ESSAY

Living by the lessons of the planet

How can human societies thrive within Earth's physical and biological limits?

By **Jonathan Foley**

Industrial farmland surrounds cerrado habitat near Emas National Park, Brazil.

PHOTO: FRANS LANTING/NATIONAL GEOGRAPHIC CREATIVE

For centuries, scientists, economists, and other scholars have been concerned about humanity's collective impact on the environment, and whether our species has started to overwhelm the biological and physical systems of our planet. As our population, technology, and economic power have rapidly grown in recent decades, so has our impact on the planet. And now, in the early 21st century, it is clear that we have started to strain entire planetary-scale systems in the environment, including biodiversity, land resources, fresh water, and even our climate system. How can science help us understand, and manage, this crucial moment in human history?

FROM MALTHUS TO LIMITS TO GROWTH

In one of the earliest known warnings of an impending crisis, Thomas Malthus suggested in the early 19th century that human populations tend to grow exponentially, whereas resources (especially food) tend to stay flat or grow linearly; populations can thus outstrip their food supplies, degrade their environment, and crash (*1*). More recently, in the mid- to late-20th century, numerous ecologists wrote about the human carrying capacity of the planet, among them Paul Ehrlich, who decried the problem of global overpopulation and its impact on the planet in his famous book *The Population Bomb* in 1968 (*2*).

In recent decades, it has become clear that the classical Malthusian view of population growth and the environment was incomplete. It overlooked the changes in technology, food production, and reproductive behavior that occur as nations develop. Today, population growth must be viewed alongside rapid, global technological change and the ongoing "demographic transition" from larger families and high mortality rates to smaller families and longer lives.

Nonetheless, with current predictions of 10 billion to 11 billion people on Earth by the end of the 21st century (*3*), the problems caused by population growth, increasing wealth and technological advancement, rapidly increasing natural resource exploitation, ongoing global environmental degradation, and increasing human vulnerability to environmental disasters are a major concern. In fact, during the past 50 years, the continued growth of the global human population and the even faster growth of per capita consumption have put unprecedented pressure on the planet.

One of the most powerful analyses of this problem was *The Limits to Growth*, published in 1972 (*4*). In this influential book, Meadows *et al.* suggested that the unrelenting growth of population, technology, and consumption cannot continue in a finite world. The study was one of the first to use system dynamics concepts and computer simulations to quantitatively analyze links between increasing human pressures on the planet, intensified environmental damage, and major natural resource decline. The precise details of Meadows *et al.*'s scenarios have been debated and critiqued over the years, but the underlying dynamics that they described—that the growth of our collective consumption is limited in a finite world—has held up extremely well. Simply put, our planet has fundamental limits imposed by physics and biology, and we humans cannot sustain activities that go far beyond those fundamental limits. Naturally, these limits are not always immediate and absolute: We can often cross a limit for a while, but we can't stay there sustainably without risking great harm to the environment and society.

PLANETARY BOUNDARIES

Today, scientists are looking at the problem through a more advanced lens. The most recent manifestation of this thinking is the notion of planetary boundaries. Originally proposed by Rockström *et al.* in 2009 (*5*) and updated significantly by Steffen *et al.* in 2015 (*6*), the concept of planetary boundaries considers the entire Earth system and asks whether human activities have pushed the planet's environmental systems outside the realm of geologic experience during the Holocene epoch (the past ~10,000 years). It considers the changes that humans have caused to Earth's climate, land resources, ecosystems and biodiversity, fresh water, ocean chemistry, atmospheric chemistry, and biogeochemical cycles.

In several aspects, especially climate, land, biodiversity, and biogeochemical flows, it is now clear that human activities have already changed the planet beyond what was normally experienced in our geologic epoch. As a result, humans have moved the planet from the natural Holocene epoch to a new, human-dominated time period widely referred to as the Anthropocene (*7*).

This is hardly surprising. Nearly 40% of Earth's land surface has been converted to agricultural production, obliterating natural ecosystems and much of Earth's biodiversity (*8*); freshwater resources are being exhausted all over the globe faster than they are being replenished (*9*); the natural cycles of nitrogen and phosphorus have been radically altered through use of fertilizers (*8*); ocean fisheries are being depleted (*10*), while oceans are also acidifying from increasing CO_2 emissions (*11*); and human activities have increased atmospheric CO_2 levels by ~50%, along with those of other greenhouse gases, thereby causing profound changes in our climate system (*12*). It is thus a fact that humans have massively changed the planet. We may be able to move beyond one of these limits for a short period of time, but not sustainably, or without serious environmental damage to the planet.

CRISIS OR OPPORTUNITY?

The Malthusian population conundrum, the limits to growth, and the planetary boundaries concepts each portray human activities running into, or crashing beyond, a limit or boundary imposed by the physics and biol-

ogy of the planet. But although the fundamental physical and biological limits to the planet are indisputable, each concept still has its detractors.

Some critics have raised good points (*13*). For example, the initial version of the planetary boundaries was criticized for defining a single global limit to highly complex, geographically variable phenomena, such as the use of land and water, and the cycling of nitrogen and phosphorus. What is a meaningful global limit of land use, which is mainly manifest at local and regional scales? Similarly, how much water can humans use globally, when water is mainly a local resource? The most recent version of planetary boundaries (*7*) addresses many of these concerns, but more work is needed to define appropriate environmental boundaries at local, regional, and global scales.

Critics believe that too much attention has focused on the biological and physical limits of the planet and the seemingly inevitable environmental crises that crossing them may precipitate, but have ignored the extraordinary levels of human ingenuity that can happen within them. Rather than looking at the limits that the planet ultimately imposes, should scientists not instead focus on the opportunity for human advancement to thrive within them?

Fishers haul a seine net onboard a commercial fishing boat as they fish for Alaska pollock in the Peter the Great Gulf.

Ultimately, these criticisms come down to the intrinsic worldview held by different authors. Whether we perceive the finite physical and biological capacity of the planet as hard limits and boundaries, or as the opportunity space for humans to operate and innovate within, reflects deeply held human beliefs and cultural narratives about scarcity and abundance. We can each look at the same planet, with the same data, with the same laws of physics and biology in mind, and reach different conclusions. The limits and boundaries still exist, of course, but each person's view of them depends on whether they look through the lens of scarcity (with limits) or abundance (and opportunity). In other words, whether one considers the planetary glass half full or half empty depends on whom you ask. But either way, it would be foolish not to acknowledge the intrinsic limits of the glass.

A FRAMEWORK FOR SOLUTIONS

The next step will be to move on from descriptions of planetary limits and boundaries, to developing frameworks for how to live within them. Any such framework must recognize that the laws of physics and biology ultimately govern what happens on this planet. For all of the human technological advances, ingenuity, and hard work, we cannot break the laws of physics. Moreover, Earth's ecosystems can still do many things that humans cannot match. For example, the rest of the biosphere operates on renewable energy and with zero waste, something humans cannot yet do.

In this context, some of the ideas embodied in the emerging circular economy framework, the "natural step" (*14*) and the "ecological footprint" (*15*), are extremely helpful. These ideas are based on the observations that the Earth system is, to very good approximation, materially closed (very little matter comes into the planet, and very little leaves, over geologic time) and energetically open (essentially all of the energy that fuels our climate, biology, and Earth system processes comes from the Sun).

Based on these ideas, and adding to them, I would suggest that natural ecological systems on Earth succeed—often where humans do not—because they adhere to the following guidelines: They do not consume resources faster than they are regenerated by the environment; do not produce wastes, especially those that disrupt the environment and the climate system, faster than they are assimilated or removed by the environment; are highly diverse, making them more robust in the face of changing conditions; and power nearly everything they do with the Sun.

These are not new ideas, of course, but they may present a helpful framework for reinventing our food, water, and energy systems. For example, they can help guide a shift to high-efficiency, renewable energy systems; to using high-efficiency irrigation instead of wasteful practices seen around the world today; or to developing more sustainable forms of agriculture that avoid biodiversity loss and deforestation. Doing so will be necessary to avoid dangerous global environmental damage, including climate change and biodiversity collapse, while providing for human well-being. The scientific and technical challenges are enormous. But the most substantial challenge will be implementing them within the current political, social, and economic systems.

We humans must ultimately respect the biological and physical limits of our world, and follow the lessons of the planet, if we hope to build a thriving and enduring civilization. The longer we delay doing so, the lower the chances of success. But the sooner we get started, the quicker we may be able to transition to a truly sustainable and prosperous future. ■

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