Biodiversity & Environmental Sustainability amid Human Domination of Global Ecosystems

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Abstract: Concern about the loss of Earth's biological diversity sparked two decades of research of unprecedented intensity, intellectual excitement, and societal relevance. This research shows that biodiversity is among the most important factors determining how ecosystems function. In particular, the loss of biodiversity decreases the productivity, stability, and efficiency of terrestrial, freshwater, and marine ecosystems. These research findings come at a time of rapidly increasing threats to global biodiversity resulting from agricultural land clearing, climate change, and pollution caused by globally accelerating demand for food and energy. The world faces the grand, multifaceted challenge of meeting global demand for food and energy while preserving Earth's biodiversity and the long-term sustainability of both global societies and the ecosystems upon which all life depends. The solutions to this challenge will require major advances in, and syntheses among, the environmental and social sciences.

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The existence of life is the defining feature of Earth, and diversity is the most striking aspect of life on Earth. Since the origins of life three billion years ago, the biological diversity of life, or its *biodiversity*, has been on an upward but jagged trajectory along which the formation of new species has exceeded, with but few exceptions, the loss of existing species. The exceptions were major extinction events, attributable to catastrophic occurrences such as meteor impacts and globally massive volcanic activity. Earth now has on the order of five million species, all descended from the same ancestor. This biodiversity has been an enduring source of wonderment and scientific mystery from the era of great naturalist-explorers, such as Darwin and Wallace, to the present.

Earth also has seven billion people who, in meeting their needs for food and energy, have become a globally dominant force affecting Earth's ecosystems and threatening their biological diversity. The

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rapid acceleration in human global impacts through land-clearing and the destruction of natural habitats, fossil fuel combustion and climate change, nutrient pollution, and other activities has led to projections that humanity may be in the process of causing species extinctions at a rate rivaling some of the largest extinction events found in the fossil record.[1] These projections have raised a series of questions and concerns, the most fundamental of which are: What caused the evolution of Earth's amazingly great biodiversity? Does the loss of this biodiversity matter? Are there practices that could consistently and stably sustain the habitability of Earth while meeting the food, energy, and other needs and demands of the nine to ten billion people who will populate the planet by mid-century? If such practices are discovered, what policies, ethics, or approaches could lead to their global adoption?

The first question, on the origins of biodiversity, has been a mainstay of evolutionary research at least since Darwin. The question of whether biodiversity loss really matters was first raised in the 1980s. By the mid-1990s, it had ignited a wave of ecological research of unprecedented intensity, intellectual excitement, controversy, and societal relevance. In so doing, it helped transform the discipline of ecology into a more mechanistic and predictive science in which hypotheses are tested against the outcomes of multiple field experiments; observations in multiple ecosystems, both natural and those experiencing human impacts; and the predictions of alternative mathematical theories.

In this essay, I consider the biodiversity revolution and its aftermath by summarizing its major discoveries, controversies, and resolutions. The scientific revolution that has occurred, as remarkable as it has been, is only the initial step toward the discoveries that are needed if society is to achieve greater environmental sustainability as well as ensure full and equitable lives for all peoples. Some of the major mysteries that remain are discussed later in the essay; as is always the case in science, many more mysteries await their discovery.

I also address social and cultural issues that arise from the application of new scientific knowledge to society. These are perhaps the greatest challenges because advances in scientific knowledge can contribute to achieving societal goals only if the knowledge is accepted and adopted by society. How, though, is this done? The ethical precepts, laws, and customs of a society are the result of hundreds to thousands of years of often-slow cultural evolution. What would or could motivate the rapid changes in customs, laws, and ethics that may be needed now that human activities have become the dominant global force affecting how ecosystems function?

In 1958, Charles Elton, the great Oxford ecologist, hypothesized that stability is greater in ecosystems containing a diverse set of species. He worked in the style of ecological research that was popular in his day, undertaking qualitative comparisons of habitats that differed in their diversity: species-rich meadows versus nearby monocultures of crop plants, for example, or isolated and depauperate islands versus highly diverse mainland communities. He further suggested that habitats with high biodiversity are less susceptible to invasion by exotic species. A century earlier, Darwin had indicated that greater plant diversity is associated with greater primary productivity, but this insight lay dormant until rediscovered in 1993 by Sam McNaughton.[2]

At about the same time that Elton was carrying out his research, G. E. Hutchinson, the noted aquatic ecologist at Yale, observed how paradoxically high the

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diversity of many ecosystems seems to be.[3] Then-current mathematical theory predicted that the number of coexisting species should be no greater than the number of distinct resources for which the species compete. In contrast, even in seemingly simple habitats such as the well-mixed open waters of lakes and the oceans, the number of coexisting species of algae was often an order of magnitude greater than the number of limiting nutrients for which they competed. Hutchinson's paradox sparked my fascination with biodiversity. I dedicated the first two decades of my career to understanding how species compete with each other, and how and why such competitive interactions so often lead to the coexistence of many species rather than to domination by one or a few species.

Elton's ideas flourished for a decade or two, only to be put aside as the discipline began to develop a tradition of experimental, observational, and theoretical research. Scientists now sought the mechanistic construction of a species-based understanding of the dynamics of multispecies communities and ecosystems. New theory played a pivotal role in this transition. Robert May, the brilliant physicist-turned-ecologist from Princeton and, later, Oxford, presented elegant mathematics showing that the stability of communities of competing species declines as communities become more diverse.[4] May's mathematical demonstration that the dynamics of individual species become less stable at higher biodiversity led to debate on how diversity affects the stability of natural ecosystems. After reviewing more than two hundred papers on the issue, Daniel Goodman criticized the superorganismal perspectives then in vogue in ecosystem ecology and concluded that Elton's diversity-stability hypothesis was not supported by a preponderance of evidence.[5]

By 1973, when the second edition of his book *Diversity and Stability in Model Ecosystems* was published, May suggested an alternative resolution to the debate – that ecosystem properties might grow more stable with diversity even as population stability declined – but his insight was overlooked. Indeed, for the next two decades, most ecologists, myself included, considered diversity of little relevance to stability or other ecosystem processes. Then-current research, much of it performed with well-replicated field experiments, focused on the mechanisms of interaction among a few species and on how the traits of each species influence the dynamics and outcome of interactions among those species. Higher-level questions about how the number of interacting species might have an impact on the functioning of ecosystems were set aside while ecologists worked to transform the field into a more mechanistic and predictive science.

During this period, a few scholars continued to study biodiversity. In 1981, Paul and Anne Ehrlich, evolutionary ecologists at Stanford, published their book *Extinction: The Causes and Consequences of the Disappearance of Species*. They raised concern about how human activities are threatening global biodiversity and how loss of this biodiversity could harm the functioning of ecosystems and the services they provide to society. Edward O. Wilson, the Harvard evolutionary biologist, also wrote extensively on this issue and was awarded a Pulitzer Prize for his 1992 book, *The Diversity of Life*. The work of the Ehrlichs, Wilson, Peter Raven, Sam McNaughton, Stuart Pimm, and others had so elevated global concerns about the loss of biodiversity that the United Nations convened an "Earth Summit" in Rio de Janeiro in 1992. This gathering led to the international Convention on Biological Diversity.

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Shortly afterward, Hal Mooney and Detlef Schulze organized a small meeting of ecologists to synthesize and evaluate how the functioning of ecosystems might depend on biodiversity. The supporting evidence, though scattered and scant by the standards of the discipline, was sufficient to reignite my interest in this question as well as the interest of almost everyone else who attended the meeting. The resulting edited book presented intriguing concepts suggesting that ecosystem functioning could be linked to biodiversity.[6]

Once rejected, an idea rarely regains traction in science because its seeming flaws are well known. Yet two papers published in *Nature* in 1994 reopened debate over the diversity-stability hypothesis. The first, "Biodiversity and Stability in Grasslands," explored how the stability of grassland plant communities in response to a major drought depends on plant diversity.[7] John Downing and I had approached these data with more than our usual level of scientific skepticism. We tried hundreds of different analyses, each aimed at rejecting the hypothesis that greater plant diversity leads to greater ecosystem stability. We instead found that every analysis supported that hypothesis. Results from more than two hundred plots showed that stability, measured as resistance to the effects of a major disturbance, is a sharply and significantly increasing function of plant diversity. In particular, during the drought, the productivity of grassland plots containing one to three species fell to about one-tenth of predrought levels, whereas plots containing fifteen to twenty-five species had their productivity fall to only about half of their predrought levels. Three months later, Shahid Naeem and collaborators published the paper "Declining Biodiversity Can Alter the Performance of Ecosystems," which reported that simpler and less diverse laboratory food webs are less productive than those that are more diverse.[8] By 1997, several papers had reported similar effects of plant diversity on primary productivity based on well-replicated biodiversity experiments performed in field conditions.[9]

As should occur in science whenever evidence seems to challenge current ideas, this growing body of evidence was met with skepticism. In the first paper to question the apparent effects of plant biodiversity on primary productivity, Michael Huston raised doubts about the ability of the experiments to reject an alternative cause called *sampling effects*.[10] He presented the intriguing hypothesis that the effects come not from diversity per se, but from the greater probability that a highly productive plant species would be present at higher diversity. If the productivity of a plot is determined mainly by the growth of its most productive species, Huston reasoned, then the greater productivity observed in higher diversity plots might merely mean that they have a greater chance of containing a highly productive species. That same year, David Wardle and collaborators published a study of a set of small islands showing that island productivity is more dependent on fire frequency and other factors than on plant biodiversity.[11] Next, in their paper "The Statistical Inevitability of Stability-Diversity Relationships in Community Ecology," Dan Doak and collaborators offered an alternative hypothesis to explain the apparent effect of diversity on ecosystem stability.[12]

The biodiversity revolution was under way, and what ensued was more than a decade of discovery characterized by numerous rounds of debate and resolution driven by the interplay of experimental results, novel analyses, theoretical predictions, and observations in natural ecosystems. Ecology, as a science, had come of age. Of all the grand debates that have occurred in ecology, the biodiversity debate

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was the first to be so thoroughly tested via the interplay of numerous focused experiments, new theory, and quantitative field observations. One after another, novel hypotheses were proposed, tested, modified, and synthesized as more than one hundred different biodiversity experiments were performed around the world. This large number of experiments opened up ecology to meta-analysis, a new tool that greatly contributed to the biodiversity synthesis.[13] As this occurred, it became increasingly clear that the loss of biodiversity has many more and larger impacts, some via newly discovered pathways, on ecosystem functioning than had ever been envisioned. An idea cast aside in the 1970s had turned into one of the most highly studied and well-understood concepts of ecology.

The evidence that led to a new biodiversity paradigm came from a confluence of results of experiments and theory.[14] To provide a flavor of this work, and especially its findings, I briefly summarize five types of ecological processes that are now known to be affected by the loss of biodiversity.

Productivity. The growth of plants provides the "primary productivity" that is the basis of all ecosystem functions. Experiments have shown that, on average, plots planted with highly diverse mixtures of plant species annually produce about 70 to 100 percent more aboveground biomass – that is, they have greater primary productivity – than plots planted with monocultures of these same species.[15] The positive effect of plant diversity on ecosystem productivity has been observed in ecosystems ranging from temperate grasslands[16] to tropical, Mediterranean, and boreal ecosystems.[17] In experiments in which fish species diversity was manipulated, treatments with greater numbers of fish species produced more fish biomass.[18]

Most of these biodiversity experiments, though, lasted only one or two years. The few long-term experiments that have been done reveal that the initial effects of biodiversity on productivity increase through time.[19] For instance, results from the longest-running biodiversity experiment, which my collaborators and I established in Minnesota in 1994, show that the annual biomass production of the highest-diversity plots (those planted with sixteen species) increased through time much more than the average biomass of the same sixteen species growing in monocultures. In particular, in the third and fourth years of the experiment, the high-diversity plots had, on average, 92 percent greater production than the monocultures. This figure increased to 157 percent by years 8 and 9, and to 190 percent by years 17 and 18, which are the source of our most recent data.

Stability. The stability of an ecosystem process is a measure of the constancy of the process in response to disturbance. Greater ecosystem stability thus means that the process is better buffered and less variable. Natural and managed ecosystems experience a wide variety of intensities and types of perturbations: climatic variation (cool or warm and/or wet or dry periods); disease or pest outbreaks, fire, erosion, landslides and other physical disturbances; and shifts in the structure of food chains, such as from loss of top predators. Long-term biodiversity experiments have provided direct tests of the dependence of ecosystem stability on plant diversity. For instance, year-to-year variation in annual biomass production was lower in higher-diversity plots in both a European grassland experiment and our Minnesota grassland biodiversity experiment,[20] showing that higher diversity leads to greater stability of primary productivity in systems experiencing year-to-year climate variation. Similarly,

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observational studies show that the stability of the productivity of marine fisheries is higher in those fisheries that have greater fish species diversity, and that greater numbers of genetic varieties of wheat lead to less variation in yields as well as higher yields.[21]

Disease. Most pathogens and disease are specific to one or a few species. As a result, the rate of disease transmission from an infected individual to a susceptible individual of the host species is proportional to the population density of the host. This fundamental principle of epidemiology suggests that the incidence of disease for a given host species should decline when the host species is living in a more diverse community. Because each plant species would be less abundant than in monoculture, the incidence of species-specific plant diseases should, on average, decline as plant diversity increases. This expectation is supported by results of numerous biodiversity experiments. For instance, fungal pathogens that grow on the surfaces of leaves are much less abundant at higher plant diversity.[22] Transmission rates for diseases of many other types of species, including amphibians, corals, fish, and birds, are similarly lower when the biodiversity of the host community is greater.[23]

Resistance to Invasion. Charles Elton's observations (discussed above) led him to suggest that more diverse ecosystems are less easily invaded by exotic species. Biodiversity experiments have provided broad support for this hypothesis. An experiment in which seeds of numerous nonresident plant species were added to plots in a biodiversity experiment that differed in both their species numbers and their functional group compositions showed two marked effects. First, the added species were less likely to invade not only when the diversity of the established plant community was high but also when the invading species were functionally similar to established abundant species. Additional work shows that the major factor inhibiting invasion is low availability of the limiting soil nutrient, and that more diverse plant communities reduce soil nutrient concentrations to lower levels.[24]

Biodiversity and Agriculture. Four crops – maize, wheat, rice, and soybeans – provide about 80 percent of the food calories consumed globally. Because of the rapidity with which crop pathogens and pests evolve and overcome plant defenses, the sustainability of these crop yields is highly dependent on continued breeding for resistance to the latest varieties of pathogens and pests. For instance, "IR8," the rice variety that began the Green Revolution in Asia in 1967, had its yield fall 24 percent over the subsequent thirty years because of pathogens and pests. Nine subsequent rice varieties had their yields decline by similar rates after their introductions.[25] For crop breeding to stay ahead of pests and pathogens, breeders must have an immense storehouse of genetic variants, at least some of which are resistant to emerging pathogens and pests. Even more genetic diversity is needed to find new genetic combinations that increase crop yields. Thus, although most such crops are grown as monocultures (and perhaps particularly because they are grown in such a way), genetic diversity is of great economic and societal value.

Biodiversity can be used as a tool to increase crop yields in some situations.[26] For instance, Youyong Zhu and collaborators found that growing two varieties of rice in alternating sets of rows (a practice called *intercropping*) greatly decreases incidence of a significant fungal pathogen that attacks a highly valued variety but to which the second variety is resistant. Long Li and collaborators observed that intercropping of faba beans and maize increases maize yields by 40 percent and

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faba bean yields by 25 percent; they also found that this over-yielding is caused by differences in the rooting depths and seasonality of growth of two crops, as well as by faba beans' ability to mobilize otherwise unavailable phosphorus. While many crop combinations do not over-yield, Li reports that combinations that do over-yield are planted on 28 million hectares in China. Intercropping is rarely practiced in Western nations today, but its ability to increase yields in particular cases might offer benefits (although intercropping also introduces a number of challenges for mechanized agriculture that need to be solved).

After the initial experimental demonstrations that biodiversity affects numerous aspects of ecosystem functioning, attention shifted to why biodiversity matters. The first discussions centered on the role that sampling effects might play versus the importance of niche differences among species. Application of a variety of increasingly sophisticated analytical techniques has shown that sampling effects (later called *selection effects*) are generally unimportant and that niche differentiation effects (also called *complementarity*) are the predominant cause. This finding was especially evident in instances where species had several years to interact and thus the effects of their interactions were well established.

The understanding of why biodiversity matters was also illuminated by mathematical theory. In particular, a sequence of papers showed that when competing species have trade-offs in their traits that allow them to coexist stably, the net result is that ecosystem stability and productivity increase with diversity.[27] In addition, more diverse ecosystems reduce limiting resources to lower levels, both contributing to their greater productivity and reducing the abilities of other species to invade, as an invading species would have to survive and grow on the resources left unconsumed by established species.

Two hypotheses have received increasingly robust support from biodiversity experiments. First, species coexist with other competing species precisely because the species have trade-offs; any trait that increases the ability of individuals in a species to deal with one limiting factor must necessarily make them less able to deal with some other limiting factor.[28] Second, changes in biodiversity have consistent and predictable impacts on many aspects of ecosystem functioning; the trade-offs among the species that share a habitat mean that larger numbers of these species will, on average, be better at dealing with limiting factors in that habitat. Thus, the very processes that have allowed Earth to accumulate such a large number of species also mean that greater diversity would affect ecosystem functioning in exactly the ways that have now been observed experimentally.

An important corollary of "biodiversity matters" is that "species matter." This point has arisen repeatedly, both from results of biodiversity experiments and from ecological theory. An important demonstration of the "if diversity matters, species must matter" hypothesis was offered by Anthony Ives, Kay Gross, and Jennifer Klug, who showed theoretically that ecosystem stability depends not on the number of species per se, but on the differences among the species.[29] Because multiple competing species can stably coexist only if they have trade-offs in their traits, the biodiversity of an ecosystem (when enumerated by the simple metric of the number of species present) affects ecosystem processes precisely because the species differ from each other.

Human well-being is highly dependent on nature. The total land surface of Earth

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is 13 billion hectares, of which 4 billion hectares are in the Arctic or Antarctic, or are desert or tundra. The vast majority of the remaining 9 billion hectares is heavily used by people, with about 5 billion hectares serving as agricultural lands, roughly one-fourth of which is farmed and the rest used for livestock production. Much of the remaining land is forested, with about 1.5 billion hectares being actively managed for tree production globally. Thus, two of humanity's most essential needs – food and shelter – are directly dependent on the productivity and stability of about 75 percent of Earth's usable lands. Moreover, because greenhouse gases are released from fossil fuel combustion, there is increased interest in also using land to produce biomass for conversion into biofuels with low greenhouse gas emissions.

Society depends on nature not only for goods such as food, timber, and energy, but also for a variety of ecosystem services.[30] We need potable water, a resource that is produced by intact grassland and forest ecosystems, and that is harmed by some agricultural and industrial activities. Intact ecosystems minimize flooding; they are a major storehouse of organic carbon that would otherwise be released into the atmosphere as carbon dioxide (CO_2) if the land were cleared; they create the fertile soils on which agricultural productivity depends.

One of the great challenges facing humanity is to find ways to meet its needs for food, timber, energy, and other goods while maintaining the ability of managed and natural ecosystems to provide vital ecosystem services. Discovery and adoption of better management practices will be essential to optimizing the production of goods and ecosystem services from managed lands, and thus increasing the long-term sustainability of the full range of goods and services that people need. It seems likely that biodiversity may play a central role in achieving greater sustainability, but this is a hypothesis in its infancy. The fate of this hypothesis – and of global biodiversity – is at present uncertain.

The next fifty years are likely the final period of rapid expansion in human population and consumption. Global population, which had increased 270 percent in the twentieth century, is likely to increase from its current seven billion people to about nine or ten billion, a 35 percent change, by the middle of this century, at which point global population growth may halt. This astounding population increase, though, is small compared to the increases in per-capita global consumption (measured as per-capita Gross Domestic Product) across this same time period. During the twentieth century, the real (inflation adjusted) buying power of a typical person increased by 360 percent, and it is projected to increase by about 150 percent during the next fifty years as the peoples of many developing nations gain "middle class" incomes.

The double-whammy of greatly increased population and even more greatly increased consumption per individual has already turned humans from being one of many species on Earth to being the dominant force affecting all ecosystems. Moreover, human environmental impacts are likely to double or triple by mid-century because of the anticipated global increases in both per-capita consumption and population size.[31] To meet an estimated doubling in global demand for food may require that about 1 billion hectares of tropical forest and grasslands be cleared for crop production and that agricultural fertilization, which can cause serious water pollution, increase about 170 percent. Land-clearing leads to the loss of biodiversity and is a major source of greenhouse gas release. Moreover,

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agriculture itself accounts for about 37 percent of total human-caused greenhouse gas releases, and such releases would more than double as food demand doubled. In comparison, all forms of transportation combined account for only 20 percent of global greenhouse gas emissions.

Global energy demand is increasing at least as rapidly as is food demand, and most of this increased demand is being met by the combustion of fossil fuels. The net result of these food and energy trajectories will be major climate changes, the irreversible loss of a significant portion of Earth's biodiversity, and greatly decreased provisioning of numerous vital ecosystem services. Although there are insights to be gained from articulating the environmental problems that human activities are causing, it is even more important to find solutions.

The science, social science, and business of sustainability are all in their infancy. What we see now is the embryo of an unknown organism. Its development will be guided by the creativity and careers of the next generation. In that spirit, I offer a few thoughts about the challenges and possibilities ahead as we seek viable solutions.

Efficiency. The expanding human domination of the globe will affect biodiversity, climate, and numerous ecosystem services largely in terms of increased demand for food and energy. There are two equally important types of solutions to this problem. The first type focuses on decreasing demand for food and energy, and the second on meeting these demands in ways that lessen environmental impacts. Demand can be reduced by increases in efficiency. Energy efficiency is a familiar topic, but food efficiency is not. About a quarter to a third of global food production is wasted, with the causes of this wastage differing among societies. The major reason why a projected 35 percent increase in global population is expected to cause a 100 to 110 percent increase in global demand for crops is that per-capita meat consumption increases with income, and each kilogram of meat protein requires that livestock be fed from 3 to 20 kilograms of crop protein. This range in values occurs because animals differ greatly in the efficiency with which they convert grain protein into edible animal protein, with farm-raised fish being about eight times more efficient than cattle, and poultry being about four times more efficient than cattle. Direct human consumption of grain protein is even more efficient. Dietary shifts toward non-livestock proteins would provide environmental benefits, as would advances in the efficiencies with which livestock convert feed into meat. Thus, there are contributions to be made toward achieving greater environmental sustainability across disciplines as divergent as the culinary arts (via the creation of delicious but environmentally efficient entrées) and animal nutrition.

Lessening the Impacts. Modern societies are highly dependent on energy. The three greatest impacts of fossil fuel combustion come from the release of greenhouse gases (which cause climate change), of fine particulate matter (which causes respiratory problems and increases mortality), and of mercury (which causes health problems). Wind and solar power are alternatives that reduce these impacts, but adoption of these technologies has been slow because of challenges related to cost and reliability. Almost all current vehicles require liquid fuels. Electric vehicles may be the solution, but in order to achieve meaningful deployment, advances in battery technology must be made that would increase mileage range to somewhere between three hundred and five hundred miles.

Air transport may always depend on liquid fuels. The challenge is to create liquid fuels that are greenhouse gas neutral and that do not compete with food crops

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for fertile land. If biofuels did compete for fertile land, their greenhouse gas benefits would likely be eliminated because of the greenhouse gas emissions associated with additional land-clearing to meet global food demand. Or, even worse, escalating food prices might harm the diets of the world's poorest people, in effect having airplanes and vehicles outcompete the already malnourished poor for food.

Using, Not Losing, Biodiversity. Biodiversity might provide a solution for this problem. Consider an as-yet untested possibility: the production of carbon-negative biofuels. As already mentioned, biomass production can be increased by 70 to 200 percent when highly diverse mixtures of species are planted. The greatest reported yield increases are from the diverse mixtures of native plants that my collaborators and I have grown in Minnesota on highly degraded soils that were no longer suitable for agriculture.[32] Although we observed no detectable increase in soil carbon and nitrogen stores for the monoculture plots, the highest diversity plots removed from the atmosphere and stored as soil organic carbon about 4.4 tons of CO_2 per hectare per year. As we reported in the paper "Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass," this biomass could be used to produce liquid transportation fuels that are carbon-negative. Because of carbon sequestration in the degraded soils, we calculated that the net effect of growing the biomass, making the fuels, and combusting the fuels would be a reduction in atmospheric CO_2. This possibility, though, is yet to be pursued.

Biodiversity might also help us better meet growing demand for food and forest products. The research showing that more diverse fisheries are more productive suggests that we might be able to harvest more seafood from aquaculture operations that have the right combination of competing or facilitating species. Similarly, the 1.5 billion hectares of managed forests may yield more timber and other forest products if they are planted to the right mixtures of tree species. Again, these possibilities have never yet been pursued commercially, much less globally.

Mysteries and Paradoxes. The path toward achieving environmental sustainability is filled with mysteries and paradoxes. Mysteries motivate science, leading to advances in fundamental science and technological breakthroughs. Although I have focused on such scientific advances in this essay, we also need fundamental advances in our understanding of ourselves. Humans are unique among all species in how dependent our welfare is on culturally transmitted knowledge. Our lives depend on knowledge accumulated during the ten thousand–year history of agriculture and on advances in public health, civil engineering, and medicine. We are now so highly dependent on knowledge that many people dedicate the first twenty-five to thirty years of their lives to obtain the knowledge needed for a professional career. The pursuit of such training by women and men is perhaps the most important force that is causing global population growth to slow.

Human behavior, though, is often confused or even paradoxical. Why do so many members of the most knowledge-dependent species on Earth act in ways that ignore, or even deny, knowledge? Why do individuals refuse to accept modern scientific knowledge as relevant or even as valid? At the same time that medical science has shown that healthy diets and active lifestyle can extend lives by a decade, people around the world are becoming more overweight and more inactive than ever before. People complain about the high cost of gasoline and yet preferentially buy expensive vehicles that have low fuel efficiency. People whose lives

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have been saved by novel antibiotics that overcame drug resistance that had evolved in a pathogen often deny the existence of evolution. Others deny climate change.

I do not make these points to disparage anyone, and I deeply value intellectually honest skepticism on any topic. Rather, I mention them because the environmental issues that Earth faces are problems generated by humanity. So, too, must it be humanity that discovers and embraces the solutions. This effort will require that we learn more not just about the environment but also about ourselves. I can imagine no issue more worthy of pursuit than the grand, multifaceted challenge of helping society live sustainably on Earth.

ENDNOTES

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