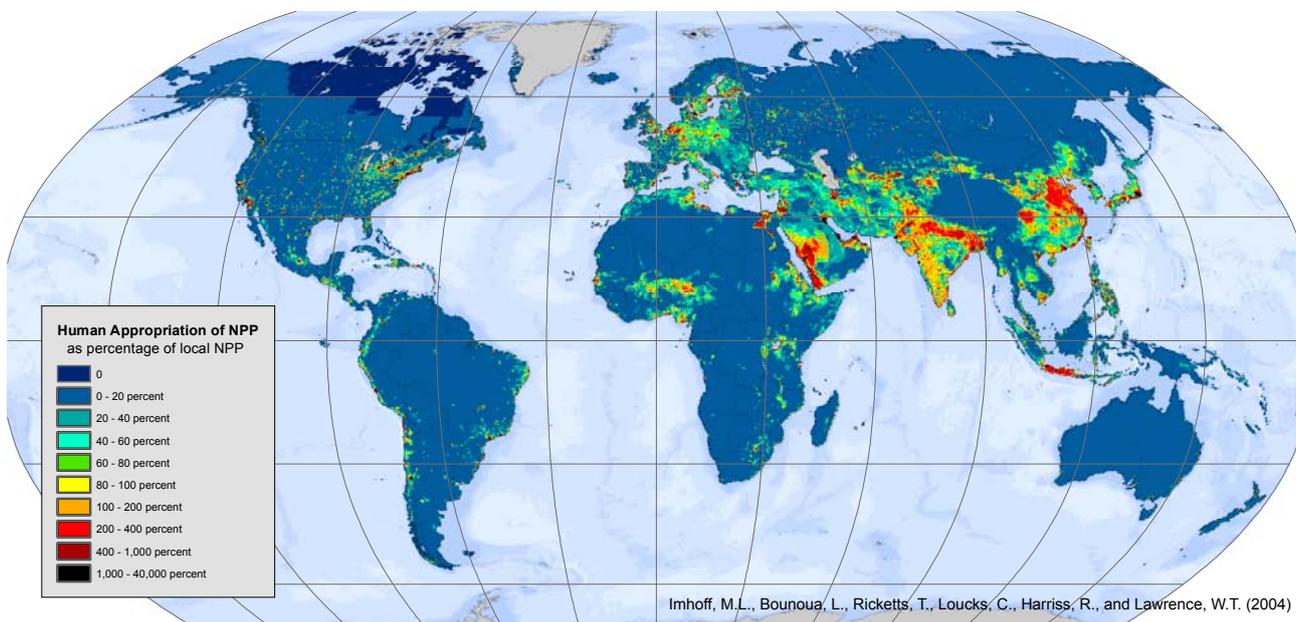
The term Anthropocene refers to the scale of human impact on all of the processes of the Earth System. Human Appropriation of Net Primary Production is a measure of human impact



jankie/Flickr

on the biosphere in particular. That humans now appropriate between roughly one-quarter to one-third of all NPP is further evidence of the size of the human footprint on Earth.

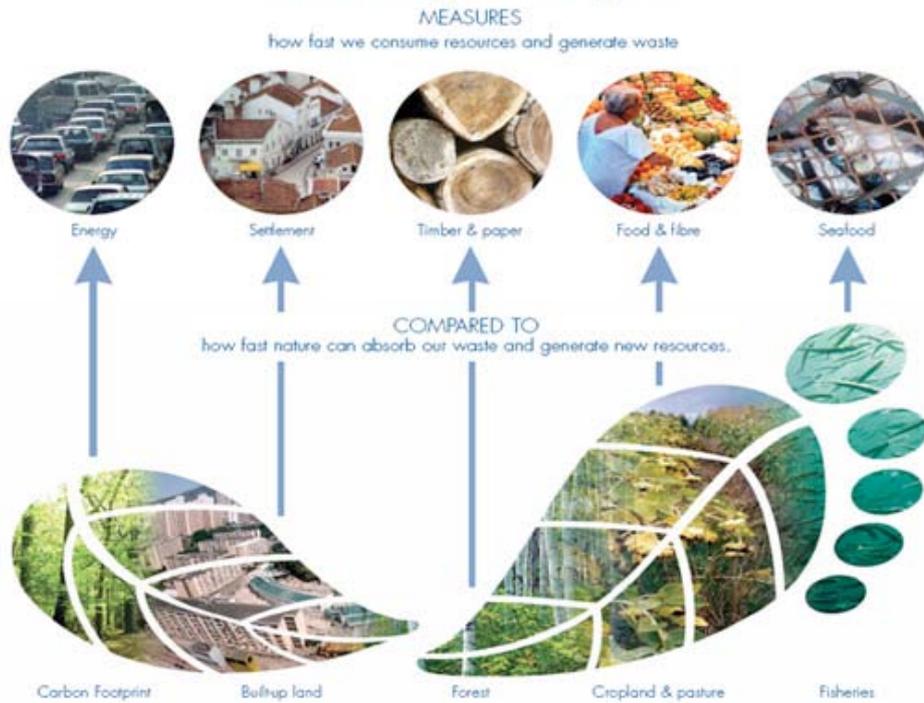
The map shows the percentage of NPP being appropriated as a percentage of local NPP. In other words it shows the local budget of NPP—available NPP minus NPP appropriated. Some areas with little NPP to appropriate (such as Saudi Arabia) and other areas with many people to do the appropriating (such as India) have areas of incredible deficits of 200 to 400 per cent of the local NPP. Presumably, areas of ongoing deficit will increasingly rely on effectively importing NPP in the form of food, fiber and materials from areas which are not in deficit. While the ultimate ceiling of total global NPP has not been reached, the impact of localized deficits are transmitted to the rest of the globe by these economic connections. In addition, the reduced resiliency in areas of deficit (for example a reduced ability to withstand a season of drought) reduce global resiliency.



Imhoff, M.L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., and Lawrence, W.T. (2004)

Box 2

The Ecological Footprint

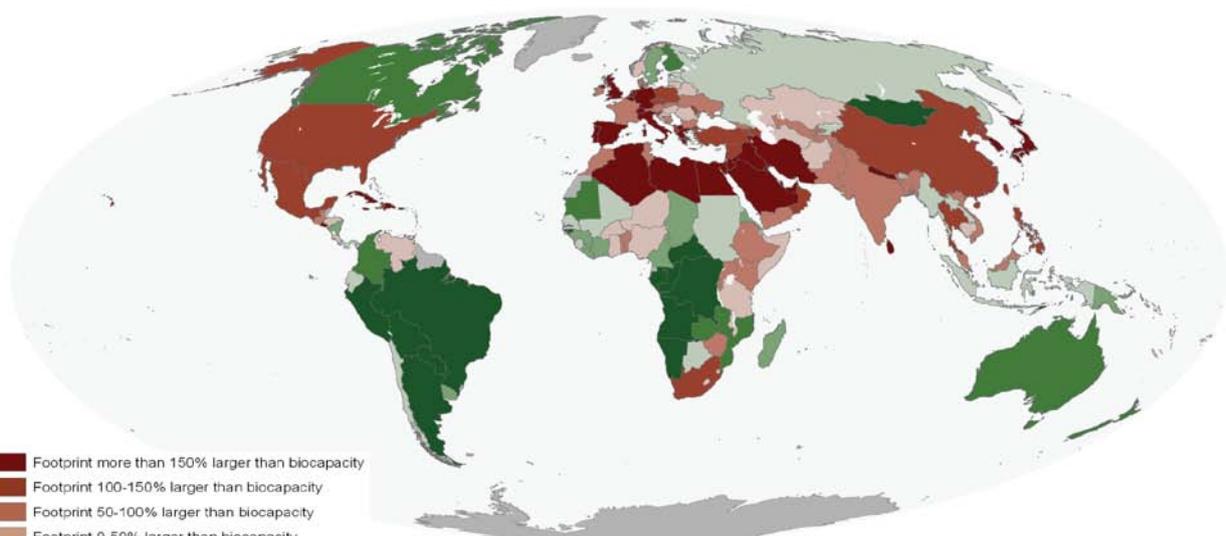


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Ecological Footprint

Conceived in 1990 by Mathis Wackernagel and William Rees at the University of British Columbia, the Ecological Footprint is a widely used measure of the demands being made on nature by human activities. It measures how much land and water area a human population requires to produce the

resources it consumes and to absorb its carbon dioxide emissions, based on current technology. This central idea of “footprint science” is in some respects similar to carrying capacity. However, carrying capacity estimates require assumptions about future per-person resource consumption, standards of living and “wants” (as distinct from “needs”), productivity of the biosphere, and advances in technology. An



- Footprint more than 150% larger than biocapacity
- Footprint 100-150% larger than biocapacity
- Footprint 50-100% larger than biocapacity
- Footprint 0-50% larger than biocapacity
- Biocapacity 0-50% larger than Footprint
- Biocapacity 50-100% larger than Footprint
- Biocapacity 100-150% larger than Footprint
- Biocapacity more than 150% larger than Footprint
- Insufficient data

The ecological creditor and debtor map for 2007 compares the Ecological Footprint of consumption with domestic biocapacity.

Source: Ewing and others 2010

area's carrying capacity for humans is thus inherently speculative and difficult to define.

Ecological Footprint accounting approaches the carrying capacity question from a different angle. Ecological Footprints are not speculative estimates about a potential state, but rather are an accounting of the past. Instead of asking how many people could be supported on the planet, the Ecological Footprint asks the question in reverse and considers only present and past years. The Footprint asks how many planets were necessary to support all of the people that lived on the planet in a given year, under that year's standard of living, biological production and technology. This is a scientific research and accounting question that footprint science approaches through the analysis of documented, historical data sets. Also the challenge lies in the Ecological Footprint's reliance on ecosystem functions, which, aside from varying spatially, are in a state of continual change with respect to their capacities due to variations in (and interactions with) land use, weather and climate.

A key concept of footprint science is ecological overshoot. This occurs when humanity turns resources into waste faster than waste can be turned back into resources. Overshoot may not be immediately apparent because we are able to utilize resources accumulated over time (or imported from elsewhere in the case of local ecological footprints). For example, fossil fuels which took hundreds of millions of years to form are being utilized at rates far beyond the Earth System's capacity to replace them.

According to Wackernagel and colleagues, humanity uses the equivalent of 1.5 planets to provide the resources we use and absorb our waste. This means it now takes the Earth one year and six months to regenerate what we use in a year. This rate of overshoot is an average for the whole globe and hides the fact that some countries are in serious overshoot while some others still have surplus biocapacity.

Adapted from Footprint Network <http://www.footprintnetwork.org/en/index.php/GFN/> Accessed: 8 June 2012.



Acknowledgment:

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References:

1. Adlaitoday (no date) Adlai Today – Adlai Quotes Accessed April 9, 2012 at: http://www.adlaitoday.org/ideas/quotes_connect.html
2. US Census Bureau (2011) U.S. Census Bureau, International Data Base Accessed April 19, 2011 at: <http://www.census.gov/ipc/www/idb/worldpopinfo.php>
3. Cohen, J. E. (2003). Human population: the next half century. [Research Support, U.S. Gov't, Non-P.H.S.]. *Science*, 302(5648), 1172-1175. doi: 10.1126/science.1088665
4. Crutzen, P.J. (2002) Geology of mankind. *Nature* 415:23.
5. Steffen, W., Persson, Å., Deutsch, L., Zalasiewicz, J., Williams, M., Richardson, K., . . . Svedin, U. (2011). The Anthropocene: From Global Change to Planetary Stewardship. *Ambio*, 40(7), 739-761. doi: 10.1007/s13280-011-0185-x
6. UNPD (2010) World Population Prospects, 2010 Revision. United Nations Population Divisions. Accessed May 10, 2011 at: http://esa.un.org/unpd/wpp/unpp/panel_population.htm
7. World Bank (2011) World Development Indicators & Global Development Finance. Accessed April 20, 2011 at: <http://data.worldbank.org/data-catalog/worlddevelopment-indicators>
8. UNPD (2011) United Nations, Department of Economic and Social Affairs, Population Division (2011). World Population Prospects: The 2010 Revision, CD-ROM Edition. Accessed April 9, 2012 at: <http://esa.un.org/unpd/wpp/Excel-Data/mortality.htm>
9. Ewing, B., Reed, A., Galli, A., Kitzes, J. and Wackernagel, M. (2010) Calculation Methodology for the National Footprint Accounts, 2010 Edition. Oakland: Global Footprint Network.
10. UNEP (2011) Decoupling natural resource use and environmental impacts from economic growth, A Report of the Working Group on Decoupling to the International Resource Panel. Fischer-Kowalski, M., Swilling, M., von Weizsäcker, E.U., Ren, Y., Moriguchi, Y., Crane, W., Krausmann, F., Eisenmenger, N., Giljum, S., Hennicke, P., Romero Lankao, P., Siriban Manalang, A.
11. Cohen, J. E. (1995a). Population growth and earth's human carrying capacity. *Science*, 269(5222), 341-346. doi: 10.1126/science.7618100
12. Van Den Bergh, J. C. J. M., & Rietveld, P. (2004). Reconsidering the Limits to World Population: Meta-analysis and Meta-prediction. *BioScience*, 54(3), 195-204. doi: 10.1641/0006-3568(2004)054[0195:rtltw p]2.0.co;2
13. Cohen, J. E. (1995b) How Many People Can the Earth Support? : W.W. Norton.
14. Bardi, U. (2011) The Limits to Growth Revisited. Springer, New York. DOI 10.1007/978-1-4419-9416-5
15. Schoijet, M. (1999). Limits To Growth And The Rise Of Catastrophism. *Environmental History*, 4(4), 515-530.
16. Hall, C. A. S. and Klitgaard, K. A. (2012). Are There Limits to Growth? Examining the Evidence Energy and the Wealth of Nations (pp. 207-220): Springer New York.
17. Simmons, M. R. (2000). Revisiting The Limits to Growth Could The Club of Rome Have Been Correct, After All? An Energy White Paper. Retrieved from http://greatchange.org/ov-simmons.club_of_rome_revisted.html
18. Brown, L. R. (2005). Outgrowing the Earth: the food security challenge in an age of falling water tables and rising temperatures: Earthscan.
19. Turner, G. M. (2008). A comparison of The Limits to Growth with 30 years of reality. *Global Environmental Change*, 18(3), 397-411. doi: 10.1016/j.gloenvcha.2008.05.001
20. IPCC (2007) The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M.M.B Tignor, H.L. Miller Jr, and Z. Chen. 996 pp. Cambridge, UK: Cambridge University Press.
21. MEA (2005) Ecosystems and Human Well-being: General Synthesis. Accessed April 9, 2012 at: <http://maweb.org/en/index.aspx>
22. Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., . . . Foley, J. A. (2009b). A safe operating space for humanity. [10.1038/461472a]. *Nature*, 461(7263), 472-475.
23. Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, III, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley (2009a) Planetary boundaries:exploring the safe operating space for humanity. *Ecology and Society* 14(2): 32. [online] URL: <http://www.ecologyandsociety.org/vol14/iss2/art32/>
24. Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T., and Rockstrom, J. (2010). Resilience Thinking: Integrating Resilience, Adaptability and Transformability. *Ecology and Society*, 15(4), 20.
25. Popper, S.W., Lempert, R.J. and Bankes, S.C. (2005) Shaping the Future. *Scientific American* 292(4), 66-71.
26. NOAA (2012) Carbon dioxide levels reach milestone at Arctic sites: NOAA cooperative measurements in remote, northern sites hit greenhouse gas milestone in April. Accessed June 12, 2012 at: <http://researchmatters.noaa.gov/news/Pages/arcticCO2.aspx>
27. NOAA (2011) NOAA/ESRL calculation of global means, NOAA, Earth System Research Laboratory, Global Monitoring Division. Accessed April 9, 2012 at: http://www.esrl.noaa.gov/gmd/ccgg/about/global_means.html
28. Meadows, D., Meadows, D., Randers, J. and Behrens, W. (1972). "The Limits to Growth". New York: Potomac
29. Kriebel, D., Tickner, J.A., Epstein, P., Lemons, J., Levins, R., Loechler, E.L., Quinn, M., Rudel, R., Schettler, T. and Stoto, M. (2001) The Precautionary Principle in Environmental Science. *Environmental Health Perspectives* 109:871-876.
30. German Advisory Council on Global Change (WBGU) (1995) Scenario for the Derivation of Global CO2 Reduction Targets and Implementation Strategies, Bremerhaven.
31. Stern, D. I. (2011). The Role of Energy in Economic Growth. *Annals of the New York Academy of Sciences* 1219, 26-51 (working paper version).
32. Solow, R. M. (1973). Is the End of the World at Hand? *Challenge*, 16(1), 39-50.
33. Daily, G. C., & Ehrlich, P. R. (1992). Population, Sustainability, and Earth's Carrying Capacity. *BioScience*, 42(10), 761-771.
34. Reijnders, L. (1998). The Factor X Debate: Setting Targets for Eco-Efficiency. *Journal of Industrial Ecology*, 2(1), 13-22. doi: 10.1162/jiec.1998.2.1.13

35. Hall, C., Lindenberger, D., KÜMmel, R., Kroeger, T., & Eichhorn, W. (2001). The Need to Reintegrate the Natural Sciences with Economics. *BioScience*, 51(8), 663-673. doi: 10.1641/0006-3568(2001)051[0663:tntr]2.0.co;2
36. Aghion, P., Acemoglu, D., Bursztyn, L. and Hemous D. (2011) The Environment and Directed Technical Change. GRASP Working Paper 21. Accessed April 30, 2012 at: <http://www.economics.harvard.edu/faculty/aghion/files/Environment%20and%20Directed.pdf>
37. Ocampo, J.A. (2012) The Transition to a Green Economy: Benefits, Challenges and Risks from a Sustainable Development Perspective. Summary of Background Papers. UN-DESA, UNEP, UN Conference on Trade and Development.
38. Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C. S., Jansson, B.O., Levin, S., Mäler, K. G., Perrings, C., and Pimentel, D. (1995). Economic growth, carrying capacity, and the environment. *Science* 268(5210), 520-521.
39. Bongaarts, J. (2009). Human population growth and the demographic transition. [Historical Article]. *Philos Trans R Soc Lond B Biol Sci*, 364(1532), 2985-2990. doi: 10.1098/rstb.2009.0137
40. DeLong, J. P., Burger, O., & Hamilton, M. J. (2010). Current demographics suggest future energy supplies will be inadequate to slow human population growth. [Research Support, U.S. Gov't, Non-P.H.S.]. *PLoS One*, 5(10). doi: 10.1371/journal.pone.0013206
41. Myrskylä, M., Kohler, H. P., & Billari, F. C. (2009). Advances in development reverse fertility declines. [Historical Article Research Support, Non-U.S. Gov't]. *Nature*, 460(7256), 741-743. doi: 10.1038/nature08230
42. Tuljapurkar, S. (2009) Demography: Babies make a comeback. *Nature* 460, 693-694.
43. Luci, A. and Thévenon, O. (2010) Does economic development drive the fertility rebound in OECD countries? INED working paper 167. Accessed April 19, 2011 at: http://www.ined.fr/fichier/t_publication/1514/publi_pdf1_dt_167.pdf
44. Valentine, S. V. (2010). Disarming the population bomb. *International Journal of Sustainable Development & World Ecology*, 17(2), 120-132. doi: 10.1080/13504500903478769
45. Murphy, D. J. and Hall, C. A. S. (2011). Energy return on investment, peak oil, and the end of economic growth. *Annals of the New York Academy of Sciences*, 1219(1), 52-72. doi: 10.1111/j.1749-6632.2010.05940.x
46. Hall, C. A. S. and Day, J. W. (2009). Revisiting the Limits to Growth After Peak Oil. *American Scientist*, 97(3).
47. Brown, J. H., Burnside, W. R., Davidson, A. D., DeLong, J. P., Dunn, W. C., Hamilton, M. J., . . . Zuo, W. (2011). Energetic Limits to Economic Growth. *BioScience*, 61(1), 19-26. doi: 10.1525/bio.2011.61.1.7
48. Nel, W. P., & van Zyl, G. (2010). Defining limits: Energy constrained economic growth. *Applied Energy*, 87(1), 168-177. doi: 10.1016/j.apenergy.2009.06.003
49. Campbell, C. Laherrère, J. (1998). The End of Cheap Oil. *Scientific American*, 3, 78-83.
50. Wilson, E.O. (2002) *The Future of Life*. Alfred A. Knopf 2002
51. WPPA (1974). World Population Plan of Action (WPPA). First World Population Conference: Bucharest, 19 – 30 August 1974.
52. Beckerman W. (1972). Economists, scientists and environmental catastrophe. *Oxford Economic Papers*, 24, 327 – 344.
53. Simon J and Kahn H eds. (1984). *The resourceful Earth: a response to the global 2000 report*. Basil Blackwell: New York.
54. World Commission on Environment and Development (1987) *Our Common Future*. Oxford University Press
55. DeFries, R., E. Ellis, F. S. Chapin III, P. Matson, B. L. Turner II, Arun Agrawal, P. Crutzen, C. Field, P. Gleick, P. Kareiva, E. Lambin, E. Ostrom, P. Sanchez, J. Syvitski, and D. Liverman. (2012, In press). Planetary Opportunities: A Social Contract for Global Change Science to Contribute to a Sustainable Future. *BioScience* 62(6), xxx-xxx. <http://www.jstor.org/stable/10.1525/bio.2012.62.issue-6>
56. D. Barnosky, A. D., Hadly, E. A., Bascompte, J., Berlow, E. L., Brown, J. H., Fortelius, M., Getz, W.M., Harte, J., Hastings, A., Marquet, P. A., Martinez, N. D., Mooers, A., Roopnarine, P., Vermeij, G., Williams, J. W., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., Mindell, D. P., Revilla, E., and A. B. Smith (2012) Approaching a state shift in Earth's biosphere. *Nature*, 486, 52–58. doi:10.1038/nature11018
57. Bartlett, A.A. (1997–98) 'Reflections on sustainability, population growth, and the environment – revisited', *Renewable Resources Journal* 15(4): 6–23.
58. Pimentel, D., Whitecraft, M., Scott, Z. R., Zhao, L., Satkiewicz, P., Scott, T. J., Moe, T. L. (2010). Will Limited Land, Water, and Energy Control Human Population Numbers in the Future? *Human Ecology*, 38(5), 599-611. doi: 10.1007/s10745-010-9346-y
59. Sen, A. (1994). *Population: Delusion and Reality*. New York Review of Books, 41(15).
60. Connelly, M. (2008) *Fatal Misconception: The Struggle to Control World Population*, Belknap Press of Harvard University Press, Cambridge, MA
61. Mosher, S.W. (2008) *Population Control: Real Costs, Illusory Benefits*. Transaction Publishers, New Brunswick, NJ.
62. Boersema, J. (2011). Does the population issue still have a valid place on the environmental agenda? *Journal of Integrative Environmental Sciences*, 8(1), 1-6. doi: 10.1080/1943815x.2011.561107
63. Royal Society (2012) *People and the planet*. The Royal Society Policy Centre Report 1/12. London.
64. Miller, G.T. (1971) quoted at *The Flow of Energy: Higher Trophic Levels*, University of Michigan "Globalchange" website: <http://www.globalchange.umich.edu/globalchange1/current/lectures/klings/energyflow/highertrophic/trophic2.html>
65. Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzer, C., Gingrich, S., Lucht, W., and M. Fischer-Kowalski. (2007). Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proc. Natl. Acad. Sci.*, 104(31), 12942-12947.
66. Rojstaczer, S., Sterling, S. M., & Moore, N. J. (2001). Human Appropriation of Photosynthesis Products. *Science*, 294(5551), 2549-2552. doi: 10.1126/science.1064375
67. Vitousek, P. M., Ehrlich, P. R., Ehrlich, A. H., & Matson, P. A. (1986). Human Appropriation of the Products of Photosynthesis. *BioScience*, 36(6), 368-373.
68. Imhoff, M. L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., & Lawrence, W. T. (2004). Global patterns in human consumption of net primary production. [10.1038/nature02619]. *Nature*, 429(6994), 870-873.

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