

Human population as a dynamic factor in environmental degradation

John Harte

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Abstract The environmental consequences of increasing human population size are dynamic and nonlinear, not passive and linear. The role of feedbacks, thresholds, and synergies in the interaction of population size and the environment are reviewed here, with examples drawn from climate change, acid deposition, land use, soil degradation, and other global and regional environmental issues. The widely-assumed notion that environmental degradation grows in proportion to population size, assuming fixed per capita consumption and fixed modes of production, is shown to be overly optimistic. In particular, feedbacks, thresholds, and synergies generally amplify risk, causing degradation to grow disproportionately faster than growth in population size.

Keywords Population · Feedback · Environment · Threshold · Synergy · Climate warming

Introduction

For the past several centuries, humanity has been increasingly polluting air and water, altering Earth's climate, eroding the soil, fragmenting and eliminating the habitat of plants and animals, and depleting the natural bank account of non-renewable resources. Of especially great long-term concern, we are as a consequence simultaneously degrading the capacity of natural ecosystems to regenerate or maintain renewable resources and ecosystem services, such as the provision of clean air and water, the control of flooding, the maintenance of a

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J. Harte (✉)
Energy and Resources Group and ESPM, University of California, Berkeley, CA 94720, USA
e-mail: jharte@berkeley.edu

tolerable climate, the conservation and regeneration of fertile soil, and the preservation of genetic and other forms of biological diversity (Daily, 1997; Harte, 1993; Harte, Torn, & Jensen, 1992; IPCC, 2001; L’Vovich & White, 1990; Myers, 1983; NRC/NAS, 1995; Postel, 1993; Postel, Daily, & Ehrlich, 1996; Rozanov, Targulian, & Orlov, 1990; Shiklomanov, 1993; Westman, 1977).

The linkages between human activity and environmental degradation are myriad but at the risk of some over-simplification one can usefully group the contributing factors in three categories: human population size, the per-capita rate of consumption of energy and materials that contribute to our affluence, and the impacts stemming from the technologies used to provide that per-capita rate of consumption. An “equation” is sometimes used to express this:

$$\begin{aligned} \text{Environmental Impact} = & (\text{Population size}) \times (\text{per -capita Affluence level}) \\ & \times (\text{impact from the Technologies used to achieve that} \\ & \text{level of per-capita affluence}) \end{aligned}$$

This “IPAT equation” (Ehrlich & Holdren, 1971) is a useful reminder that population, affluence, and technology all play a role in determining environmental impacts. But it is also misleading if taken too literally, for it conveys the notion that population is a linear multiplier. In particular, it suggests that if per-capita affluence is held constant, and the technologies and other means used to achieve that level of per-capita affluence are also held constant, then the impacts simply grow in proportion to population size....if the population doubles in size, then the impacts double in magnitude.

In this article, I examine the more dynamic and complex role that population size actually plays in shaping environmental quality. I argue that the notion that impacts are roughly proportional to our numbers is hugely optimistic. In particular, it ignores a host of threshold effects, synergies, feedbacks and other nonlinear phenomena that tend to amplify environmental impacts and cause them to grow considerably faster than linearly in population size, *even if the per-capita level of affluence and the types of technological systems deployed to achieve that affluence remain constant.*

I first pointed out the misleading nature of the linearity implied by the IPAT formulation ten years ago in the journal *Biodiversity and Conservation* (Harte, 1996). Since writing that article, I have become even more aware of and concerned about the many non-linear multipliers that magnify the consequences of a growing human population. This article reviews the basic mechanisms that induce non-linearity, expanding on the examples introduced in 1996 and providing a rationale for increasing concern about these issues.

Thresholds, synergies, feedbacks: an overview

Thresholds

There are many situations in which a small or intermediate-sized stress to a system generates little or no impact, but when the stress exceeds a certain level (the

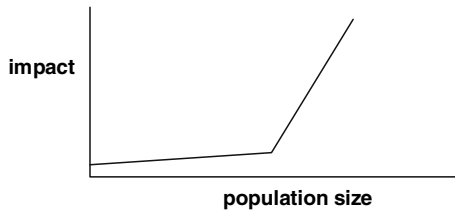


Fig. 1 A threshold relationship

threshold), then the impact increases dramatically. Then if the stress is simply proportional to population size, the impact will behave as shown in Fig. 1. A prominent example is the existence of threshold behavior in the response of surface waters to acid deposition. In particular, the shape of the familiar acid buffer curve describing pH as function of the amount of acid added to an initially alkaline solution implies a threshold level of added acid. Below that threshold, alkalinity prevents the lake water pH from falling significantly (that is, the lake water from acidifying significantly), but above a certain level of added acid, corresponding to the amount of alkalinity present originally in the water, the pH falls rapidly (Fig. 2).

Suppose we assume that the amount of acid rain falling to Earth each year is simply proportional to the amount of coal being burned, and that the amount of coal being burned is proportional to population size (because affluence and technology are held constant). Then an increase in population size from a level below the threshold to one above the level can generate a disproportionately large decrease in the pH of the lake.

But the situation is even more non-linear than indicated by Fig. 2. Of the major fossil fuels used today (coal, petroleum, and natural gas), coal is generally the one that produces the most acidity per unit of energy. Thus, people interested in reducing the threat of acid rain urge policy makers to replace coal with the cleanest of these fuels, natural gas. Similarly, natural gas produces considerably less climate-altering carbon dioxide than does coal for the same amount of produced energy. But

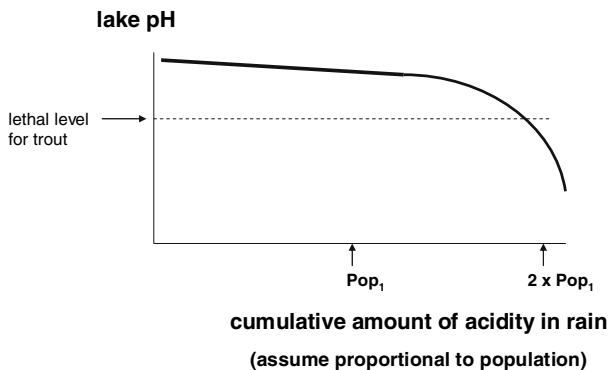


Fig. 2 The non-linear relationship between lake water pH and cumulative acid deposition

unfortunately, natural gas supplies are far more limited than are coal supplies. Hence, with every increase in the size of the human population, the day arrives sooner when more coal, per capita, has to be used. In the IPAT formulation, one would express this by stating that *T*, the technology, changed at the same time that *P* increased. But the point is that this change in *T* is *caused* by a change in *P*, and thus *T* should be considered as a function of *P*. And this means that *P* is not simply a linear multiplier.

Another example of a threshold effect concerns the response of coral reefs to global warming. The health of a coral reef is relatively insensitive to water temperature provided temperatures remain below about 80°F (or about 27°C). Reef productivity will exhibit temperature dependence, but the reef will remain viable within a temperature of 5°F or 10°F. But above 80°F a phenomenon called “coral bleaching” occurs. In this process, the algae that combine with small animals to create the symbiosis that comprises a living reef die, exhibiting what is called “coral bleaching” (Harte, 1993). Because many reefs occur in waters with temperatures just a little below the critical value of 80°F, as global warming raises sea water temperatures around the world a time will come when coral reefs will rather suddenly bleach and die.

For yet another example, we turn to the effect of habitat loss on the survival of species. In places such as Amazonia, where roughly a quarter of the rain forest has been destroyed, numerous species are driven to extinction because they depended on intact habitat. Although we lack the knowledge needed to predict accurately how many species are lost when a specified area of original habitat is lost, general ecological principles do provide a way of characterizing the qualitative features of the relationship between habitat area and species diversity. That understanding is summarized in Fig. 3, which shows two alternative quantitative predictions that are consistent with general ecological principles (Kinzig & Harte, 2000; NRC/NAS, 1995). Both exhibit a “soft-threshold” behavior, in which the loss of species increases quite non-linearly as habitat loss increases. One of the curves in the figure (based on species-area relationship) derives from the fact that the number of species

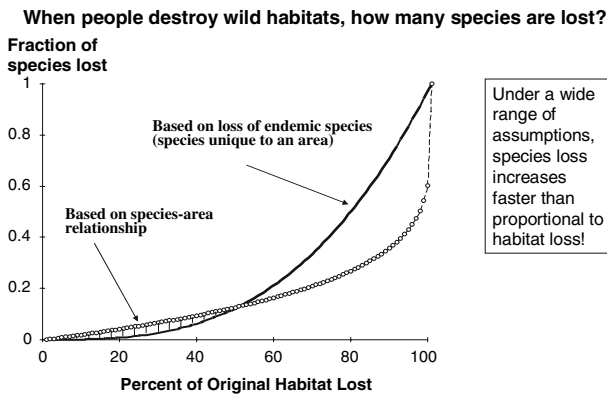


Fig. 3 The non-linear relationship between land degradation and species extinction

that can be sustained in a region of intact habitat is a function of the area of that intact habitat; the other (based on loss of endemic species) is derived from the fact that the species that will go extinct when habitat is destroyed is determined by the number of species that were endemic to (lived only in) the habitat area that was destroyed. The inability of current ecological theory to pin down a unique response function should not obscure the fact that virtually all ecological models predict that the fraction of extinct species will increase faster than linearly with habitat loss.

Thresholds abound in nature. For example, threshold-like non-linearities characterize the relationship between population density and the probability of an infectious disease becoming epidemic in a region (Murray, 1989); a similar non-linearity is likely to characterize the relation between the area of a monoculture crop and the probability that a plague-like crop-pest outbreak will occur there. In some instances, contingent and unpredictable factors blur the actual threshold level of a stress, rendering it difficult to predict the level of an activity that causes a sudden increase in impacts. For example, predicting the future time at which a lake will lose its alkalinity and suffer a rapid drop in pH under increased acid loading is extremely difficult because of uncertainties over rates and types of mineral weathering processes and the dependence of those rates on water chemistry. In global warming science, it is difficult to determine at what level of heating Greenland and West Antarctic ice will rapidly melt, resulting in a rapid and very dangerous rise in sea level. These difficulties point to a gap in predictive capability, however, and should not obscure the fact that actual points of rapid response exist.

In some instances, however, there is controversy regarding just the existence of thresholds. For example, in the toxicology of radiation, debate exists over whether there is a threshold level of radiation exposure, below which no harm (and possibly even some benefit) is conferred but above which health effects arise and increase with the dose (Harte, Holdren, Schneider, & Shirley, 1991).

Synergies

Synergy occurs when the combined effect of two causes is greater than the sum of the effects of the two causes acting in isolation of each other. Clearly, if two environmental stresses act synergistically, and each stress grows in proportion to population size, then the combined effect of both stresses may grow faster than linearly with increasing population size.

Synergies can either be “good” for us or “bad” for us, depending on whether the effects are helpful or harmful. The combined benefit of eating a more healthy diet and getting more exercise may exceed the sum of the benefits of each alone. On the other hand, when anthropogenic stresses are acting on an ecosystem there can be a harmful synergy, in which the harms from each are reinforcing. One possible reason for this is that such stresses may not be ones to which ecosystems were subjected when the links within and between these systems were forged over evolutionary and geologic time scales. Under these unusual stresses, the links that form life-sustaining synergies under natural conditions turn against the health of the system as they amplify, rather than dampen, stress (Harte, 1993; Harte, Torn, & Jensen, 1992).

Consider the following example. Both climate warming and deforestation are predicted to stress biodiversity in currently forested areas of the world. The former is also projected to result in forest dieback because of increased frequency of drought conditions while the latter releases carbon dioxide, a greenhouse gas, to the atmosphere, thereby exacerbating climate warming. Thus the sum of the effects of each of these two stresses, climate warming and deforestation, generates additional stresses that reinforce the total response.

While greenhouse gases result in global warming at the Earth's surface and in the lower atmosphere, they result in a cooling of the stratosphere, thereby increasing ice-cloud formation there (IPCC, 2001). These ice clouds speed up stratospheric ozone depletion by freezing up nitrogen compounds that would otherwise inhibit the ozone-depleting reactions. Thus the greenhouse effect will worsen the problem of stratospheric ozone depletion. At the same time, stratospheric ozone depletion can lead to more intense smog because the additional ultraviolet radiation penetrating a thinned stratospheric ozone layer will speed up the chemical reactions that produce smog. Greenhouse gas warming at Earth's surface also makes the urban ozone pollution problem worse by speeding up the chemical reactions that lead to smog formation. Deforestation can contribute to the problem of acid rain, as has been observed in Africa where nitric acid is formed from burning vegetation.

To make matters worse, plants and animals weakened by any one of these threats will generally be more vulnerable to the others. There are numerous examples of this. Fish weakened by radiation have been shown to be more easily damaged by thermal pollution than are healthy fish, and trees subjected to some air pollutants become more susceptible to insect damage.

Figure 4 illustrates the dominant interactions between pairs of selected environmental stresses. Here a plus sign indicates a synergistic effect that exacerbates the activity toward which the arrow points and a minus sign indicates a canceling effect, in which one activity reduces the threat from another. As an example of the complexity of the interactions, consider the case of fish and

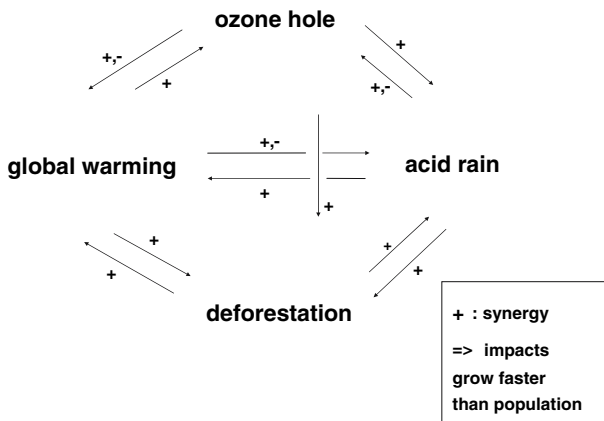


Fig. 4 Synergies among environmental stresses

amphibians threatened by lake acidification. Damage from acidification is often observed in spring time when a pulse of acid is released from snowmelt right at the time when aquatic life is at its most vulnerable: when eggs are developing. Under global warming, less snowfall and more rain is anticipated in many regions where snow is currently a major component of precipitation, and with reduced snowpack and earlier snowmelt, the acid pulse may weaken in strength, to the benefit of aquatic life. On the other hand, global warming may result in either a drying up of lakes, or if not a total drying up, at least decreased lake-water oxygen levels, either of which can result in the death of aquatic animals.

In the previous subsection “Thresholds” showed that if habitat loss is linearly proportional to the size of the human population, the loss of species would likely increase faster than linearly with population growth because of an intrinsic nonlinearity in the relationship between habitat loss and species loss. But the situation is even worse than this because habitat loss is likely to increase faster than linearly with population size. To see this, consider Fig. 5, which illustrates how a doubling of population can lead to a greater-than-doubling loss of habitat. Imagine that initially a nation has three cities indicated by the three dots in the left panel. Between each of the cities are highways and transmission line rights-of-way, which are barriers to wildlife movement, death traps for some species, and opportunities for invasive species (that may displace native species) to spread. The right-hand panel shows the situation when the population has doubled and there become six cities. Now there are 12 connecting lines, implying a fourfold increase in these harmful stresses on plants and animals. While Fig. 5 is only a schematic and not to be taken too literally, it does indicate how the web of infrastructural interconnections in human society, which becomes increasingly dense as population grows, can result in synergistic land use effects that are damaging to biodiversity.

Feedback

When the global climate system, an ecosystem, an organism, or any other complex entity is disturbed by some perturbation, the effect on the entity (expressed, for example, as a temperature change, an alteration of species diversity, or a change in lifespan) is the sum of two terms. The first is the direct response. In the case of climate change from the buildup of greenhouse gases in the atmosphere, the direct response is the change in surface temperature due to the extra heat-absorbing capacity of these gases. As the general circulation models (GCMs) consistently show, this direct effect is roughly 1°C for a doubling of atmospheric carbon dioxide (IPCC, 2001).



Fig. 5 Non-linear habitat implications of population growth

But this direct warming can also trigger secondary or indirect effects (Lashof, DeAngelo, Saleska, & Harte, 1997). In the case of climate change, the area of Earth that is covered by ice or snow decreases under warming. This induces a feedback to the warming because ice and snow reflect more sunlight back to space than does the surface exposed when the ice or snow melts, and hence melting results in an additional warming due to the greater amount of sunlight absorbed at Earth's surface. This is called a positive feedback effect because it causes an even greater warming than would have occurred in the absence of the process. Had warming led to a shinier Earth surface, and thus caused some cooling, the feedback would be negative.

The mathematical description of feedback is understood: if the direct effect of warming is denoted by ΔT_0 , then the full effect with all the feedbacks is given by $\Delta T = \Delta T_0 / (1 - g)$. The quantity g is called the feedback factor and a mathematical procedure (Harte, 1988; Torn & Harte, 2006) exists for calculating its numerical value provided the mechanisms that induce feedback are sufficiently understood. If g is positive but less than 1, then the feedback results in $\Delta T > \Delta T_0$, which corresponds to positive feedback. If g is negative, $\Delta T < \Delta T_0$ and the feedback is negative. If $g > 1$ the system is unstable and the analysis fails.

Torn and Harte (2006) explored the consequences of the fact that when g is near 1, say 0.8, then a relatively small increase in g can cause a proportionally large increase in the factor $1/(1 - g)$. For example, a 10% increase in g from 0.80 to 0.88 results in a 67% increase in $1/(1 - g)$, from 5 to 8.33. If the magnitude of g is linearly proportional to population size then it is easy to see that the full impact will grow faster than linearly in population size because the function $1/(1 - g)$ grows faster than linearly in g as g gets larger.

In environmental science, are there feedback processes in which the feedback factor, g , grows with the size of the human population? Some very important feedback processes have feedback factors that are essentially independent of population size. Consider, for example, the snow- and ice-melt effect discussed above. The direct temperature change that triggers the feedback will depend on population (because people emit greenhouse gases), but the feedback factor, g , depends only on the physical properties of ice and snow, and on the relative response of temperature to a unit change in surface reflectance; it will not depend on population size.

On the other hand, there are classes of feedback mechanisms for which g does grow with population size—mechanisms that directly involve human response to the direct effect. For example, in a warmer climate people may rely more on air-conditioning, thereby burning more fossil fuel, augmenting emissions of carbon dioxide, and causing a positive feedback. A decreased use of heating fuels during warmer winters associated with global warming would have the opposite effect and result in a negative feedback. More significant feedback effects involving population size and climate involve the interaction of climate-independent human activities and biophysical responses to warming. For example, carbon dioxide release from soils is likely to increase with soil temperature and population size. In particular, climate warming is likely to accelerate the decomposition of soil organic matter, particularly in tilled, fertilized, and irrigated soils (Schlesinger, 1991) and

this will lead to the release to the atmosphere of carbon dioxide. Because the total area of such lands depends on population size, the gain factor, g , associated with this positive feedback is dependent on population size.

Another example concerns wildfire, which will become more frequent and more intense under the drier conditions anticipated under global warming. The positive feedback arises because forest fires release significant quantities of carbon dioxide to the atmosphere, and thus contribute to further climate warming. The value of the feedback factor is population-dependent because even though fires are exacerbated by drought they are often inadvertently, or sometimes purposely, triggered by people.

Additional reasons why impacts grow disproportionately faster than population

In addition to thresholds, synergies, and feedbacks, there are an assortment of other reasons why it is overly optimistic to assume that impacts merely increase in proportion to the size of the human population. One has to do with the exhaustion of the natural processes that result in “sinks” for our pollutants. For example, each year the oceans and forests remove from the atmosphere a net quantity of carbon dioxide, thus alleviating somewhat the problem of global warming. Currently a quantity of carbon dioxide equal to about a third of what we emit each year is removed each year, with somewhat more than half of that going into the oceans and much of the remainder going into net growth of forests. But these natural sinks have only a limited capacity to take up carbon, and like kitchen sinks they can partially clog if too much is put down them. Thus the rate at which carbon dioxide can be removed from the atmosphere is a declining function of the amount that has already been removed, and so, in effect, is a declining function of population size at a fixed per capita affluence level and fixed technology.

The natural carbon sinks can be thought of as a non-renewable resource. As with natural gas, which is a cleaner alternative fuel to coal but one which we are rapidly exhausting, environmental problems increase when we use up the carbon sink. With both natural gas and the carbon sink, the faster our population grows, the quicker we use up these desirable resources and thus the greater the impacts on the environment. Similarly, when natural supplies of clean water, either in aquifers or in surface streams, are exhausted, then for substitutes we have to turn to new technologies to provide water, and many of these, such as dams and desalination, bring about environmental costs.

For another example of this, consider the effect of climate change on water supplies. As hotter temperatures and more frequent and intense drought increase water demand in agriculture, with both the magnitude of climate warming and the amount of agricultural land and water needed to grow food increasing with population size, we will be forced into more energy-intensive means of obtaining water and thus will accelerate the warming in order to sustain a fixed level of per-capita affluence. Hence we can think of the term T in IPAT, the impacts from the technologies needed to sustain a given per capita level of affluence, as inevitably a function of population, P . These two drivers cannot be disentangled and expressed as a product.

It is not just the magnitude of environmental impacts, I , that increase disproportionately with P when A and T are fixed. In addition, our efforts to solve social problems, such as environmental injustice arising from inequitable distribution of impacts and of resources across income, cultural, and racial groups, are hindered by rapidly growing population. Institutions cannot maintain a sufficiently fast enough growth to provide universal access to education and health care for a rapidly growing population. And again there is a pernicious feedback at work here: the existence of these social problems makes it more difficult to solve environmental problems. For example, in an equitable society with only small income disparities, a carbon tax to discourage fossil fuel consumption would make a great deal of sense. While it is a sales tax, its burden would not fall on a particular group (the poor, who spend a larger fraction of their income on fuel than do the rich), and thus it could replace an income tax without exacerbating inequality. Thus the population trap catches us twice. Growing population size exacerbates social problems and growing social problems exacerbate efforts to confront environmental problems.

As discussed previously (Harte, 1996) it cannot even be claimed that the IPAT equation is a units identity, the way we can write $J = WT$, where J is joules of energy consumed, W is watts of power consumed, and T is time over which the power is utilized. $J = WT$ is a valid equation because it simply expresses a conversion between units. It works because the first joule consumed is no different from the last joule consumed—all joules, all watts, and all time intervals are equivalent here and our time scale does not depend on how much energy we have used. Unlike the situation for fungible quantities such as joules, seconds, or watts, a unit of “impact per unit of economic activity” does not exist. A *marginal* increment in activity often leads to impacts that are different from the impacts from the *average* increment in activity.

Implications for confronting global warming

Insight into the policy options for dealing with global warming has been provided by Pacala and Socolow (2004), who have introduced the idea of policy wedges. They argue that no single technology is going to lead to a substantial reduction in the future level of carbon dioxide emissions, and so a collection of small contributions from many technologies will be needed. Figure 6a, modified from their paper, illustrates this idea and the reason for calling the contributions “wedges”. The wedges that are potentially available include improving the efficiency with which we use energy, switching from coal to natural gas, sequestering carbon underground, and relying more on solar photovoltaics, wind, nuclear and biomass. Although not included in the Socolow/Pacala conceptualization, reduction of human population size could be considered to be an additional wedge.

In Figure 6a I have slightly modified their original figure to include not just a future stabilization of emissions, but rather a stabilization of the climate. The point is that if emissions could be held in the future to 2000 emissions levels, global

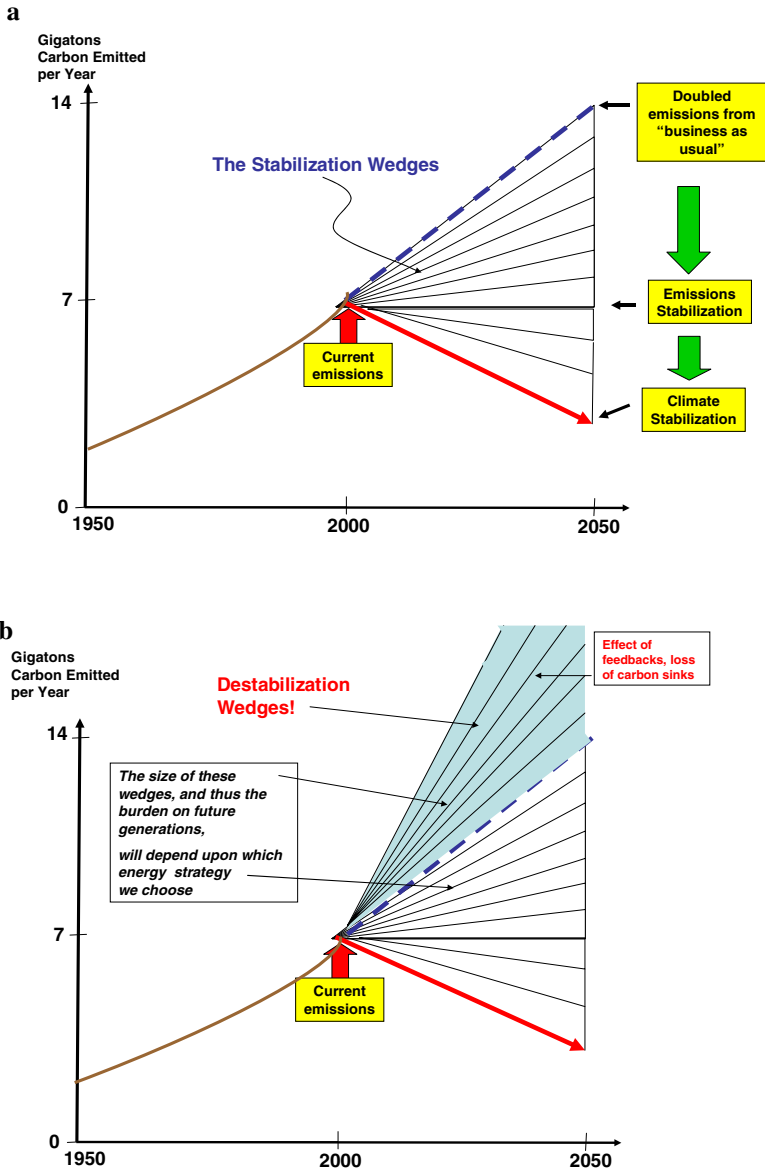


Fig. 6 Future carbon dioxide emissions: **a.**, The Socolow stabilization wedges for mitigating climate change; **b.** Adding destabilization wedges, exacerbated by population growth, makes the task of climate mitigation more difficult

warming will still intensify in the future because a steady level of emissions at the year 2000 rate will lead to a continuing buildup of carbon dioxide in the atmosphere. To eventually stabilize the human contribution to climate change, we actually have to reduce emissions down to a level at which the removal of carbon dioxide from the

atmosphere by natural sinks will result in a constant concentration of this greenhouse gas. The figure sketches a possible future trajectory of emissions that would be needed to eventually accomplish the goal of climate stabilization.

The concept of stabilization wedges, whether it be emissions or climate stabilization, is appealing because it delineates the challenge in a manner that provides an antidote to those who say “nuclear power is the answer” or to those who say “we can never build enough windmills to solve this problem”. But it is helpful to understand the full dimensions of a problem, and so in Figure 6b I have included in the Socolow wedge diagram a needed modification. It reminds us that there are also destabilization wedges...that is, Earth-system processes such as feedbacks and clogging of the carbon sinks that will operate in the future to actually increase the magnitude of global warming above the level currently projected. These destabilization wedges are additional increments of greenhouse gases that will be emitted to the atmosphere as a feedback response to climate warming, and their magnitude will be exacerbated by population growth. Additional sources of greenhouse gas imply that additional remedial wedges will be needed to bring about climate stabilization.

Conclusion

There are five underlying reasons why the effect of population size on environmental problems is much greater than is suggested by a simple linear multiplier equation such as IPAT....five general principles that in various combinations apply to virtually all instances of resource use and environmental degradation:

1. *Thresholds lurk throughout nature:* The “dose-response” relation between environmental stresses (such as acidity of precipitation, or area of drained wetlands, or amount of carbon dioxide loaded to the atmosphere) and the response of the natural environment to that stress (such as acidification of soil and lake water, or useful lifetime of an aquifer, or amount of warming induced by carbon dioxide) are often nonlinear, with threshold-like responses increasing faster than stress over a range of stresses relevant to current conditions. Thus, even if stresses are merely proportional to population, the responses increase faster than proportionally.
2. *The whole is often more than the sum of the parts:* Numerous synergies exist among different kinds of environmental responses; these synergies are such that the impacts from deforestation, acidification, ozone depletion, climate change, erosion, water impoundment, pesticide use, etc., tend to mutually reinforce each other, making the whole environmental impact from many stresses much more damaging than the sum of the component impacts.
3. *Scientific feedbacks amplify environmental degradation:* Positive feedback processes in which the gain factor is proportional to population size generate impacts that can increase considerably faster than linear population growth.
4. *Low-hanging fruit gets picked first:* Because we would like to use the most fertile soil, the cleanest water, the least polluting fuels now, the effect of future

drawdown of these desirable resources implies that over time our options will be increasingly limited to second-rate resources. While this tendency may be partially remedied by putative technological innovations (such as carbon sequestration), the effect of increasing population size on the rapidity with which we use up or degrade the most desirable resources implies yet another non-linear role of population growth in exacerbating our environmental problems.

5. *Rising numbers impede governance and problem-solving*: High rates of population growth make it more difficult to ensure adequate schooling, material resources, and civic order, thereby worsening social conditions. That, in turn, makes implementing solutions to environmental problems more difficult. Unsolved environmental problems further exacerbate injustice and inequity, again weakening the social order. The overall effect is an intensifying downward spiral.

The relation between population size and the sustainability of the human enterprise is complex, indeed. For a specified means of achieving a constant per-capita level of well-being, impacts can grow far faster than linearly in population size. The general structure of that relation is such that considerably greater concern over population growth is warranted than has generally been shown by public policy makers. The synergies, feedbacks, and thresholds discussed above force us to reassess the traditional viewpoint that impacts are simply a product of population size times some population-independent measure of the impacts of achieving a given per-capita level of well-being.

To conclude, humanity is degrading environmental goods and services such as clean water, air, soil, and biodiversity, and simultaneously reducing the capacity of natural processes to replenish these contributors to the quality of life. As abhorrent as is the current inequity in the distribution of resources between north and south, rich and poor, it pales in comparison with the impending inequity between us, living today, and those who will be born tomorrow and who, under current trends, will inherit a rapidly deteriorating planetary life support system. The future habitability of our planet will be shaped by highly nonlinear dynamical mechanisms that have the potential to generate unintended and undesirable consequences for future generations. As the stewards of our descendents, it is our moral obligation to better understand that landscape and seek pathways to the future that avoid such rapidly escalating damages. Implementation of family planning policies throughout the world that give people greater control over reproduction, in under-developed and over-developed nations alike, is a critical step toward that end.

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