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REVIEW

The interaction of human population, food production, and biodiversity protection

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Research suggests that the scale of human population and the current pace of its growth contribute substantially to the loss of biological diversity. Although technological change and unequal consumption inextricably mingle with demographic impacts on the environment, the needs of all human beings—especially for food—imply that projected population growth will undermine protection of the natural world. Numerous solutions have been proposed to boost food production while protecting biodiversity, but alone these proposals are unlikely to staunch biodiversity loss. An important approach to sustaining biodiversity and human well-being is through actions that can slow and eventually reverse population growth: investing in universal access to reproductive health services and contraceptive technologies, advancing women's education, and achieving gender equality.

Achieving high standards of human welfare and ensuring the long-term viability of the natural world are both cornerstone goals of sustainable human development (*1*). Biodiversity and natural ecosystems have intrinsic value and are also essential for supporting human life (*2*). Many scenarios have been proposed to meet human food demand, while also maintaining biodiversity, in a world with a global population growing toward 10 billion people (*3*–*6*). Approaches include a broader implementation and transference of technologies to increase food production through intensification rather than expansion (*3*), reducing food waste (*4*), and changes in diet (*5*, *6*).

These approaches remain largely idealistic. Engineering the capacity to feed the world's population has proceeded at the cost of substantial disregard for ecological impacts. Given the conflicts surrounding the use of land and ocean for food production while also protecting biodiversity, some people question whether feeding the world and maintaining biodiversity are even compatible objectives (*7*–*9*). The deterioration of nature results from economic, technological, and demographic dynamics, yet unfortunately the scientific community generally remains reticent to discuss global population size and increase (Fig. 1).

This reticence may stem from common perceptions of a history of overreach and even abuse in population policies, and from common convictions that human numbers cannot be influenced other than through coercive "population control" (*10*). We argue that research increasingly demonstrates that continuing population growth plays a substantial role in the destruction of biodiversity, and that this role deserves more exploration in scientific circles. Policies for slowing and eventually reversing the size of the global population, within a framework of human rights, are a feasible pathway to reducing humanity's impact, increasing human welfare, and protecting biodiversity.

Neglect for the population factor

The 1990s and 2000s saw a desertion of concerns about population in scientific, policy, and public arenas (*11*–*13*). A number of factors converged to downplay ecological and socioeconomic issues related to population growth. A globally declining fertility rate promoted a widespread perception that the population problem was on the way to solving itself (*14*). Additionally, the combination of an aging population and low fertility rates in some developed nations has generated concerns that a shrinking workforce might adversely affect public finances and standards of living (*15*). Another contributing factor to neglecting the population question was the emergence of climate change as a major challenge, which shifted attention toward the problem of overconsumption in developed countries.

The absence of a dominant scientific opinion on the question of a sustainable human population has also contributed to the silence enveloping population matters (*16*, *17*). Lack of agreement about the scale (or even the existence) of risk that population growth presents can be traced to the history of the issue since at least the early 1970s. At the time, some environmental scientists predicted massive famines in the near future due to "the population explosion" outstripping food

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production (*18*, *19*). These predictions did not materialize, in large part because Green Revolution crop varieties, technologies, and inputs increased the food supply—at a rate even faster than population grew in the same period. The success of the Green Revolution cast doubt on the idea of human "carrying capacity" (i.e., the maximal population of a species that an environment can support without being degraded) (*20*). It encouraged the belief to prevail that human numbers are not constrained by environmental parameters but can defy limits through technological and agronomic innovations (*21*). These factors, along with others, converged to marginalize concern about human population size and growth.

Renewed focus on population growth and sustainable intensification

Recently, focus on the global population has resurfaced (*22*–*29*). Reaching a population of 7 billion in 2011 contributed to a resurgence of interest (*30*); more important, attention to population growth has been spurred by the question of whether food production capacity will be able to meet coming demand (*4*, *31*–*33*). The United Nations projects, as a median scenario, a population of 9.7 billion by midcentury and 11.2 billion by century's end (*34*) (Fig. 2). Food production will need to increase by roughly 70% by 2050 and double or triple by 2100 (*31*, *35*). The link between human numbers and food production has stimulated multiple analyses on how to secure food for all. Most of these have focused on raising productivity, facilitating access to markets, reducing waste, or changing diets (*3*–*6*, *36*).

Food production profoundly intersects the human and ecological worlds. Because the ecological impact of food production is amply documented (*4*), researchers urge that production must be increased without losing more biodiversity and converting additional natural areas to cultivation. Such "sustainable intensification" (*35*, *37*), it is argued, may be achieved through a number of approaches: by increasing yields on agricultural lands already in production; by increasing efficiency in freshwater use; by applying fertilizers and pesticides through more cautious methodologies; and possibly by genetically modifying crops to produce higher yields or to tailor them for specific challenges. Reduction of meat consumption in the developed world is also encouraged, because meat and other animal products are ecologically costly to produce (*38*, *39*). Through such agronomic adjustments, efficiency gains, and perhaps consumer shifts, researchers are hopeful that food supplies can meet demand without added biodiversity losses.

Even if sustainable intensification could succeed on its own terms, it would have to be implemented globally and expeditiously to counter the escalating impact of food production, given rising demand (*40*). The production and trade of soybeans and palm oil serve to illustrate the point. Chinese soybean imports, for example, grew from $75 million in 1995 to $38 billion in 2013. On the basis of present trends, one agribusiness study estimated that by 2024, Chinese soybean demand could outstrip the current soybean production of the United States, Brazil, and Argentina combined (*41*, *42*). How such demand, reflecting growing meat consumption in only one developing nation, can be met without conversion of more forested or other uncultivated lands is unclear. Growing demand for soybeans (and other feed grains) will likely be perceived as an economic opportunity by constituencies unconcerned with the need for sustainable intensification (*42*). Another trend has been the expansion of oil palm plantations replacing tropical forests (*43*). Palm oil has become a major ingredient in processed foods (and nonfood commodities). The lucrative prospect of increasing palm oil production might also override the mandate to avoid additional biodiversity destruction.

Notwithstanding the best intentions for the global implementation of biodiversity conservation, escalating human stressors continue to drive extinctions, wild species population declines, and habitat destruction (*44*–*49*). Land for agriculture and animal grazing has come to occupy about 40% of the planet's ice-free land (*4*). Ongoing tropical deforestation (*50*–*52*), anticipated expansion of cultivated areas (*40*, *53*), a projected 55% increase in demand for water by 2050 (*54*), expected growth in global pesticide use (*40*), the steady increase of greenhouse gases (with agriculture a major contributor), and the expansion of global trade of foods and other products (*55*) all foreshadow a mounting ecological impact of food production. It appears questionable whether sustainable intensification can prevail over biodiversity-encroaching food production trends.

Rethinking the population question

Although improvements in conservation, agronomic, and harvesting practices are clearly needed, the above trends suggest that the demand side must also be prioritized. Achieving a sustainable world—providing a high quality of life for all people while safeguarding Earth's biodiversity—calls for bringing population growth to the forefront of international concerns. Addressing the population challenge invites overcoming obstacles to a productive discussion in science, policy, and public circles. We suggest two ways of rethinking the population question that may contribute to removing roadblocks to such dialogue.

The first is to move beyond the prevailing dichotomy of whether it is excessive consumption or unsustainable population that fundamentally underlies humanity's impact. Excessive consumption is, indeed, the major factor impinging on the biosphere. Humanity is using Earth excessively both as source (for land cultivation and grazing, freshwater, wild fish, bushmeat, fossil fuels, wood products, and so on) and as sink (for nonabsorbable wastes such as trash, nitrogen, pesticides, confined livestock manure, plastic, and industrial chemicals). Stabilizing and lowering our numbers globally—noncoercively, through the exercise of reproductive rights—is a strategy for scaling down consumption on all fronts.

International developments further contradict binary arguments of excessive consumption as a developed-world problem and population concerns as a developing-world issue. A crisp dichotomy between the global North and the global South is becoming outmoded by the growth of a global consumer class, which has increased by hundreds of millions of people in the past two decades and will grow by billions in the decades ahead (*56*, *57*). A global middle class of 3.2 billion people in 2016 is expected to rise to roughly 5 billion by 2030 (*57*). Forty percent of India's population is predicted to join the ranks of the middle class by midcentury, adding almost half a billion consumers to the global economy (up from 50 million in 2006) (*58*). Africa is estimated to reach between 3 billion and 6.1 billion people by 2100, from 1.2 billion people today (*59*). As the middle class in Africa, Asia, and Latin America continues to grow—an equitable expectation and policy orientation—the stress added to that of the developed world on the biosphere will become extreme.

As the global middle class grows, the world is converging in the direction of increased consumption. Rising meat consumption, increasing purchases of processed and packaged foods, more international

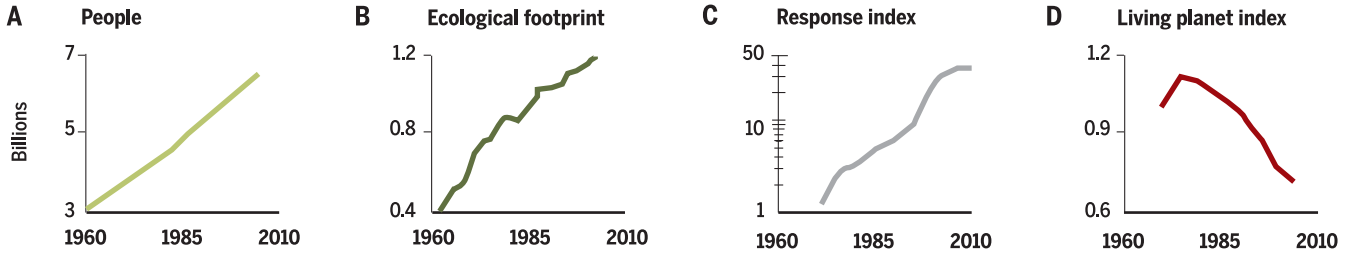

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Fig. 1. Linkage between the number of people and impact on nature. (**A** to **D**) Recent global trends in human population (A); its ecological footprint (B); response index, a metric reflecting the extent of implementation of conservation actions (C); and the status of biodiversity (D). Although considerable variability may exist at smaller scales, these globally available statistics suggest that no conservation action so far has able to significantly avert the impact on biodiversity triggered by the footprint of humanity's increasing numbers and consumption.

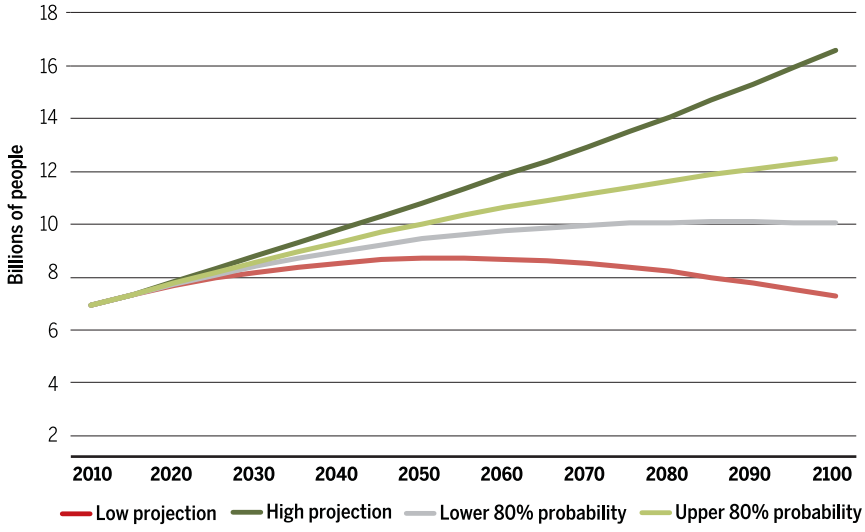

Fig. 2. World population growth in the 21st century: Four projections indicating range of possibilities and what is "80 percent probable." Source: (*34*).

travel, and burgeoning numbers of automobiles, personal computers, and electronic devices are only a few areas in which the impacts from consumer demand for food, energy, materials, and infrastructure are poised to escalate. The global consumer society emerging in our time invites recognition that stabilizing and eventually reducing the global population is crucial for lowering total consumption. Reducing excessive per-person consumption, along with other shifts and policies, is also needed (see below).

The second way of rethinking the population question is in conjunction with the requirements of biodiversity. Until recently, the question of whether and to what extent population growth is sustainable has tended to overlook ecological constraints for avoiding extinctions and for sustaining wild species at healthy levels of abundance, metapopulation structure, and dispersal or migratory needs (*14*, *21*).

If protection of Earth's remaining species, genetic heritage, and natural ecosystems were to be included as a constraining factor of human development, the question of how many people can sustainably inhabit the planet would appear in a new light. Denials of identifiable limits to human numbers (or affirmations of their great elasticity) typically ignore the fact that extending humanity's carrying capacity has succeeded by means of usurping resources from other species. For example, the transformation of the American plains for food production wiped out 99% of the grasslands biome along with the great diversity of plants, animals, and other organisms that constituted it (*60*). Looking toward the future, conservation scientists contend that if humanity wishes to conserve Earth's biodiversity, protecting large areas of terrestrial and marine habitats is needed (*61*, *62*). Such large-scale protection of nature from intensified agriculture, industrial fishing, road building, and other high-impact development—if embraced—would imply limits to how many people, at an equitable standard of living, a biodiverse Earth can support.

Some may object that biodiversity protection is not a universal value, and therefore should not be included as a constraining factor of development and population size. Contrary to such an objection, averting the anthropogenic mass extinction now under way and conserving natural ecosystems, species, healthy populations of biota, and robust ecological and evolutionary processes are needed to ensure a better and safer future. Whether people value the natural world for its intrinsic standing or for the ecological services it provides humanity (e.g., food, clean water, climate regulation, crop pollination, recreational spaces), sustaining Earth's biological wealth is an ecumenical good (*63*, *64*). Addressing catastrophic biodiversity decline is therefore an inescapable responsibility.

Undertaking this responsibility requires that a sufficient amount of land and ocean be protected for the livelihood of other species (*61*, *62*, *65*, *66*). Such division of Earth's sources of livelihood, to facilitate both humanity's and nature's well-being, has led to proposals of a sustainable human population ranging between 1.5 billion and 5 billion people (depending on per-person levels of consumption assumed) (*67*). Daily *et al.* estimated a global population of roughly 2 billion as more "optimum"—where optimum means human numbers that can accommodate large-scale nature protection and secure a high-quality life for all people, while sustaining a globally interconnected civilization (*68*).

What a sustainable population on a biodiverse planet will be is difficult to foresee, for it depends on the standard of living that future people will choose, the food system and diet they will gravitate toward, and technological developments that are difficult if not impossible to predict. But from the present vantage point of a mass extinction event (*2*), it is clear that consumption levels that can accommodate conserving Earth's biological wealth have been exceeded. What makes the case starkly is the impact of food production—the consumption activity most directly linked with human numbers.

Food production and biodiversity

The impact of food production on biodiversity affects every system of the planet. Land conversion for crop and animal agriculture is the chief driver of habitat loss, which, along with direct killing, continues to be the leading threat to biodiversity (*48*, *52*, *69*) (Fig. 3). Of the freshwater resources appropriated for human use, 80% is claimed by agriculture (*4*). At least one-fifth of anthropogenic greenhouse gases are attributed to the food system (*70*, *71*). Agriculture is also largely responsible for the world's 400 dead zones, which have been increasing in number and extent since the 1960s (*72*), and agricultural pollution also affects freshwater systems worldwide (*40*).

Many ecosystems and biomes have fallen to food production. Temperate grasslands are among the hardest hit, with habitat conversion exceeding habitat protection by a ratio of 8:1 (*73*). More than half of the world's species-rich wetlands have been drained over the past century, largely for repurposing into agriculture (*74*, *75*). Aquaculture operations are driving mangrove declines (*76*). Freshwater biodiversity is endangered worldwide, with an estimated 10,000 to 20,000 freshwater species at risk of extinction; river biodiversity is most threatened in regions of intensive agriculture and dense settlement (*77*). Most tropical deforestation since the 1980s is due to the expansion of plantations and ranches (*50*, *78*). Coastal seas are critically endangered and continental shelves are endangered primarily as a result of overfishing (*79*), while trawlers have additionally turned to seamount habitats (*80*). Many commercial fisheries are depleted, most big fish are gone, and large-scale aquaculture and livestock operations contribute to the depletion of the ocean's small fish for feed (*80*–*86*). Scientists recently warned of a high risk of extinction of large ocean animals, with the chief culprit being industrial fishing (*87*). On land, steep population declines of big herbivores and carnivores are also linked to crop and animal agriculture (*88*–*91*). Indeed, the two least disturbed biomes on Earth—boreal forests and tundra (*73*)—are, tellingly, two biomes where large-scale food production does not occur.

The adverse impact of livestock on the biosphere has been extensively documented (*70*, *92*–*95*). Many people in the developed world could eat fewer animal products, and advocacy on that front is valuable, but for the foreseeable future the trends point toward increasing consumption of meat, fish, dairy, and eggs, especially in the developing world. At the same time, so-called "landless" livestock operations (concentrated animal feeding operations) are not a solution. Most cereal croplands in the developed world are devoted to feed production, whereas the livestock facilities themselves are resource-intensive (especially in water use); polluting of air, groundwater, and waterways; vulnerable to diseases and epidemics; and ethically unjust in the treatment of farm animals (*95*–*97*).

The intent of sustainable intensification is laudable, but we argue that its reasoning is flawed in two ways: (i) in its apparent acceptance of the

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current massive impact of food production as a roughly acceptable baseline impact for supporting humans—one among Earth's millions of species; and (ii) in encouraging an impression among scientists, policy makers, and the public that Earth can provide for an additional 2 to 4 billion people without escalating biodiversity destruction—an implausible idealization when trends are tallied.

Global solutions

The world is demographically diverse. Many regions are experiencing moderate to rapid growth, while developed countries and several emerging economies have entered a phase of low to negative growth (*98*). Despite this diversity, a common thread links policies promoting ecologically as well as socially sustainable population change worldwide.

A commonplace misperception is that population growth will resolve itself as economic development and urbanization encourage smaller families (*99*). Several 20th-century cases, however, demonstrate the efficacy of population policies in reducing fertility in the absence of strong economic development (*100*). Such policies simultaneously promote human rights and support important development goals. Lessons from successful population strategies in countries as diverse as Thailand, Bangladesh, Costa Rica, South Korea, and Iran, among others, reveal that the most effective transcultural approach to lowering fertility rates is to embark on comprehensive, well-designed, and well-funded campaigns that support that purpose while simultaneously promoting women's and overall well-being (*13*, *27*).

Wherever human rights–promoting policies to lower fertility rates have been implemented, birth rates have declined within a generation or two. Policies include prominent public discourse on the issue; prioritizing the education of girls and women; establishing accessible and affordable family planning services; provisioning modern contraceptive methods through diverse outlets; deploying health workers for grassroots education and support; making counseling for couples available; eliminating governmental incentives for large families; and making sexuality education mandatory in school curricula (*101*).

High priority on the international agenda must be that people everywhere have ready access and unhindered agency to use family planning services and contraceptive technologies, along with counseling to assist individuals' and couples' preferences (*102*). International funding for family planning declined in the past two decades, even though the financial backing to bring services that allow women to control their fertility has been pivotal in countries where fertility rates have fallen (*103*). Reversing the recent shortfall and investing financially and in technology transfer in this space are crucial, and developed nations should lead on this front (*104*). Additionally, prioritizing the avoidance of unintended pregnancies in all nations is crucial. Unplanned pregnancies are globally pervasive, and in the Americas they may account for more than half of all pregnancies (*105*) (Fig. 4). Demographic analyses indicate that if unintended pregnancies could be minimized, the fertility rate would decline (*106*). Overall, the fertility tide can be turned by making family planning, modern contraception, and cultural narratives about them part of normal everyday life (*107*).

Responding to global growth with the urgency it deserves not only will help on the front of ecological challenges but also advances human rights, especially women's and children's rights (*23*, *28*). Wherever women are empowered educationally, culturally, economically, politically, and legally, fertility rates fall (*59*). Populations tend to move toward states of zero or negative growth when women achieve equal standing with men, as long as family planning services and contraceptives are readily available (*13*). Female education has been singled out as key. Although other factors play important roles, the number of years of a girl's or woman's education, on average, varies inversely with the number of children she will have (*108*–*110*).

Making education for girls and women an ambitiously pursued international policy is laudable in itself as well as pivotal for the future of the global population. The importance of female education can be illustrated by a striking statistic from Africa. African women with no education have, on average, 5.4 children; women who have completed primary school have 4.3 children, and a big drop, to 2.7, correlates with completion of secondary school; for those who go on to college, fertility is 2.2 (*59*). These figures signal that ensuring educational opportunities for girls and women can move the world more swiftly toward a smaller population. Indeed, achieving full gender equality would, in all likelihood, eventually lead to global fertility below—and possibly well below—the replacement value of roughly 2.1 children. Such a development could result in a population trajectory even lower than the United Nations' "low variant" projection, which suggests a population peak at 8.7 billion in mid-century (*111*).

As women achieve full equality and fertility declines follow, societies tend to move through a period where the elderly population becomes large relative to the active workforce. This may present challenges for public pensions and healthcare programs (*98*). But these challenges are tractable (*112*), and when they arise they are best faced directly rather than by reverting to pronatalist policies. Each country will need to address potential problems accompanying an aging population according to its specific economic, social, and cultural circumstances. General approaches include encouraging higher savings rates, extending the retirement age, raising taxes, and shifting to governmental food policies that support longer but also healthier and more productive lives. Additionally, in a century where substantial movements of people are all but certain in response to environmental degradation and climate change, as well as economic dislocation and conflict, negative population growth in developed nations could encourage greater tolerance toward immigration allowances and thus less political upheaval around this sensitive issue (*113*). At the same time, by prioritizing strategies for slowing or ending population growth in rapidly growing countries, the resulting economic and environmental dividends (*114*) will counter pressures on people to emigrate.

Pursuing policies that will create conditions encouraging the deceleration of the global population will alone not suffice to stave off biodiversity destruction and other pressing ecological problems. Addressing excessive consumption worldwide calls for such actions as pursuing efficiency gains and conservation in energy and materials use; shifting from fossil fuels to renewable

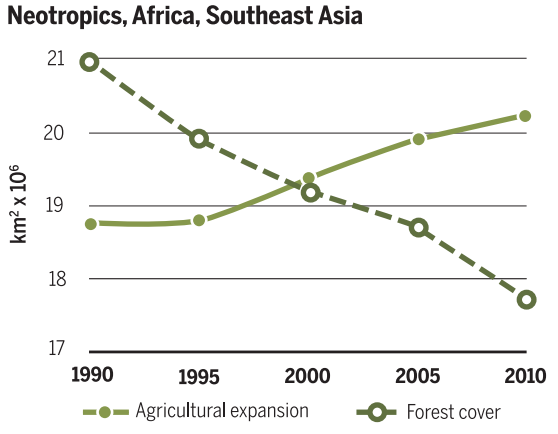

Fig. 3. Agricultural expansion and declines in forest cover (1990–2010) in primate range regions. Sixty percent of primate species are threatened with extinction and 75% have declining populations. [Source: (*69*); original data source: FAOSTAT.]

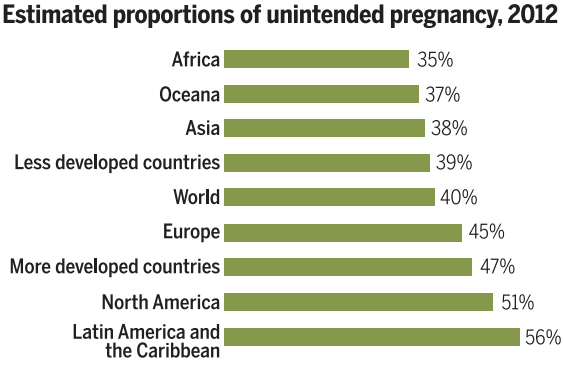

Fig. 4. Estimated proportions of unintended pregnancies (those not planned or wanted by the pregnant women in the next 2 years or longer) vary from one-third to more than one-half worldwide. Source: (*105*).

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energy; reducing extractive industries while advancing recycling; drastically reducing waste, including food waste; drastically reducing the production of throwaway and rapidly obsolescing products; abolishing destructive subsidies such as those that encourage fossil fuel production and overfishing; and shrinking the production and consumption of ecologically costly foods, especially animal products. Additionally, in most immediate terms, saving Earth's remaining biodiversity requires international willingness to considerably expand terrestrial and marine protected areas, as well as to institute stricter laws, enforcement, and surveillance of natural areas so as to protect species everywhere from the current poaching epidemic and from unregulated (and often illegal) industrial fishing.

The size of the human population is not the only variable stressing Earth. But it is a powerful force that is also eminently amenable to change, if the international political will can be mustered. Scientific willingness to engage with this issue will contribute to raising public awareness and helping to shift policies (*11*, *115*). In our efforts to halt the extinction crisis and to bequeath a biodiverse planet to future generations, willingness to marshal the resources and deploy proven tactics to address the population question is crucial.

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