LIVING ON A NEW EARTH

Humankind has fundamentally altered the planet. But new thinking and new actions can prevent us from destroying ourselves

Forget banking and the automotive industry. Earth is the one system that is truly "too big to fail." For centuries humans have used up the planet's resources, saddled it with our waste and simply moved on when a wellspring dried up or the back forty became polluted. But now we've exhausted that strategy. Scientists, social thinkers and the global public are realizing that humankind has transformed the natural planet into an industrialized one, and we must transition again to a sustainable planet if we are to survive.

So what is the bailout plan? The first step is determining how close to "failure" the world is. On page 54, environmental scientist Jonathan Foley presents the results of a major international collaboration that calculated safe limits for pivotal environmental processes, such as climate change and ocean acidification, that could undermine sustainability if allowed to go too far. The numerical boundaries may need fine-tuning, but knowing which processes matter most tells us where to look for solutions. On page 58, Scientific American invites eight experts to propose specific remedies.

Those fixes could slow environmental degradation but might not solve the underlying cause. That culprit, according to Middlebury College scholar in residence Bill McKibben, is the very driver of modern society: a relentless quest for economic growth. In an exclusive excerpt from his upcoming book, on page 61, McKibben argues that we must give up growth and reorganize based on smart maintenance of resources. Critics say the idea is unrealistic; on page 66, staff editor Mark Fischetti challenges him to respond. —*The Editors*

JEN CHRISTIANSEN

Scientists have set thresholds for key environmental processes that, if crossed, could threaten Earth's habitability. Ominously, three have already been exceeded • **BY JONATHAN FOLEY**

BOUNDARIES FOR HEALTHY PLANET

KEY CONCEPTS

- Although climate change gets ample attention, species loss and nitrogen pollution exceed safe limits by greater degrees. Other environmental processes are also headed toward dangerous levels.
- Promptly switching to low-carbon energy sources, curtailing land clearing and revolutionizing agricultural practices are crucial to making human life on Earth more sustainable.

—The Editors

For nearly 10,000 years—since the dawn of civilization and the Holocene era—our world seemed unimaginably large. Vast frontiers of land and ocean offered infinite resources. Humans could pollute freely, and they could avoid any local repercussions simply by moving elsewhere. People built entire empires and economic systems on their ability to exploit what seemed to be inexhaustible riches, never realizing that the privilege would come to an end.

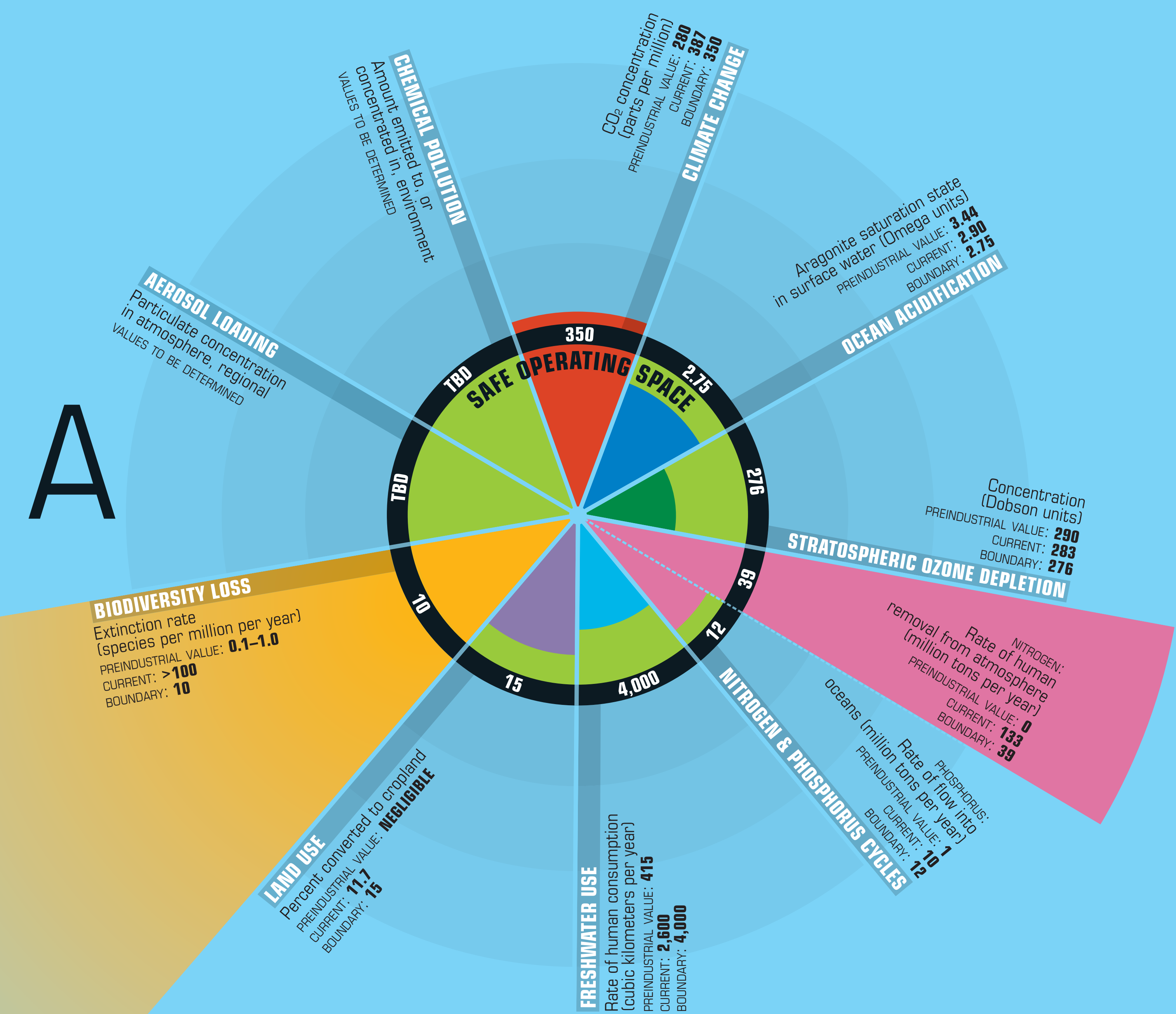
But thanks to advances in public health, the industrial revolution and later the green revolution, population has surged from about one billion in 1800 to nearly seven billion today. In the past 50 years alone, our numbers have more than doubled. Fueled by affluence, our use of resources has also reached staggering levels; in 50 years the global consumption of food and freshwater has more than tripled, and fossil-fuel use has risen fourfold. We now co-opt between one third and one half of all the photosynthesis on the planet.

This wanton growth has also expanded pollution from a local problem to a global assault. Stratospheric ozone depletion and greenhouse gas concentrations are obvious complications, but many other deleterious effects are rising.

The sudden acceleration of population growth, resource consumption and environmental damage has changed the planet. We now live in a "full" world, with limited resources and capacity to absorb waste. The rules for living on such a world are different, too. Most fundamentally, we must take steps to ensure that we function within the "safe operating space" of our environmental systems. If we do not revise our ways, we will cause catastrophic changes that could have disastrous consequences for humankind.

What would cause these changes? And how can we avoid them? A worldwide team of scientists—led by Johan Rockström of the Stockholm Resilience Center in Sweden, with colleagues from Europe, the U.S. (including me) and Australia—recently sought answers through a larger, related question: Are we nearing planetary "tipping points" that would push the global environment into dangerous new territory, outside anything seen during human history?

After examining numerous interdisciplinary studies of physical and biological systems, our team determined that nine environmental processes could disrupt the planet's ability to support human life. We then set boundaries for these processes—limits within which humankind can operate safely. Seven of the processes have clear



boundaries [*see illustration above*], scientifically defined by a single number (that of course carries some uncertainty). Three of those boundaries—for climate change, ocean acidification and stratospheric ozone depletion—represent tipping points, and the other four signify the onset of irreversible degradation. The remaining two processes—atmospheric aerosol pollution and global chemical pollution—have not been as extensively studied, so limits are not set yet.

Our group's analysis shows that three processes already exceed their boundaries: biodiversity loss, nitrogen pollution and climate change. And all the others are moving toward the thresholds. Individual limits might be fine-tuned, and others could perhaps be added in the future, but the set represents a "first order" summary of the world's most perilous environmental conditions and provides a framework for thinking about how to manage the threats.

Fossil-Fuel Complications

Understanding the causes of our most pressing environmental problems offers clues to solving them. In two cases—climate change and ocean acidification—one driver is all too familiar: humankind's use of fossil fuels, which releases carbon dioxide (CO_2) into the atmosphere.

Climate change. Although our planet has already undergone significant human-induced warming and will experience more, scientists and policy makers are seeking ways to avoid the most devastating consequences—including the loss of polar ice sheets, the collapse of freshwater supplies and the disruption of regional weather systems. Already, CO_2 concentration is 387 ppm

PIVOTAL ENVIRONMENTAL PROCESSES should remain within certain limits, otherwise the safe operating space within which humankind can exist will be threatened. Shading represents how far a process has advanced from preindustrial levels toward or beyond a boundary; biodiversity, nitrogen flow and climate change have already crossed their thresholds. (Nitrogen and phosphorus flows are paired because they tend to occur together.)

JEN CHRISTIANSEN

(by volume, the usual measure), and debate continues over what level of all greenhouse gases would cause dangerous climate change; suggested values range from 350 to 550 ppm of CO_2. In our analysis, we suggest a conservative, long-term target of 350 ppm, to keep the planet well away from climatic tipping points. To meet that target, the world has to take immediate action to stabilize greenhouse gas emissions and, over the next few decades, substantially reduce them below their current levels.

Ocean acidification. The ongoing acidification of the seas is the lesser-known cousin of climate change. As atmospheric CO_2 concentration rises, so does the amount of CO_2 that dissolves in water as carbonic acid, which makes the surface ocean more acidic. The oceans are naturally basic, with a pH of about 8.2, but data show that pH has already slipped to nearly 8.0 and continues to drop. The metric our group used to quantify damage from such change is the falling level of aragonite (a form of calcium carbonate) that is created in the surface layer. Many creatures—from corals to a multitude of phytoplankton that underlie the ocean's food chain—depend on aragonite to build their skeletons or shells. Increasing acidity could severely weaken ocean ecosystems and food webs, providing another compelling reason for nations to shift toward a low-carbon energy future.

[THE AUTHOR]

Jonathan Foley is director of the University of Minnesota's Institute on the Environment. Originally trained as an atmospheric scientist, he works primarily on the nexus of land use, agriculture and the global environment.

PUSHING THE LIMIT

Allowing environmental processes to exceed certain limits could have serious repercussions, but decisive actions can keep the processes within safe bounds. [For more, see "Solutions to Environmental Threats," starting on page 58.]

ENVIRONMENTAL PROCESS	CONSEQUENCES IF SURPASSED	POSSIBLE SOLUTIONS
Biodiversity loss	Land and ocean ecosystems fail	Slow land clearing and development; pay for ecosystem services
Nitrogen cycle	Freshwater and ocean dead zones expand	Reduce fertilizer use; process animal waste; switch to hybrid vehicles
Phosphorus cycle	Ocean food chains are disrupted	Reduce fertilizer use; process animal waste; process human waste better
Climate change	Polar ice and glaciers melt; regional climates shift	Switch to low-carbon energy and fuels; put a price on carbon emissions
Land use	Ecosystems fail; carbon dioxide escapes	Limit urban sprawl; improve farm efficiency; pay for ecosystem services
Ocean acidification	Microorganisms and corals die; carbon sink lessens	Switch to low-carbon energy and fuels; reduce fertilizer runoff
Freshwater use	Aquatic ecosystems fail; water supplies disappear	Improve irrigation efficiency; install low-flow appliances
Stratospheric ozone depletion	Radiation harms humans, animals and plants	Phase out hydrochlorofluorocarbons; test effects of new chemicals

Food Production Implicated

Humankind already commandeers 35 percent of Earth's land surface for crops and pastures, and expanding agriculture is the prime motivation for clearing new land, thereby destroying natural ecosystems. Several planetary boundaries are in jeopardy of being crossed because of human land-use practices:

Biodiversity loss. Land development is causing one of the greatest extinctions in Earth's history. We are losing species 100 to 1,000 times faster than the natural background rates seen in the geologic record. The rate of loss is found across the world's terrestrial and marine ecosystems and could undermine ecological processes on regional and global scales. Efforts to conserve biodiversity, especially in sensitive tropical forests, need much more attention. Initiatives such as the U.N.'s Reducing Emissions from Deforestation and Forest Degradation program (known as REDD), which develops funding to slow the clearing of tropical forests, can simultaneously address biodiversity decline and carbon emissions and could be very effective.

Nitrogen and phosphorus pollution. Extensive spreading of industrial fertilizers has upset the chemistry of the planet. Fertilizer use has more than doubled the flows of nitrogen and phosphorus through the environment, at a rate of 133 million tons of nitrogen and 10 million tons of phosphorus per year. Both flows are causing widespread water pollution, degrading numerous lakes and rivers and disrupting coastal oceans by creating large, hypoxic "dead zones." Needed are new agricultural practices that increase food production yet also sustain the environment.

Freshwater depletion. Across the globe, we withdraw a staggering 2,600 cubic kilometers of water annually from rivers, lakes and aquifers, for irrigation (70 percent), industry (20 percent) and domestic use (10 percent). As a result, many large rivers have diminished flows, and some are drying up altogether. Iconic examples include the Colorado River, which no longer reaches the ocean, and the Aral Sea in Central Asia, now largely desert. Future demand could be enormous. Dramatic improvements in the efficiency of global water use, particularly for irrigation, would help avoid even more serious declines.

Stay Far Away

Our group's initial publication in *Nature* several months ago has generated healthy scientific debate. For the most part, the work has been well received and seen for what it is: a thought

COURTESY OF JOE TRELEVEN (*Foley*)

experiment that attempts to define dangerous "do not cross" lines for the world. We have, however, been roundly criticized by some scientists for even attempting to set boundaries; others do not agree with the numbers we set.

Perhaps the most important comment is that by setting thresholds, we might be encouraging people to think that environmental destruction is acceptable as long as it stays inside the limits. For the record, that is not what we are proposing! Society should not allow the world to drift toward a boundary before acting. Advancing from, say, one third of the way to a boundary to two thirds of the way will still cause severe damage. We urge people to be smart enough and altruistic enough (toward future generations) to stay as far from the limits as possible, because each one represents an environmental crisis.

Most criticisms have been reasonable, and our group anticipated many of them. We knew the notion of boundaries would require more study—especially in refining the numbers, which we continue to work on. But we felt the concept was powerful and would help frame collective thinking about environmental limits to human existence. And we hoped the results would stimulate discussion across the scientific community; it appears we have gotten that wish.

A Start at Solutions

A comprehensive set of planetary boundaries should be respected as the world addresses the economic, social and environmental requirements for global sustainability. Society has begun to attack some of the challenges, but only in a piecemeal way, thinking of each boundary independently. But the limits are strongly interconnected. When one threshold is crossed, it puts pressure on others, increasing the risk of breaching them. For example, exceeding the climate change limit may push extinction rates higher. Likewise, nitrogen and phosphorus pollution may undermine the resilience of aquatic ecosystems, greatly accelerating their loss of biological diversity. As well intended as our remediations have been, trying to solve one factor at a time most likely will fail.

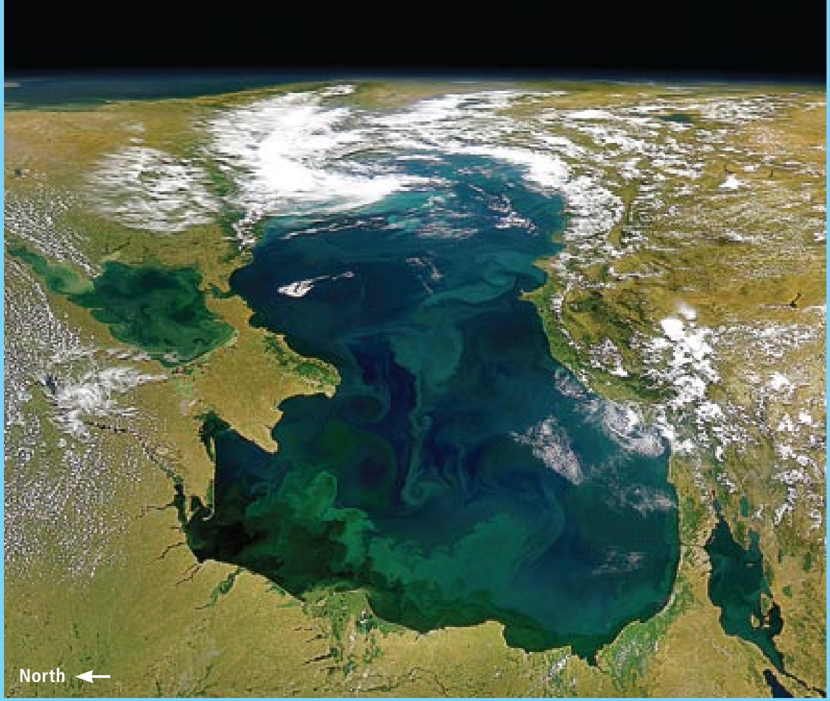
In this critical time, it is not enough for scientists to simply define the problems and go home. We must also begin to propose solutions. Here are a few ideas to start with:

- Make the transition to an efficient, low-carbon energy system. The pressing issues of climate change and ocean acidification require that we stabilize atmospheric CO_2 concentrations as soon as possible, preferably below 350 ppm. The transition will require massive improvements in energy efficiency, followed by bringing low-carbon energy sources to scale quickly.

- Sharply curtail land clearing and degradation, especially tropical deforestation. Many of the planetary limits, notably biodiversity loss, are compromised by the relentless expansion of human settlements.

- Invest in revolutionary agricultural practices. Several boundaries, including those relating to nutrient pollution and water consumption, are affected by our industrialized agricultural systems. New approaches are possible, including new plant varieties and precision agriculture techniques, as well as far more efficient use of water and fertilizer.

As we implement solutions, we should recognize that no simple rulebook exists for achieving a more sustainable future. We will develop new working principles as we go for our economic systems, political institutions and social actions, remaining acutely aware of our limited understanding of environmental and human processes. Any benchmarks or innovative practices should allow us to react to changing indicators of environmental health and social needs, while helping us enhance the resilience of natural and human systems so that they are more robust and less vulnerable to unexpected shocks that very likely will occur. To maximize that resiliency, we will have to do our best to live within the boundaries of a shrinking planet. ■



MASSIVE ALGAE BLOOMS (*green swirls near bottom*) in the Black Sea are spawned by agricultural runoff carried there by the Danube River (*bottom*), killing aquatic life—an example of the interrelated nature of critical environmental processes, in this case land use and biodiversity.

COURTESY OF THE SEAWIFS PROJECT, NASA/GODDARD SPACE FLIGHT CENTER AND ORBIMAGE

➥ MORE TO EXPLORE

A Safe Operating Space for Humanity. Johan Rockström et al. in *Nature,* Vol. 461, pages 472–475; September 24, 2009.

Commentaries: Planetary Boundaries. *Nature Reports Climate Change,* Vol. 3, pages 112–119; October 2009. **http://blogs.nature.com/climatefeedback/2009/09/planetary_boundaries.html**

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SOLUTIONS TO ENVIRONMENTAL

Experts tell SCIENTIFIC AMERICAN which actions will keep key processes

BIODIVERSITY LOSS

Gretchen C. Daily, *professor of environmental science, Stanford University*

RAIN FOREST, COSTA RICA

It is time to confront the hard truth that traditional approaches to conservation, taken alone, are doomed to fail. Nature reserves are too small, too few, too isolated and too subject to change to support more than a tiny fraction of Earth's biodiversity. The challenge is to make conservation attractive—from economic and cultural perspectives. We cannot go on treating nature like an all-you-can-eat buffet.

We depend on nature for food security, clean water, climate stability, seafood, timber, and other biological and physical services. To maintain these benefits, we need not just remote reserves but places everywhere—more like "ecosystem service stations."

A few pioneers are integrating conservation and human development. The Costa Rican government is paying landowners for ecosystem services from tropical forests, including carbon offsets, hydropower production, biodiversity conservation and scenic beauty. China is investing $100 billion in "ecocompensation," including innovative policy and finance mechanisms that reward conservation and restoration. The country is also creating "ecosystem function conservation areas" that make up 18 percent of its land area. Colombia and South Africa have made dramatic policy changes, too.

Three advances would help the rest of the world scale such models of success. One: new science and tools to value and account for natural capital, in biophysical, economic and other terms. For example, the Natural Capital Project has developed InVEST software that integrates valuation of ecosystem services with trade-offs, which governments and corporations can use in planning land and resource use and infrastructure development. Two: compelling demonstrations of such tools in resource policy. Three: cooperation among governments, development organizations, corporations and communities to help nations build more durable economies while also maintaining critical ecosystem services.

NITROGEN CYCLE

Robert Howarth, *professor of ecology and environmental biology, Cornell University*

Human activity has greatly altered the flow of nitrogen across the globe. The single largest contributor is fertilizer use. But the burning of fossil fuels actually dominates the problem in some regions, such as the northeastern U.S. The solution in that case is to conserve energy and use it more efficiently. Hybrid vehicles are another excellent fix; their nitrogen emissions are significantly less than traditional vehicles because their engines turn off while the vehicle is stopped. (Emissions from conventional vehicles actually rise when the engine is idling.) Nitrogen emissions from U.S. power plants could be greatly reduced, too, if plants that predate the Clean Air Act and its amendments were required to comply; these plants pollute far out of proportion to the amount of electricity they produce.

In agriculture, many farmers could use less fertilizer, and the reductions in crop yields would be small or nonexistent. Runoff from corn fields is particularly avoidable because corn's roots penetrate only the top few inches of soil and assimilate nutrients for only two months of the year. In addition, nitrogen losses can be reduced by 30 percent or more if farmers plant winter cover crops, such as rye or wheat, which can help the soil hold nitrogen. These crops also increase carbon sequestration in soils, mitigating climate change. Better yet is to grow perennial plants such as grasses rather than corn; nitrogen losses are many times lower.

Nitrogen pollution from concentrated animal feeding operations (CAFOs) is a huge problem. As recently as the 1970s, most animals were fed local crops, and the animals' wastes were returned to the fields as fertilizer. Today most U.S. animals are fed crops grown hundreds of miles away, making it "uneconomical" to return the manure. The solution? Require CAFO owners to treat their wastes, just as municipalities must do with human wastes. Further, if we ate less meat, less waste would be generated and less synthetic fertilizer would be needed to grow animal feed. Eating meat from animals that are range-fed on perennial grasses would be ideal.

The explosive growth in the production of ethanol as a biofuel is greatly aggravating nitrogen pollution. Several studies have suggested that if mandated U.S. ethanol targets are met, the amount of nitrogen flowing down the Mississippi River and fueling the Gulf of Mexico dead zone may increase by 30 to 40 percent. The best alternative would be to forgo the production of ethanol from corn. If the country wants to rely on biofuels, it should instead grow grasses and trees and burn these to co-generate heat and electricity; nitrogen pollution and greenhouse gas emissions would be much lower.

DOUG WECHSLER *Animals Animals/Earth Scenes*

THREATS

in bounds

PHOSPHORUS CYCLE

David A. Vaccari, *director of civil, environmental and ocean engineering, Stevens Institute of Technology*

Phosphorus demand is increasing faster than population because of rising living standards. At current rates, the readily accessible reserves will last less than a century. Thus, our two objectives are to conserve phosphorus as a resource as well as reduce its runoff, which damages coastal ecosystems.

The most sustainable flow of phosphorus through the environment would be the natural flux: seven million metric tons per year (Mt/yr). To hit that mark yet satisfy our usage of 22 Mt/yr, we would have to recycle or reuse 72 percent of our phosphorus, and if demand rose further, even more recycling would have to be done.

The flow could be reduced with existing technologies. Conservation agriculture techniques, such as no-till farming and terracing, could reduce the flow entering rivers by 7.2 Mt/yr. Most farm animal phosphorus waste that is not recycled—about 5.5 Mt/yr finds its way to the sea—could essentially be eliminated by transporting it to agricultural areas where it could be used. For human waste, technologies can increase recovery from 50 to about 85 percent, saving 1.05 Mt/yr.

These actions are the "low-hanging fruit," based on what is doable rather than what is needed to avoid dangerous scenarios. Yet they would lower the loss to waterways from 22 to 8.25 Mt/yr, not very much above the natural flux.

CLIMATE CHANGE

Adele C. Morris, *policy director, Climate and Energy Economics Project, Brookings Institution*

Choosing an atmospheric concentration at which to stabilize greenhouse gases, though seemingly a scientific decision, requires weighing the benefits and costs of achieving different targets and determining who will pay. Given how hard that is, we should adopt policies that minimize costs and preserve the consensus for action for many years.

The first step is to not kill consensus in the cradle with short-term ambition, because angry voters will demand defeat of a program they view as excessively costly.

Price-based climate policies can avoid such economic and political thresholds. Domestically, one option is a rising but reasonable economy-wide greenhouse gas tax. Another option is a cap-and-trade system in which emissions permits trade at prices within a preset range that rises over time. A regulated price range would keep the cost of emissions high enough to prompt ambitious reductions but would limit the risk to the economy (and the program itself) if the cap turned out to be inadvertently stringent.

International agreements should also allow price-based commitments as an alternative to strict emissions limits that might prove infeasible. A climate treaty could allow countries to commit to a tax of an agreed level. This flexibility could allay concerns in developing countries that caps could stifle poverty alleviation. Staying within a "safe operating space" will require staying within all the relevant boundaries, including the electorate's willingness to pay.

LAND USE

Eric F. Lambin, *professor of earth systems, Stanford University and University of Louvain*

To control the impact of land use, we should focus on the distribution of cropland globally. Intensive agriculture should be concentrated on land that has the best potential for high-yield crops. But a significant fraction of this prime land is being lost. We risk reaching a point where any increase in food (not to mention biofuel) production would prompt rapid clearing of tropical forests and other ecosystems, as well as cropland expansion onto marginal tracts that have lower yields.

We can avoid losing the best agricultural land by controlling land degradation, freshwater depletion and urban sprawl. This step will require zoning and the adoption of more efficient agricultural practices, especially in developing countries. The need for farmland can be lessened, too, by decreasing waste along the food distribution chain, encouraging slower population growth, ensuring more equitable food distribution worldwide and significantly reducing meat consumption in rich countries.

More land for nature can also be spared by enacting strong set-aside policies, as the European Union has done. A few developing countries (China, Vietnam, Costa Rica) have managed to shift from deforestation to reforestation thanks to better environmental governance, a strong political will to modernize land use, cultural changes and policies that rely on land-use regulations, and incentives to maintain ecosystem services. The challenge for these nations is to continue such policies without having to import more food.

CROPS AND SPRAWL

JEN CHRISTIANSEN (*graphic display*); CORBIS (*aerial landscape*)

OCEAN ACIDIFICATION

Scott C. Doney, *senior scientist, Woods Hole Oceanographic Institution*

The oceans are becoming more acidic because of worldwide carbon dioxide emissions, yet global, regional and local solutions are possible. Globally, we need to stop putting CO_2 into the atmosphere and to perhaps, eventually, reduce the concentration toward preindustrial levels. The main tactics are raising energy efficiency, switching to renewable and nuclear power, protecting forests and exploring carbon sequestration technologies.

Regionally, nutrient runoff to coastal waters not only creates dead zones but also amplifies acidification. The excess nutrients cause more phytoplankton to grow, and as they die the added CO_2 from their decay acidifies the water. We have to be smarter about how we fertilize fields and lawns and treat livestock manure and sewage. Another measure is to lessen acid rain, caused mostly by power plant and industry emissions; the rain does not stop when it reaches the coastline.

Locally, acidic water could be buffered with limestone or chemical bases produced electrochemically from seawater and rocks. More practical may be protecting specific shellfish beds and aquaculture fisheries. Larval mollusks such as clams and oysters appear to be more susceptible to acidification than adults, and recycling old clamshells into the mud may help buffer pH and provide better substrate for larval attachment. Shellfish hatcheries can control water chemistry and switch to more robust species.

The drop in ocean pH is expected to accelerate in coming decades, so marine ecosystems will have to adapt. We can enhance their chances for success by reducing other insults such as water pollution and overfishing, making them better able to withstand some acidification while we transition away from a fossil-fuel energy economy.

FRESHWATER USE

Peter H. Gleick, *president, Pacific Institute*


DRIP IRRIGATION

Few rational observers deny the need for boundaries to freshwater use. More controversial is defining where those limits are or what steps to take to constrain ourselves within them.

Another way to describe these boundaries is the concept of peak water. Three different ideas are useful. "Peak renewable" water limits are the total renewable flows in a watershed. Many of the world's major rivers are already approaching this threshold—when evaporation and consumption surpass natural replenishment from precipitation and other sources. "Peak nonrenewable" limits apply where human use of water far exceeds natural recharge rates, such as in fossil groundwater basins of the Great Plains, Libya, India, northern China and parts of California's Central Valley. In these basins, an increase in extraction is followed by a leveling off and then reduction, as the costs and amount of effort needed to acquire the dwindling resource rise—a concept similar to that of peak oil.

"Peak ecological" water is the idea that for any hydrological system, increasing withdrawals eventually reach the point where any additional economic benefit of taking the water is outweighed by the additional ecological destruction that causes. Although it is difficult to quantify this point accurately, we have clearly passed the point of peak ecological water in many basins around the world where huge damage has occurred, including the Aral Sea, the Everglades, the Sacramento–San Joaquin Valley and many watersheds in China.

The good news is that the potential for savings, without hurting human health or economic productivity, is vast. Improvements in water-use efficiency are possible in every sector. More food can be grown with less water (and less water contamination) by shifting from conventional flood irrigation to drip and precision sprinklers, along with more accurately monitoring and managing soil moisture. Conventional power plants can change from water cooling to dry cooling, and more energy can be generated by sources that use extremely little water, such as photovoltaics and wind. Domestically, millions of people can replace water-inefficient appliances with efficient ones, notably washing machines, toilets and showerheads.

OZONE DEPLETION

David W. Fahey, *physicist, National Oceanic and Atmospheric Administration*

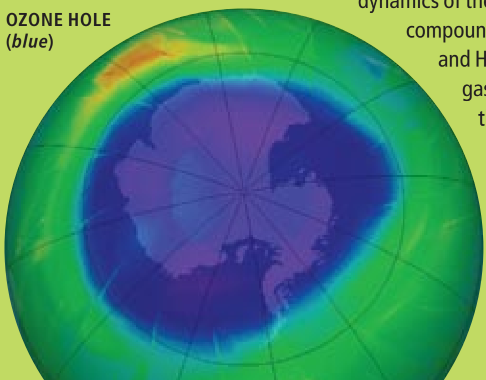
The Montreal Protocol under the Vienna Convention for the Protection of the Ozone Layer has reduced use of ozone-depleting substances—primarily chlorofluorocarbons (CFCs) and halons—by 95 percent over two decades. As of January 1, no more production is to occur in the 195 nations that signed the protocol. As a result, stratospheric ozone depletion will largely reverse by 2100. The gain has relied, in part, on intermediate substitutes, notably hydrochlorofluorocarbons (HCFCs), and the growing use of compounds that cause no depletion, such as hydrofluorocarbons (HFCs).

Ongoing success depends on several steps:

- Continue observing the ozone layer to promptly reveal unexpected changes. Ensure that nations adhere to regulations; for example, the HCFC phaseout will not be complete until 2030.
- Maintain the Scientific Assessment Panel under the protocol. It attributes causes of changes in the ozone layer and evaluates new chemicals for their potential to destroy ozone and contribute to climate change.
- Maintain the Technology and Economic Assessment Panel. It provides information on technologies and substitute compounds that helps nations assess how the demand for applications such as refrigeration, air-conditioning and foam insulation can be met while protecting the ozone layer.

The two panels will also have to evaluate climate change and ozone recovery together. Climate change affects ozone abundance by altering the chemical composition and dynamics of the stratosphere, and compounds such as HCFCs and HFCs are greenhouse gases. For example, the large projected demand for HFCs could significantly contribute to climate change.

OZONE HOLE (*blue*)



BOB ROWAN *Progressive Image/Corbis (drip irrigation)*; COURTESY OF OZONE HOLE WATCH/NASA *(globe)*