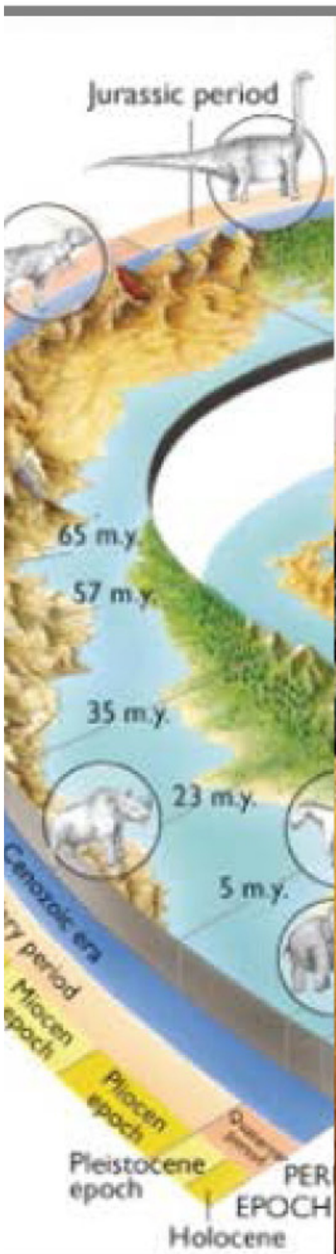
Living In The
Anthropocene




20 YEARS

DEPARTMENT *of* ENVIRONMENTAL
SCIENCE, POLICY, AND MANAGEMENT

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PREFACE

20 YEARS
DEPARTMENT of ENVIRONMENTAL SCIENCE, POLICY, AND MANAGEMENT

This year we will celebrate the 20th anniversary of the Department of Environmental Science, Policy and Management at the University of California, Berkeley by hosting lectures and discussions that pertain to the theme of “Living in the Anthropocene.” Admittedly, thinking about how to live in the Anthropocene is a challenge, given that 20 years ago the term and the concept itself had yet to be articulated and conceived. However, if there is one point of agreement among scientists and those in many other professions, it is that humans are a force to be reckoned with, and what we chose to do will in turn determine our own future, and that of much of the Earth’s biota.

The choices in this reader follow and amplify the arc of the seminars that will be presented in our Spring 2014 ESPM seminar series: putting humans in a geologic perspective, considering the challenge of what the pre-Anthropocene world was like, the biodiversity and sustainability issues that face us this century, and the complex challenges we face in discussing and communicating possible solutions. The choices here are by no means complete, but are at least a road marker of where we are in 2014.

We prepared the reader to also highlight the great science journalism that is currently being published in an array of magazines and newspapers. These writers not only distill the essence of the science they write about, but add an essential layer of analysis that helps the non-science reader (and scientists as well) sort through the cacophony of voices and opinions that populate these issues.

The first chapter outlines the concept of geological time, a history of Earth where the boundary between one geological period and another is commonly marked by catastrophic environmental change and mass extinction. In that spirit, ESPM’s mission is to help us live within, and maintain, a very long, and very prosperous, epoch of human beings.

Long live the Anthropocene.

- Ronald Amundson, Department Chair

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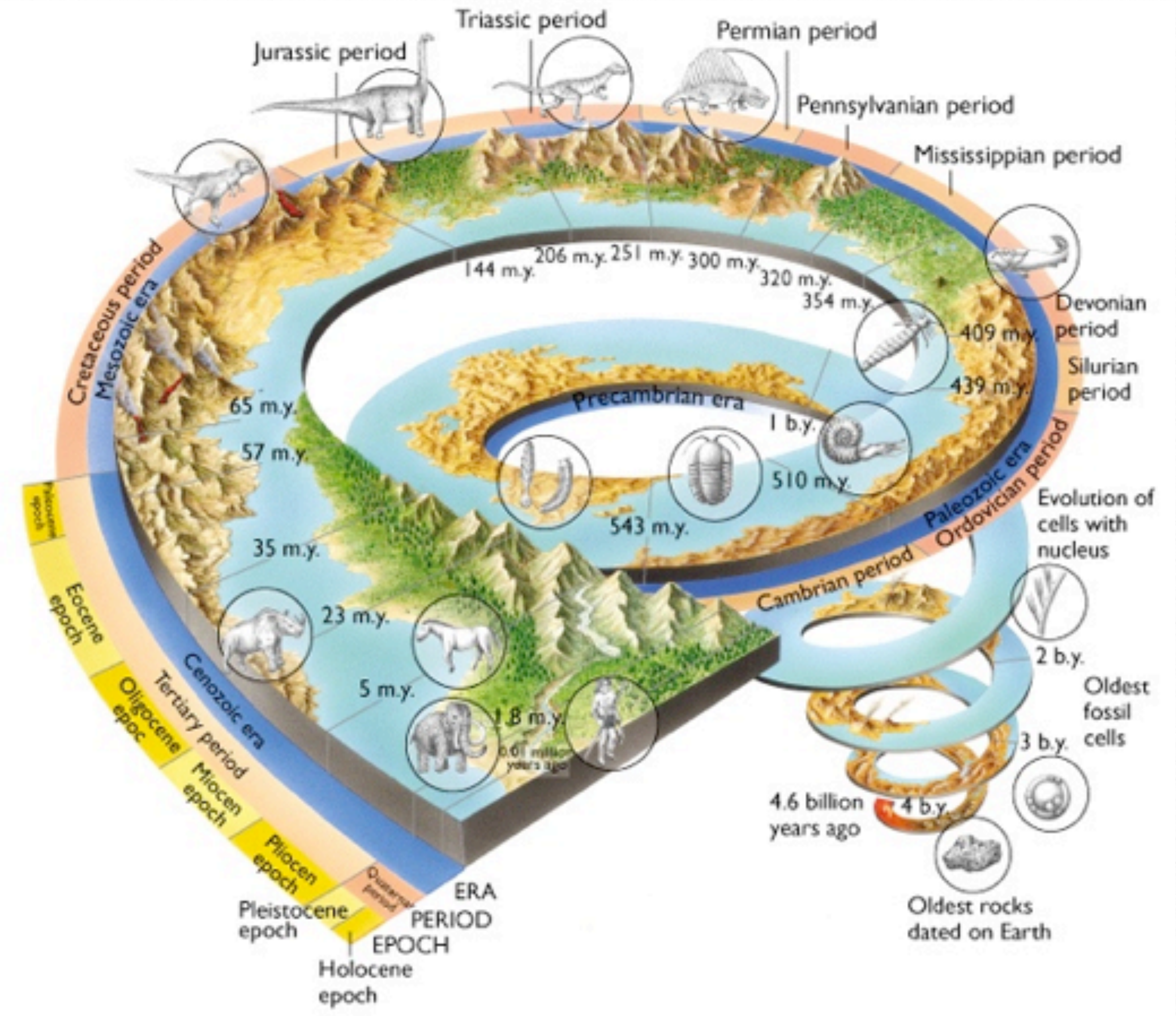
Telling Time Like a Geologist



Deep Time

Stephen Jay Gould

Sigmund Freud remarked that each major science has made one signal contribution to the reconstruction of human thought—and that each step in this painful progress had shattered yet another facet of an original hope for our own transcendent importance in the universe:

"*Humanity has in course of time had to endure from the hand of science two great outrages upon its naive self-love. The first was when it realized that our earth was not the center of the universe, but only a speck in a world-system of a magnitude hardly conceivable . . . The second was when biological research robbed man of his particular privilege of having been specially created and relegated him to a descent from the animal world.*"

(In one of history's least modest pronouncements, Freud then stated that his own work had toppled the next, and perhaps last, pedestal of this unhappy retreat—the solace that, though evolved from a lowly ape, we at least possessed rational minds.)

But Freud omitted one of the greatest steps from his list, the bridge between spatial limitation of human dominion (the Galilean revolution), and our physical union with all "lower" creatures (the Darwinian revolution). He neglected the great temporal limitation imposed by geology upon human importance-the discovery of "deep time" (in John McPhee's beautifully apt phrase). What could be more comforting, what more convenient for human domination, than the traditional concept of a young earth, ruled by human will within days of its origin. How threatening, by contrast, the notion of an almost incomprehensible immensity, with human habitation restricted to a millimicrosecond at the very end! Mark Twain captured the difficulty of finding solace in such fractional existence:

"*Man has been here 32,000 years. That it took a hundred million years to prepare the world for him is proof that that is what it was done for. I suppose it is, I dunno. If the Eiffel Tower were now representing the world's age, the skin of paint on the pinnacle-knob at its summit would represent man's share of that age; and anybody would perceive that that skin was what the tower was built for. I reckon they would, I dunno.*"

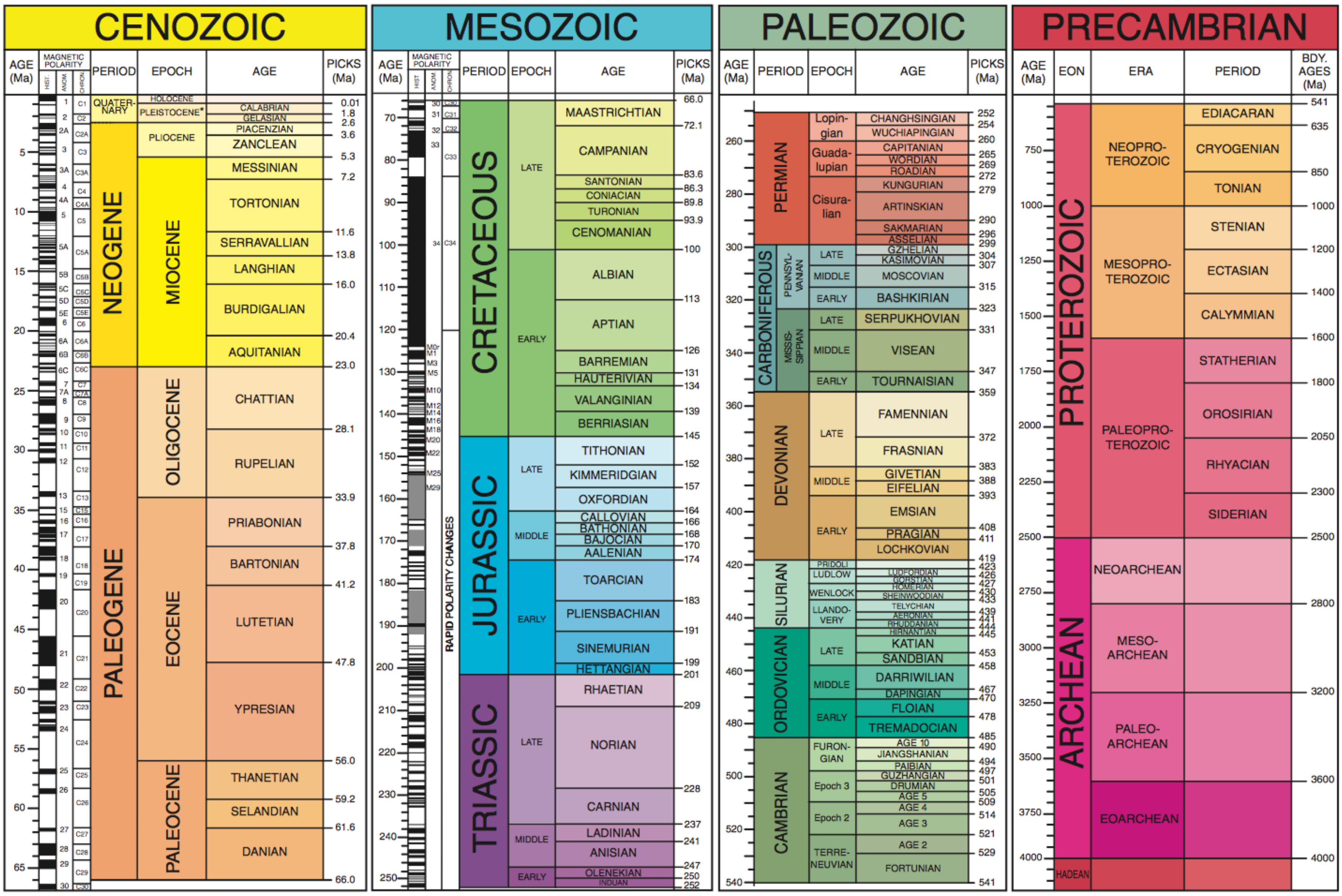
Charles Lyell expressed the same theme in more somber tones in describing James Hutton's world without vestige of a beginning or prospect of an end. This statement thus links the two traditional heroes of deep time in geology-and also expresses the metaphorical tie of time's new depth to the breadth of space in Newton's cosmos:
Such views of the immensity of past time, like those unfolded by the Newtonian philosophy in regard to space, were too vast to awaken ideas of sublimity unmixed with a painful sense of our incapacity to conceive a plan of such infinite extent. Worlds are seen beyond worlds immeasurably distant from each other, and beyond them all innumerable other systems are faintly traced on the confines of the visible universe.

Deep time is so difficult to comprehend, so outside our ordinary experience, that it remains a major stumbling block to our understanding. An abstract, intellectual understanding of deep time comes easily enough-I know how many zeroes to place after the 10 when I mean billions. Getting it into the gut is quite another matter. Deep time is so alien that we can really only comprehend it as metaphor. And so we do in all our pedagogy. We tout the geological mile (with human history occupying the last few inches); or the cosmic calendar (with Homo sapiens appearing but a few moments before Auld Lang Syne). A Swedish correspondent told me that she set her pet snail Bjorn (meaning bear) at the South Pole during the Cambrian period and permits him to advance slowly toward Malmo, thereby visualizing time as geography. John McPhee has provided the most striking metaphor of all (in Basin and Range): Consider the earth's history as the old measure of the English yard, the distance from the king's nose to the tip of his outstretched hand. **One stroke of a nail file on his middle finger erases human history.**

from:

Time's Arrow, Time's Cycle. Myth and Metaphor in the Discovery of Geological Time. Harvard University Press.

GSA GEOLOGIC TIME SCALE v. 4.0



*The Pleistocene is divided into four ages, but only two are shown here. What is shown as Calabrian is actually three ages—Calabrian from 1.8 to 0.78 Ma, Middle from 0.78 to 0.13 Ma, and Late from 0.13 to 0.01 Ma.

Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., compilers, 2012, Geologic Time Scale v. 4.0: Geological Society of America, doi: 10.1130/2012.CTS004R3C. ©2012 The Geological Society of America.

The Cenozoic, Mesozoic, and Paleozoic are the Eras of the Phanerozoic Eon. Names of units and age boundaries follow the Gradstein et al. (2012) and Cohen et al. (2012) compilations. Age estimates and picks of boundaries are rounded to the nearest whole number (1 Ma) for the pre-Cenomanian, and rounded to one decimal place (100 ka) for the Cenomanian to Pleistocene interval. The numbered epochs and ages of the Cambrian are provisional.

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REFERENCES CITED Cohen, K.M., Finney, S., and Gibbard, P.L., 2012, International Chronostratigraphic Chart: International Commission on Stratigraphy, www.stratigraphy.org (last accessed May 2012). (Chart reproduced for the 34th International Geological Congress, Brisbane, Australia, 5–10 August 2012.)

Gradstein, F.M, Ogg, J.G., Schmitz, M.D., et al., 2012, The Geologic Time Scale 2012: Boston, USA, Elsevier, DOI: 10.1016/B978-0-444-59425-9.00004-4.

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The World Before The Anthropocene

The Atlantic

BEFORE IT BECAME THE NEW WORLD, THE WESTERN HEMISPHERE WAS VASTLY MORE POPULOUS AND SOPHISTICATED THAN HAS BEEN THOUGHT—AN ALTOGETHER MORE SALUBRIOUS PLACE TO LIVE AT THE TIME THAN, SAY, EUROPE. NEW EVIDENCE OF BOTH THE EXTENT OF THE POPULATION AND ITS AGRICULTURAL ADVANCEMENT LEADS TO A REMARKABLE CONJECTURE: THE AMAZON RAIN FOREST MAY BE LARGELY A HUMAN ARTIFACT

By Charles C. Mann

The plane took off in weather that was surprisingly cool for north-central Bolivia and flew east, toward the Brazilian border. In a few minutes the roads and houses disappeared, and the only evidence of human settlement was the cattle scattered over the savannah like jimmies on ice cream. Then they, too, disappeared. By that time the archaeologists had their cameras out and were clicking away in delight. Below us was the Beni, a Bolivian province about the size of Illinois and Indiana put together, and nearly as flat. For almost half the year rain and snowmelt from the mountains to the south and west cover the land with an irregular, slowly moving skin of water that eventually ends up in the province's northern rivers, which are sub-subtributaries of the Amazon. The rest of the year the water dries up and the bright-green vastness turns into something that resembles a desert. This peculiar, remote, watery plain was what had drawn the researchers' attention, and not just because it was one of the few places on earth inhabited by people who might never have seen Westerners with cameras.

Clark Erickson and William Balée, the archaeologists, sat up front. Erickson is based at the University of Pennsylvania; he works in concert with a Bolivian archaeologist, whose seat in the plane I usurped that day. Balée is at Tulane University, in New Orleans. He is actually an anthropologist, but as native peoples have vanished, the distinction between anthropologists and archaeologists has blurred. The two men differ in build, temperament, and scholarly proclivity, but they pressed their faces to the windows with identical enthusiasm.

Dappled across the grasslands below was an archipelago of forest islands, many of them startlingly round and hundreds of acres across. Each island rose ten or thirty or sixty feet above the floodplain, allowing trees to grow that would otherwise never survive the water. The forests were linked by raised berms, as straight as a rifle shot and up to three miles long. It is Erickson's belief that this entire landscape—30,000 square miles of forest mounds surrounded by raised fields and linked by causeways—was constructed by a complex, populous society more than 2,000 years ago. Balée, newer to the Beni, leaned toward this view but was not yet ready to commit himself.

Erickson and Balée belong to a cohort of scholars that has radically challenged conventional notions of what the Western Hemisphere was like before

Columbus. When I went to high school, in the 1970s, I was taught that Indians came to the Americas across the Bering Strait about 12,000 years ago, that they lived for the most part in small, isolated groups, and that they had so little impact on their environment that even after millennia of habitation it remained mostly wilderness. My son picked up the same ideas at his schools. One way to summarize the views of people like Erickson and Balée would be to say that in their opinion this picture of Indian life is wrong in almost every aspect. Indians were here far longer than previously thought, these researchers believe, and in much greater numbers. And they were so successful at imposing their will on the landscape that in 1492 Columbus set foot in a hemisphere thoroughly dominated by humankind.

Given the charged relations between white societies and native peoples, inquiry into Indian culture and history is inevitably contentious. But the recent scholarship is especially controversial. To begin with, some researchers—many but not all from an older generation—deride the new theories as fantasies arising from an almost willful misinterpretation of data and a perverse kind of political correctness. "I have seen no evidence that large numbers of people ever lived in the Beni," says Betty J. Meggers, of the Smithsonian Institution. "Claiming otherwise is just wishful thinking." Similar criticisms apply to many of the new scholarly claims about Indians, according to Dean R. Snow, an anthropologist at Pennsylvania State University. The problem is that "you can make the meager evidence from the ethnohistorical record tell you anything you want," he says. "It's really easy to kid yourself."

More important are the implications of the new theories for today's ecological battles. Much of the environmental movement is animated, consciously or not, by what William Denevan, a geographer at the University of Wisconsin, calls, polemically, "the pristine myth"—the belief that the Americas in 1491 were an almost unmarked, even Edenic land, "untrammeled by man," in the words of the Wilderness Act of 1964, one of the nation's first and most important environmental laws. As the University of Wisconsin historian William Cronon has written, restoring this long-ago, putatively natural state is, in the view of environmentalists, a task that society is morally bound to undertake. Yet if the new view is correct and the work of humankind was pervasive, where does that leave efforts to restore nature?

The Beni is a case in point. In addition to building up the Beni mounds for houses and gardens, Erickson says, the Indians trapped fish in the seasonally flooded grassland. Indeed, he says, they fashioned dense zigzagging networks of earthen fish weirs between the causeways. To keep the habitat clear of unwanted trees and undergrowth, they regularly set huge areas on fire. Over the centuries the burning created an intricate ecosystem of fire-adapted plant species dependent on native pyrophilia. The current inhabitants of the Beni still burn, although now it is to maintain the savannah for cattle. When we flew over the area, the dry season had just begun, but mile-long lines of flame were already on the march. In the charred areas behind the fires were the blackened spikes of trees—many of them, one assumes, of the varieties that activists fight to save in other parts of Amazonia.

After we landed, I asked Balée, Should we let people keep burning the Beni? Or should we let the trees invade and create a verdant tropical forest in the grasslands, even if one had not existed here for millennia?

Balée laughed. "You're trying to trap me, aren't you?" he said.

Like a Club Between the Eyes

According to family lore, my great-grandmother's great-grandmother's great-grandfather was the first white person hanged in America. His name was John Billington. He came on the *Mayflower*, which anchored off the coast of Massachusetts on November 9, 1620. Billington was not a Puritan; within six months of arrival he also became the first white person in America to be tried for complaining about the police. "He is a knave," William Bradford, the colony's governor, wrote of Billington, "and so will live and die." What one historian called Billington's "troublesome career" ended in 1630, when he was hanged for murder. My family has always said that he was framed—but we *would* say that, wouldn't we?

A few years ago it occurred to me that my ancestor and everyone else in the colony had voluntarily enlisted in a venture that brought them to New England without food or shelter six weeks before winter. Half the 102 people on the *Mayflower* made it through to spring, which to me was amazing. How, I wondered, did they survive?

In his history of Plymouth Colony, Bradford provided the answer: by robbing Indian houses and graves. The *Mayflower* first hove to at Cape Cod. An armed company staggered out. Eventually it found a recently deserted Indian settlement. The newcomers—hungry, cold, sick—dug up graves and ransacked houses, looking for underground stashes of corn. "And sure it was God's good providence that we found this corn," Bradford wrote, "for else we know not how we should have done." (He felt uneasy about the thievery, though.) When the colonists came to Plymouth, a month later, they set up shop in another deserted Indian village. All through the coastal forest the Indians had "died on heapes, as they lay in their houses," the English trader Thomas Morton noted. "And the bones and skulls upon the severall places of their habitations made such a spectacle" that to Morton the Massachusetts woods seemed to be "a new found Golgotha"—the hill of executions in Roman Jerusalem.

To the Pilgrims' astonishment, one of the corpses they exhumed on Cape Cod had blond hair. A French ship had been wrecked there several years earlier. The Patuxet Indians imprisoned a few survivors. One of them supposedly learned enough of the local language to inform his captors that God would destroy them for their misdeeds. The Patuxet scoffed at the threat. But the Europeans carried a disease, and they bequeathed it to their jailers. The epidemic (probably of viral hepatitis, according to a study by Arthur E. Spiess, an archaeologist at the Maine Historic Preservation Commission, and Bruce D. Spiess, the director of clinical research at the Medical College of Virginia) took years to exhaust itself and may have killed 90 percent of the people in coastal New England. It made a huge difference to American history. "The good hand of God favored our beginnings," Bradford mused, by "sweeping away great multitudes of the natives ... that he might make room for us."

By the time my ancestor set sail on the *Mayflower*, Europeans had been visiting New England for more than a hundred years. English, French, Italian, Spanish, and Portuguese mariners regularly plied the coastline, trading what they could, occasionally kidnapping the inhabitants for slaves. New England, the Europeans saw, was thickly settled and well defended. In 1605 and 1606 Samuel de Champlain visited Cape Cod, hoping to establish a French base. He abandoned the idea. Too many people already lived there. A year later Sir Ferdinando Gorges—British despite his name—tried to establish an English community in southern Maine. It had more founders than Plymouth and seems to have been better organized. Confronted by numerous well-armed local Indians, the settlers abandoned the project within months. The Indians at Plymouth would surely have been an equal obstacle to my ancestor and his ramshackle expedition had disease not intervened.

Faced with such stories, historians have long wondered how many people lived in the Americas at the time of contact. "Debated since Columbus attempted a partial census on Hispaniola in 1496," William Denevan has written, this "remains one of the great inquiries of history." (In 1976 Denevan assembled and edited an entire book on the subject, *The Native Population of the Americas in 1492*.) The first scholarly estimate of the indigenous population was made in 1910 by James Mooney, a distinguished ethnographer at the Smithsonian Institution. Combing through old documents, he concluded that in 1491 North America had 1.15 million inhabitants. Mooney's glittering reputation ensured that most subsequent researchers accepted his figure uncritically.

That changed in 1966, when Henry F. Dobyns published "Estimating Aboriginal American Population: An Appraisal of Techniques With a New Hemispheric Estimate," in the journal *Current Anthropology*. Despite the carefully neutral title, his argument was thunderous, its impact long-lasting. In the view of James Wilson, the author of *The Earth Shall Weep* (1998), a history of indigenous Americans, Dobyns's colleagues "are still struggling to get out of the crater that paper left in anthropology." Not only anthropologists were affected. Dobyns's estimate proved to be one of the opening rounds in today's culture wars.

Dobyns began his exploration of pre-Columbian Indian demography in the early 1950s, when he was a graduate student. At the invitation of a friend, he spent a few months in northern Mexico, which is full of Spanish-era missions. There he poked through the crumbling leather-bound ledgers in which Jesuits recorded local births and deaths. Right away he noticed how many more deaths there were. The Spaniards arrived, and then Indians died—in huge numbers, at incredible rates. It hit him, Dobyns told me recently, "like a club right between the eyes."

It took Dobyns eleven years to obtain his Ph.D. Along the way he joined a rural-development project in Peru, which until colonial times was the seat of the Incan empire. Remembering what he had seen at the northern fringe of the Spanish conquest, Dobyns decided to compare it with figures for the south. He burrowed into the papers of the Lima cathedral and read apologetic Spanish histories. The Indians in Peru, Dobyns concluded, had faced plagues from the day the conquistadors showed up—in fact, before then: smallpox arrived around 1525, seven years ahead of the Spanish. Brought to Mexico apparently by a single sick Spaniard, it swept south and eliminated more than half the population of the Incan empire. Smallpox claimed the Incan dictator Huayna Capac and much of his family, setting off a calamitous war of succession. So complete was the chaos that Francisco Pizarro was able to seize an empire the size of Spain and Italy combined with a force of 168 men.

Smallpox was only the first epidemic. Typhus (probably) in 1546, influenza and smallpox together in 1558, smallpox again in 1589, diphtheria in 1614, measles in 1618—all ravaged the remains of Incan culture. Dobyns was the first social scientist to piece together this awful picture, and he naturally rushed his findings into print. Hardly anyone paid attention. But Dobyns was already working on a second, related question: If all those people died, how many had been living there to begin with? Before Columbus, Dobyns calculated, the Western Hemisphere held ninety to 112 million people. Another way of saying this is that in 1491 more people lived in the Americas than in Europe.

His argument was simple but horrific. It is well known that Native Americans had no experience with many European diseases and were therefore immunologically unprepared—"virgin soil," in the metaphor of epidemiologists. What Dobyns realized was that such diseases could have swept from the coastlines initially visited by Europeans to inland areas controlled by Indians who had never seen a white person. The first whites to explore many parts of the Americas may therefore have encountered places that were already depopulated. Indeed, Dobyns argued, they must have done so.

Peru was one example, the Pacific Northwest another. In 1792 the British navigator George Vancouver led the first European expedition to survey Puget Sound. He found a vast charnel house: human remains "promiscuously scattered about the beach, in great numbers." Smallpox, Vancouver's crew discovered, had preceded them. Its few survivors, second lieutenant Peter Puget noted, were "most terribly pitted ... indeed many have lost their Eyes." In *Pox Americana,* (2001), Elizabeth Fenn, a historian at George Washington University, contends that the disaster on the northwest coast was but a small part of a continental pandemic that erupted near Boston in 1774 and cut down Indians from Mexico to Alaska.

Because smallpox was not endemic in the Americas, colonials, too, had not acquired any immunity. The virus, an equal-opportunity killer, swept through the Continental Army and stopped the drive into Quebec. The American Revolution would be lost, Washington and other rebel leaders feared, if the contagion did to the colonists what it had done to the Indians. "The small Pox! The small Pox!" John Adams wrote to his wife, Abigail. "What shall We do with it?" In retrospect, Fenn says, "One of George Washington's most brilliant moves was to inoculate the army against smallpox during the Valley Forge winter of '78." Without inoculation smallpox could easily have given the United States back to the British.

So many epidemics occurred in the Americas, Dobyns argued, that the old data used by Mooney and his successors represented population nadirs. From the few cases in which before-and-after totals are known with relative certainty, Dobyns estimated that in the first 130 years of contact about 95 percent of the people in the Americas died—the worst demographic calamity in recorded history.

Dobyns's ideas were quickly attacked as politically motivated, a push from the hate-America crowd to inflate the toll of imperialism. The attacks continue to this day. "No question about it, some people want those higher numbers," says Shepard Krech III, a Brown University anthropologist who is the author of *The Ecological Indian* (1999). These people, he says, were thrilled when Dobyns revisited the subject in a book, *Their Numbers Become Thinned* (1983)—and revised his own estimates upward. Perhaps Dobyns's most vehement critic is David Henige, a bibliographer of Africana at the University of Wisconsin, whose *Numbers From Nowhere* (1998) is a landmark in the literature of demographic fulmination. "Suspect in 1966, it is no less suspect nowadays," Henige wrote of Dobyns's work. "If anything, it is worse."

When Henige wrote *Numbers From Nowhere*, the fight about pre-Columbian populations had already consumed forests' worth of trees; his bibliography is ninety pages long. And the dispute shows no sign of abating. More and more people have jumped in. This is partly because the subject is inherently fascinating. But more likely the increased interest in the debate is due to the growing realization of the high political and ecological stakes.

Inventing by the Millions

On May 30, 1539, Hernando de Soto landed his private army near Tampa Bay, in Florida. Soto, as he was called, was a novel figure: half warrior, half venture capitalist. He had grown very rich very young by becoming a market leader in the nascent trade for Indian slaves. The profits had helped to fund Pizarro's seizure of the Incan empire, which had made Soto wealthier still. Looking quite literally for new worlds to conquer, he persuaded the Spanish Crown to let him loose in North America. He spent one fortune to make another. He came to Florida with 200 horses, 600 soldiers, and 300 pigs.

From today's perspective, it is difficult to imagine the ethical system that would justify Soto's actions. For four years his force, looking for gold, wandered through what is now Florida, Georgia, North and South Carolina, Tennessee, Alabama, Mississippi, Arkansas, and Texas, wrecking almost everything it touched. The inhabitants often fought back vigorously, but they had never before encountered an army with horses and guns. Soto died of fever with his expedition in ruins; along the way his men had managed to rape, torture, enslave, and kill countless Indians. But the worst thing the Spaniards did, some researchers say, was entirely without malice—bring the pigs.

According to Charles Hudson, an anthropologist at the University of Georgia who spent fifteen years reconstructing the path of the expedition, Soto crossed the Mississippi a few miles downstream from the present site of Memphis. It was a nervous passage: the Spaniards were watched by several thousand Indian warriors. Utterly without fear, Soto brushed past the Indian force into what is now eastern Arkansas, through thickly settled land —"very well peopled with large towns," one of his men later recalled, "two or three of which were to be seen from one town." Eventually the Spaniards approached a cluster of small cities, each protected by earthen walls, sizeable moats, and deadeye archers. In his usual fashion, Soto brazenly marched in, stole food, and marched out.

After Soto left, no Europeans visited this part of the Mississippi Valley for more than a century. Early in 1682 whites appeared again, this time

Frenchmen in canoes. One of them was Réné-Robert Cavelier, Sieur de la Salle. The French passed through the area where Soto had found cities cheek by jowl. It was deserted—La Salle didn't see an Indian village for 200 miles. About fifty settlements existed in this strip of the Mississippi when Soto showed up, according to Anne Ramenofsky, an anthropologist at the University of New Mexico. By La Salle's time the number had shrunk to perhaps ten, some probably inhabited by recent immigrants. Soto "had a privileged glimpse" of an Indian world, Hudson says. "The window opened and slammed shut. When the French came in and the record opened up again, it was a transformed reality. A civilization crumbled. The question is, how did this happen?"

The question is even more complex than it may seem. Disaster of this magnitude suggests epidemic disease. In the view of Ramenofsky and Patricia Galloway, an anthropologist at the University of Texas, the source of the contagion was very likely not Soto's army but its ambulatory meat locker: his 300 pigs. Soto's force itself was too small to be an effective biological weapon. Sicknesses like measles and smallpox would have burned through his 600 soldiers long before they reached the Mississippi. But the same would not have held true for the pigs, which multiplied rapidly and were able to transmit their diseases to wildlife in the surrounding forest. When human beings and domesticated animals live close together, they trade microbes with abandon. Over time mutation spawns new diseases: avian influenza becomes human influenza, bovine rinderpest becomes measles. Unlike Europeans, Indians did not live in close quarters with animals—they domesticated only the dog, the llama, the alpaca, the guinea pig, and, here and there, the turkey and the Muscovy duck. In some ways this is not surprising: the New World had fewer animal candidates for taming than the Old. Moreover, few Indians carry the gene that permits adults to digest lactose, a form of sugar abundant in milk. Non-milk-drinkers, one imagines, would be less likely to work at domesticating milk-giving animals. But this is guesswork. The fact is that what scientists call zoonotic disease was little known in the Americas. Swine alone can disseminate anthrax, brucellosis, leptospirosis, taeniasis, trichinosis, and tuberculosis. Pigs breed exuberantly and can transmit diseases to deer and turkeys. Only a few of Soto's pigs would have had to wander off. Indeed, the calamity wrought by Soto apparently extended across the whole Southeast. The Coosa city-states, in western Georgia, and the Caddoan-speaking civilization, centered on the Texas-Arkansas border, disintegrated soon after Soto appeared. The Caddo had had a taste for monumental architecture: public plazas, ceremonial platforms, mausoleums. After Soto's army left, notes Timothy K. Perttula, an archaeological consultant in Austin, Texas, the Caddo stopped building community centers and began digging community cemeteries. Between Soto's and La Salle's visits, Perttula believes, the Caddoan population fell from about 200,000 to about 8,500—a drop of nearly 96 percent. In the eighteenth century the tally shrank further, to 1,400. An equivalent loss today in the population of New York City would reduce it to 56,000—not enough to fill Yankee Stadium. "That's one reason whites think of Indians as nomadic hunters," says Russell Thornton, an anthropologist at the University of California at Los Angeles. "Everything else—all the heavily populated urbanized societies—was wiped out."

Could a few pigs truly wreak this much destruction? Such apocalyptic scenarios invite skepticism. As a rule, viruses, microbes, and parasites are rarely lethal on so wide a scale—a pest that wipes out its host species does not have a bright evolutionary future. In its worst outbreak, from 1347 to 1351, the European Black Death claimed only a third of its victims. (The rest survived, though they were often disfigured or crippled by its effects.) The Indians in Soto's path, if Dobyns, Ramenofsky, and Perttula are correct, endured losses that were incomprehensibly greater.

One reason is that Indians were fresh territory for many plagues, not just one. Smallpox, typhoid, bubonic plague, influenza, mumps, measles, whooping cough—all rained down on the Americas in the century after Columbus. (Cholera, malaria, and scarlet fever came later.) Having little experience with epidemic diseases, Indians had no knowledge of how to combat them. In contrast, Europeans were well versed in the brutal logic of quarantine. They boarded up houses in which plague appeared and fled to the countryside. In Indian New England, Neal Salisbury, a historian at Smith College, wrote in *Manitou and Providence* (1982), family and friends gathered with the shaman at the sufferer's bedside to wait out the illness—a practice that "could only have served to spread the disease more rapidly."

Indigenous biochemistry may also have played a role. The immune system constantly scans the body for molecules that it can recognize as foreign—molecules belonging to an invading virus, for instance. No one's immune system can identify all foreign presences. Roughly speaking, an individual's set of defensive tools is known as his MHC type. Because many bacteria and viruses mutate easily, they usually attack in the form of several slightly different strains. Pathogens win when MHC types miss some of the strains and the immune system is not stimulated to act. Most human groups contain many MHC types; a strain that slips by one person's defenses will be nailed by the defenses of the next. But, according to Francis L. Black, an epidemiologist at Yale University, Indians are characterized by unusually homogenous MHC types. One out of three South American Indians have similar MHC types; among Africans the corresponding figure is one in 200. The cause is a matter for Darwinian speculation, the effects less so.

In 1966 Dobyns's insistence on the role of disease was a shock to his colleagues. Today the impact of European pathogens on the New World is almost undisputed. Nonetheless, the fight over Indian numbers continues with undiminished fervor. Estimates of the population of North America in 1491 disagree by an order of magnitude—from 18 million, Dobyns's revised figure, to 1.8 million, calculated infect the forest. by Douglas H. Ubelaker, an anthropologist at the Smithsonian. To some "high counters," as David Henige calls them, the low counters' refusal to relinquish the vision of an empty continent is irrational or worse. "Non-Indian 'experts' always want to minimize the size of aboriginal populations," says Lenore Stiffarm, a Native American-education specialist at the University of Saskatchewan. The smaller the numbers of Indians, she believes, the easier it is to regard the continent as having been up for grabs. "It's perfectly acceptable to move into unoccupied land," Stiffarm says. "And land with only a few 'savages' is the next best thing."

"Most of the arguments for the very large numbers have been theoretical," Ubelaker says in defense of low counters. "When you try to marry the theoretical arguments to the data that are available on individual groups in different regions, it's hard to find support for those numbers." Archaeologists, he says, keep searching for the settlements in which those millions of people supposedly lived, with little success. "As more and more excavation is done, one would expect to see more evidence for dense populations than has thus far emerged." Dean Snow, the Pennsylvania State anthropologist, examined Colonial-era Mohawk Iroquois sites and found "no support for the notion that ubiquitous pandemics swept the region." In his view, asserting that the continent was filled with people who left no trace is like looking at an empty bank account and claiming that it must once have held millions of dollars.

The low counters are also troubled by the Dobynsian procedure for recovering original population numbers: applying an assumed death rate, usually 95 percent, to the observed population nadir. Ubelaker believes that the lowest point for Indians in North America was around 1900, when their numbers fell to about half a million. Assuming a 95 percent death rate, the pre-contact population would have been 10 million. Go up one percent, to a 96 percent death rate, and the figure jumps to 12.5 million—arithmetically creating more than two million people from a tiny increase in mortality rates. At 98 percent the number bounds to 25 million. Minute changes in baseline assumptions produce wildly different results.

"It's an absolutely unanswerable question on which tens of thousands of words have been spent to no purpose," Henige says. In 1976 he sat in on a seminar by William Denevan, the Wisconsin geographer. An "epiphanic moment" occurred when he read shortly afterward that scholars had "uncovered" the existence of eight million people in Hispaniola. *Can you just invent millions of people?* he wondered. "We can make of the historical record that there was depopulation and movement of people from internecine warfare and diseases," he says. "But as for how much, who knows? When we start putting numbers to something like that—applying large figures like ninety-five percent—we're saying things we shouldn't say. The number implies a level of knowledge that's impossible."

Nonetheless, one must try—or so Denevan believes. In his estimation the high counters (though not the highest counters) seem to be winning the argument, at least for now. No definitive data exist, he says, but the majority of the extant evidentiary scraps support their side. Even Henige is no low counter. When I asked him what he thought the population of the Americas was before Columbus, he insisted that any answer would be speculation and made me promise not to print what he was going to say next. Then he named a figure that forty years ago would have caused a commotion.

To Elizabeth Fenn, the smallpox historian, the squabble over numbers obscures a central fact. Whether one million or 10 million or 100 million died, she believes, the pall of sorrow that engulfed the hemisphere was immeasurable. Languages, prayers, hopes, habits, and dreams—entire ways of life hissed away like steam. The Spanish and the Portuguese lacked the germ theory of disease and could not explain what was happening (let alone stop it). Nor can we explain it; the ruin was too long ago and too all-encompassing. In the long run, Fenn says, the consequential finding is not that many people died but that many people once lived. The Americas were filled with a stunningly diverse assortment of peoples who had knocked about the continents for millennia. "You have to wonder," Fenn says. "What were all those people *up* to in all that time?"

Buffalo Farm

In 1810 Henry Brackenridge came to Cahokia, in what is now southwest Illinois, just across the Mississippi from St. Louis. Born close to the frontier, Brackenridge was a budding adventure writer; his *Views of Louisiana*, published three years later, was a kind of nineteenth-century *Into Thin Air*, with terrific adventure but without tragedy. Brackenridge had an eye for archaeology, and he had heard that Cahokia was worth a visit. When he got there, trudging along the desolate Cahokia River, he was "struck with a degree of astonishment." Rising from the muddy bottomland was a "stupendous pile of earth," vaster than the Great Pyramid at Giza. Around it were more than a hundred smaller mounds, covering an area of five square miles. At the time, the area was almost uninhabited. One can only imagine what passed through Brackenridge's mind as he walked alone to the ruins of the biggest Indian city north of the Rio Grande.

To Brackenridge, it seemed clear that Cahokia and the many other ruins in the Midwest had been constructed by Indians. It was not so clear to everyone else. Nineteenth-century writers attributed them to, among others, the Vikings, the Chinese, the "Hindoos," the ancient Greeks, the ancient Egyptians, lost tribes of Israelites, and even straying bands of Welsh. (This last claim was surprisingly widespread; when Lewis and Clark surveyed the Missouri, Jefferson told them to keep an eye out for errant bands of Welsh-speaking white Indians.) The historian George Bancroft, dean of his profession, was a dissenter: the earthworks, he wrote in 1840, were purely natural formations.

Bancroft changed his mind about Cahokia, but not about Indians. To the end of his days he regarded them as "feeble barbarians, destitute of commerce and of political connection." His characterization lasted, largely unchanged, for more than a century. Samuel Eliot Morison, the winner of two Pulitzer Prizes, closed his monumental *European Discovery of America* (1974) with the observation that Native Americans expected only "short and brutish lives, void of hope for any future." As late as 1987*American History: A Survey*, a standard high school textbook by three well-known historians, described the Americas before Columbus as "empty of mankind and its works." The story of Europeans in the New World, the book explained, "is the story of the creation of a civilization where none existed."

Alfred Crosby, a historian at the University of Texas, came to other conclusions. Crosby's *The Columbian Exchange: Biological Consequences of 1492* caused almost as much of a stir when it was published, in 1972, as Henry Dobyns's calculation of Indian numbers six years earlier, though in different circles. Crosby was a standard names-and-battles historian who became frustrated by the random contingency of political events. "Some trivial thing happens and you have this guy winning the presidency instead of that guy," he says. He decided to go deeper. After he finished his manuscript, it sat on his shelf—he couldn't find a publisher willing to be associated with his new ideas. It took him three years to persuade a small editorial house to put it out. *The Columbian*

Exchange has been inprint ever since; a companion, *Ecological Imperialism: The Biological Expansion of Europe,900-1900*, appeared in 1986. Human history, in Crosby's interpretation, is marked by two world-altering centers of invention: the Middle East and central Mexico, where Indian groups independently created nearly all of the Neolithic innovations, writing included. The Neolithic Revolution began in the Middle East about 10,000 years ago. In the next few millennia humankind invented the wheel, the metal tool, and agriculture. The Sumerians eventually put these inventions together, added writing, and became the world's first civilization. Afterward Sumeria's heirs in Europe and Asia frantically copied one another's happiest discoveries; innovations ricocheted from one corner of Eurasia to another, stimulating technological progress. Native Americans, who had crossed to Alaska before Sumeria, missed out on the bounty. "They had to do everything on their own," Crosby says. Remarkably, they succeeded.

When Columbus appeared in the Caribbean, the descendants of the world's two Neolithic civilizations collided, with overwhelming consequences for both. American Neolithic development occurred later than that of the Middle East, possibly because the Indians needed more time to build up the requisite population density. Without beasts of burden they could not capitalize on the wheel (for individual workers on uneven terrain skids are nearly as effective as carts for hauling), and they never developed steel. But in agriculture they handily outstripped the children of Sumeria. Every tomato in Italy, every potato in Ireland, and every hot pepper in Thailand came from this hemisphere. Worldwide, more than half the crops grown today were initially developed in the Americas.

Maize, as corn is called in the rest of the world, was a triumph with global implications. Indians developed an extraordinary number of maize varieties for different growing conditions, which meant that the crop could and did spread throughout the planet. Central and Southern Europeans became particularly dependent on it; maize was the staple of Serbia, Romania, and Moldavia by the nineteenth century. Indian crops dramatically reduced hunger, Crosby says, which led to an Old World population boom.

Along with peanuts and manioc, maize came to Africa and transformed agriculture there, too. "The probability is that the population of Africa was greatly increased because of maize and other American Indian crops," Crosby says. "Those extra people helped make the slave trade possible." Maize conquered Africa at the time when introduced diseases were leveling Indian societies. The Spanish, the Portuguese, and the British were alarmed by the death rate among Indians, because they wanted to exploit them as workers. Faced with a labor shortage, the Europeans turned their eyes to Africa. The continent's quarrelsome societies helped slave traders to siphon off millions of people. The maize-fed population boom, Crosby believes, let the awful trade continue without pumping the well dry.

Back home in the Americas, Indian agriculture long sustained some of the world's largest cities. The Aztec capital of Tenochtitlán dazzled Hernán Cortés in 1519; it was bigger than Paris, Europe's greatest metropolis. The Spaniards gawped like hayseeds at the wide streets, ornately carved buildings, and markets bright with goods from hundreds of miles away. They had never before seen a city with botanical gardens, for the excellent reason that none existed in Europe. The same novelty attended the force of a thousand men that kept the crowded streets immaculate. (Streets that weren't ankle-deep in sewage! The conquistadors had never heard of such a thing.) Central America was not the only locus of prosperity. Thousands of miles north, John Smith, of Pocahontas fame, visited Massachusetts in 1614, before it was emptied by disease, and declared that the land was "so planted with Gardens and Corne fields, and so well inhabited with a goodly, strong and well proportioned people ... [that] I would rather live here than any where."

Smith was promoting colonization, and so had reason to exaggerate. But he also knew the hunger, sickness, and oppression of European life. France —"by any standards a privileged country," according to its great historian, Fernand Braudel— experienced seven nationwide famines in the fifteenth century and thirteen in the sixteenth. Disease was hunger's constant companion. During epidemics in London the dead were heaped onto carts "like common dung" (the simile is Daniel Defoe's) and trundled through the streets. The infant death rate in London orphanages, according to one contemporary source, was 88 percent. Governments were harsh, the rule of law arbitrary. The gibbets poking up in the background of so many old paintings were, Braudel observed, "merely a realistic detail."

The Earth Shall Weep, James Wilson's history of Indian America, puts the comparison bluntly: "the western hemisphere was larger, richer, and more populous than Europe." Much of it was freer, too. Europeans, accustomed to the serfdom that thrived from Naples to the Baltic Sea, were puzzled and alarmed by the democratic spirit and respect for human rights in many Indian societies, especially those in North America. In theory, the sachems of New England Indian groups were absolute monarchs. In practice, the colonial leader Roger Williams wrote, "they will not conclude of ought ... unto which the people are averse."

Pre-1492 America wasn't a disease-free paradise, Dobyns says, although in his "exuberance as a writer," he told me recently, he once made that claim. Indians had ailments of their own, notably parasites, tuberculosis, and anemia. The daily grind was wearing; life-spans in America were only as long as or a little longer than those in Europe, if the evidence of indigenous graveyards is to be believed. Nor was it a political utopia—the Inca, for instance, invented refinements to totalitarian rule that would have intrigued Stalin. Inveterate practitioners of what the historian Francis Jennings described as "state terrorism practiced horrifically on a huge scale," the Inca ruled so cruelly that one can speculate that their surviving subjects might actually have been better off under Spanish rule.

I asked seven anthropologists, archaeologists, and historians if they would rather have been a typical Indian or a typical European in 1491. None was delighted by the question, because it required judging the past by the standards of today—a fallacy disparaged as "presentism" by social scientists. But every one chose to be an Indian. Some early colonists gave the same answer. Horrifying the leaders of Jamestown and Plymouth, scores of English ran off to live with the Indians. My ancestor shared their desire, which is what led to the trumped-up murder charges against him—or that's what my grandfather told me, anyway.

As for the Indians, evidence suggests that they often viewed Europeans with disdain. The Hurons, a chagrined missionary reported, thought the French possessed "little intelligence in comparison to themselves." Europeans, Indians said, were physically weak, sexually untrustworthy, atrociously ugly, and just plain dirty. (Spaniards, who seldom if ever bathed, were amazed by the Aztec desire for personal cleanliness.) A Jesuit reported that the "Savages" were disgusted by handkerchiefs: "They say, we place what is unclean in a fine white piece of linen, and put it away in our pockets as something very precious, while they throw it upon the ground." The Micmac scoffed at the notion of French superiority. If Christian civilization was so wonderful, why were its inhabitants leaving?

Like people everywhere, Indians survived by cleverly exploiting their environment. Europeans tended to manage land by breaking it into fragments for farmers and herders. Indians often worked on such a grand scale that the scope of their ambition can be hard to grasp. They created small plots, as Europeans did (about 1.5 million acres of terraces still exist in the Peruvian Andes), but they also reshaped entire landscapes to suit their purposes. A principal tool was fire, used to keep down underbrush and create the open, grassy conditions favorable for game. Rather than domesticating animals for meat, Indians retooled whole ecosystems to grow bumper crops of elk, deer, and bison. The first white settlers in Ohio found forests as open as English parks—they could drive carriages through the woods. Along the Hudson River the annual fall burning lit up the banks for miles on end; so flashy was the show that the Dutch in New Amsterdam boated upriver to goggle at the blaze like children at fireworks. In North America, Indian torches had their biggest impact on the Midwestern prairie, much or most of which was created and maintained by fire. Millennia of exuberant burning shaped the plains into vast buffalo farms. When Indian societies disintegrated, forest invaded savannah in Wisconsin, Illinois, Kansas, Nebraska, and the Texas Hill Country. Is it possible that the Indians changed the Americas more than the invading Europeans did? "The answer is probably yes for most regions for the next 250 years or so" after Columbus, William Denevan wrote, "and for some regions right up to the present time."

When scholars first began increasing their estimates of the ecological impact of Indian civilization, they met with considerable resistance from anthropologists and archaeologists. Over time the consensus in the human sciences changed. Under Denevan's direction, Oxford University Press has just issued the third volume of a huge catalogue of the "cultivated landscapes" of the Americas. This sort of phrase still provokes vehement objection—but the main dissenters are now ecologists and environmentalists. The disagreement is encapsulated by Amazonia, which has become *the* emblem of vanishing wilderness—an admonitory image of untouched Nature. Yet recently a growing number of researchers have come to believe that Indian societies had an enormous environmental impact on the jungle. Indeed, some anthropologists have called the Amazon forest itself a cultural artifact—that is, an artificial object.

Green Prisons

Northern visitors' first reaction to the storied Amazon rain forest is often disappointment. Ecotourist brochures evoke the immensity of Amazonia but rarely dwell on its extreme flatness. In the river's first 2,900 miles the vertical drop is only 500 feet. The river oozes like a huge runnel of dirty metal through a landscape utterly devoid of the romantic crags, arroyos, and heights that signify wildness and natural spectacle to most North Americans. Even the animals are invisible, although sometimes one can hear the bellow of monkey choruses. To the untutored eye—mine, for instance—the forest seems to stretch out in a monstrous green tangle as flat and incomprehensible as a printed circuit board.

The area east of the lower-Amazon town of Santarém is an exception. A series of sandstone ridges several hundred feet high reach down from the north, halting almost at the water's edge. Their tops stand drunkenly above the jungle like old tombstones. Many of the caves in the buttes are splattered with ancient petroglyphs—renditions of hands, stars, frogs, and human figures, all reminiscent of Miró, in overlapping red and yellow and brown. In recent years one of these caves, La Caverna da Pedra Pintada (Painted Rock Cave), has drawn attention in archaeological circles.

Wide and shallow and well lit, Painted Rock Cave is less thronged with bats than some of the other caves. The arched entrance is twenty feet high and lined with rock paintings. Out front is a sunny natural patio suitable for picnicking, edged by a few big rocks. People lived in this cave more than 11,000 years ago. They had no agriculture yet, and instead ate fish and fruit and built fires. During a recent visit I ate a sandwich atop a particularly inviting rock and looked over the forest below. The first Amazonians, I thought, must have done more or less the same thing.

In college I took an introductory anthropology class in which I read *Amazonia: Man and Culture in a Counterfeit Paradise* (1971), perhaps the most influential book ever written about the Amazon, and one that deeply impressed me at the time. Written by Betty J. Meggers, the Smithsonian archaeologist, *Amazonia* says that the apparent lushness of the rain forest is a sham. The soils are poor and can't hold nutrients—the jungle flora exists only because it snatches up everything worthwhile before it leaches away in the rain. Agriculture, which depends on extracting the wealth of the soil, therefore faces inherent ecological limitations in the wet desert of Amazonia.

As a result, Meggers argued, Indian villages were forced to remain small—any report of "more than a few hundred" people in permanent settlements, she told me recently, "makes my alarm bells go off." Bigger, more complex societies would inevitably overtax the forest soils, laying waste to their own foundations. Beginning in 1948 Meggers and her late husband, Clifford Evans, excavated a chiefdom on Marajó, an island twice the size of New Jersey that sits like a gigantic stopper in the mouth of the Amazon. The Marajóara, they concluded, were failed offshoots of a sophisticated culture in the Andes. Transplanted to the lush trap of the Amazon, the culture choked and died.

Green activists saw the implication: development in tropical forests destroys both the forests and their developers. Meggers's account had enormous public impact—*Amazonia* is one of the wellsprings of the campaign to save rain forests.

Then Anna C. Roosevelt, the curator of archaeology at Chicago's Field Museum of Natural History, re-excavated Marajó. Her complete report, *Moundbuilders of the Amazon* (1991), was like the anti-matter version of *Amazonia*. Marajó, she argued, was "one of the outstanding indigenous cultural achievements of the New World," a powerhouse that lasted for more than a thousand years, had "possibly well over 100,000" inhabitants, and covered thousands of square miles. Rather than damaging the forest, Marajó's "earth construction" and "large, dense populations" had *improved* it: the most luxuriant and diverse growth was on the mounds formerly occupied by the Marajóara. "If you listened to Meggers's theory, these places should have been ruined," Roosevelt says.

Meggers scoffed at Roosevelt's "extravagant claims," "polemical tone," and "defamatory remarks." Roosevelt, Meggers argued, had committed the beginner's error of mistaking a site that had been occupied many times by small, unstable groups for a single, long-lasting society. "[Archaeological remains] build up on areas of half a kilometer or so," she told me, "because [shifting Indian groups] don't land exactly on the same spot. The decorated types of pottery don't change much over time, so you can pick up a bunch of chips and say, 'Oh, look, it was all one big site!' Unless you know what you're doing, of course." Centuries after the conquistadors, "the myth of El Dorado is being revived by archaeologists," Meggers wrote last fall in the journal *Latin American Antiquity*, referring to the persistent Spanish delusion that cities of gold existed in the jungle.

The dispute grew bitter and personal; inevitable in a contemporary academic context, it has featured vituperative references to colonialism, elitism, and employment by the CIA. Meanwhile, Roosevelt's team investigated Painted Rock Cave. On the floor of the cave what looked to me like nothing in particular turned out to be an ancient midden: a refuse heap. The archaeologists slowly scraped away sediment, traveling backward in time with every inch. When the traces of human occupation vanished, they kept digging. ("You always go a meter past sterile," Roosevelt says.) A few inches below they struck the charcoal-rich dirt that signifies human habitation—a culture, Roosevelt said later, that wasn't supposed to be there.

For many millennia the cave's inhabitants hunted and gathered for food. But by about 4,000 years ago they were growing crops—perhaps as many as 140 of them, according to Charles R. Clement, an anthropological botanist at the Brazilian National Institute for Amazonian Research. Unlike Europeans, who planted mainly annual crops, the Indians, he says, centered their agriculture on the Amazon's unbelievably diverse assortment of trees: fruits, nuts, and palms. "It's tremendously difficult to clear fields with stone tools," Clement says. "If you can plant trees, you get twenty years of productivity out of your work instead of two or three."

Planting their orchards, the first Amazonians transformed large swaths of the river basin into something more pleasing to human beings. In a widely cited article from 1989, William Balée, the Tulane anthropologist, cautiously estimated that about 12 percent of the nonflooded Amazon forest was of anthropogenic origin—directly or indirectly created by human beings. In some circles this is now seen as a conservative position. "I basically think it's all human-created," Clement told me in Brazil. He argues that Indians changed the assortment and density of species throughout the region. So does Clark Erickson, the University of Pennsylvania archaeologist, who told me in Bolivia that the lowland tropical forests of South America are among the finest works of art on the planet.

"Some of my colleagues would say that's pretty radical," he said, smiling mischievously. According to Peter Stahl, an anthropologist at the State University of New York at Binghamton, "lots" of botanists believe that "what the eco-imagery would like to picture as a pristine, untouched Urwelt [primeval world] in fact has been managed by people for millennia." The phrase "built environment," Erickson says, "applies to most, if not all, Neotropical landscapes."

"Landscape" in this case is meant exactly—Amazonian Indians literally created the ground beneath their feet. According to William I. Woods, a soil geographer at Southern Illinois University, ecologists' claims about terrible Amazonian land were based on very little data. In the late 1990s Woods and others began careful measurements in the lower Amazon. They indeed found lots of inhospitable terrain. But they also discovered swaths of *terra preta*—rich, fertile "black earth" that anthropologists increasingly believe was created by human beings.

Terra preta, Woods guesses, covers at least 10 percent of Amazonia, an area the size of France. It has amazing properties, he says. Tropical rain doesn't leach nutrients from *terra preta* fields; instead the soil, so to speak, fights back. Not far from Painted Rock Cave is a 300-acre area with a two-foot layer of *terra preta* quarried by locals for potting soil. The bottom third of the layer is never removed, workers there explain, because over time it will re-create the original soil layer in its initial thickness. The reason, scientists suspect, is that *terra preta* is generated by a special suite of microorganisms that resists depletion. "Apparently," Woods and the Wisconsin geographer Joseph M. McCann argued in a presentation last summer, "at some threshold level ... dark earth attains the capacity to perpetuate—even *regenerate* itself—thus behaving more like a living 'super'-organism than an inert material."

In as yet unpublished research the archaeologists Eduardo Neves, of the University of São Paulo; Michael Heckenberger, of the University of Florida; and their colleagues examined *terra preta* in the upper Xingu, a huge southern tributary of the Amazon. Not all Xingu cultures left behind this living earth, they discovered. But the ones that did generated it rapidly—suggesting to Woods that *terra preta* was created deliberately. In a process reminiscent of dropping microorganism-rich starter into plain dough to create sourdough bread, Amazonian peoples, he believes, inoculated bad soil with a transforming bacterial charge. Not every group of Indians there did this, but quite a few did, and over an extended period of time.

When Woods told me this, I was so amazed that I almost dropped the phone. I ceased to be articulate for a moment and said things like "wow" and "gosh." Woods chuckled at my reaction, probably because he understood what was passing through my mind. Faced with an ecological problem, I was thinking, the Indians *fixed* it. They were in the process of terraforming the Amazon when Columbus showed up and ruined everything.

Scientists should study the microorganisms in *terra preta*, Woods told me, to find out how they work. If that could be learned, maybe some version of Amazonian dark earth could be used to improve the vast expanses of bad soil that cripple agriculture in Africa—a final gift from the people who brought us tomatoes, corn, and the immense grasslands of the Great Plains.

"Betty Meggers would just die if she heard me saying this," Woods told me. "Deep down her fear is that this data will be misused." Indeed, Meggers's recent *Latin American Antiquity* article charged that archaeologists who say the Amazon can support agriculture are effectively telling "developers [that they] are entitled to operate without restraint." Resuscitating the myth of El Dorado, in her view, "makes us accomplices in the accelerating pace of environmental degradation." Doubtless there is something to this—although, as some of her critics responded in the same issue of the journal, it is difficult to imagine greedy plutocrats "perusing the pages of *Latin American Antiquity* before deciding to rev up the chain saws." But the new picture doesn't automatically legitimize paving the forest. Instead it suggests that for a long time big chunks of Amazonia were used nondestructively by clever people who knew tricks we have yet to learn.

I visited Painted Rock Cave during the river's annual flood, when it wells up over its banks and creeps inland for miles. Farmers in the floodplain build houses and barns on stilts and watch pink dolphins sport from their doorsteps. Ecotourists take shortcuts by driving motorboats through the drowned forest. Guys in dories chase after them, trying to sell sacks of incredibly good fruit.

All of this is described as "wilderness" in the tourist brochures. It's not, if researchers like Roosevelt are correct. Indeed, they believe that fewer people may be living there now than in 1491. Yet when my boat glided into the trees, the forest shut out the sky like the closing of an umbrella. Within a few hundred yards the human presence seemed to vanish. I felt alone and small, but in a way that was curiously like feeling exalted. If that place was not wilderness, how should I think of it? Since the fate of the forest is in our hands, what should be our goal for its future?

Novel Shores

Hernando de Soto's expedition stomped through the Southeast for four years and apparently never saw bison. More than a century later, when French explorers came down the Mississippi, they saw "a solitude unrelieved by the faintest trace of man," the nineteenth-century historian Francis Parkman wrote. Instead the French encountered bison, "grazing in herds on the great prairies which then bordered the river."

To Charles Kay, the reason for the buffalo's sudden emergence is obvious. Kay is a wildlife ecologist in the political-science department at Utah State University. In ecological terms, he says, the Indians were the "keystone species" of American ecosystems. A keystone species, according to the Harvard biologist Edward O. Wilson, is a species "that affects the survival and abundance of many other species." Keystone species have a disproportionate impact on their ecosystems. Removing them, Wilson adds, "results in a relatively significant shift in the composition of the [ecological] community."

When disease swept Indians from the land, Kay says, what happened was exactly that. The ecological ancien régime collapsed, and strange new phenomena emerged. In a way this is unsurprising; for better or worse, humankind is a keystone species everywhere. Among these phenomena was a population explosion in the species that the Indians had kept down by hunting. After disease killed off the Indians, Kay believes, buffalo vastly extended their range. Their numbers more than sextupled. The same occurred with elk and mule deer. "If the elk were here in great numbers all this time, the archaeological sites should be chock-full of elk bones," Kay says. "But the archaeologists will tell you the elk weren't there." On the evidence of middens the number of elk jumped about 500 years ago.

Passenger pigeons may be another example. The epitome of natural American abundance, they flew in such great masses that the first colonists were stupefied by the sight. As a boy, the explorer Henry Brackenridge saw flocks "ten miles in width, by one hundred and twenty in length." For hours the birds darkened the sky from horizon to horizon. According to Thomas Neumann, a consulting archaeologist in Lilburn, Georgia, passenger pigeons "were incredibly dumb and always roosted in vast hordes, so they were very easy to harvest." Because they were readily caught and good to eat, Neumann says, archaeological digs should find many pigeon bones in the pre-Columbian strata of Indian middens. But they aren't there. The mobs of birds in the history books, he says, were "outbreak populations—always a symptom of an extraordinarily disrupted ecological system."

Throughout eastern North America the open landscape seen by the first Europeans quickly filled in with forest. According to William Cronon, of the University of Wisconsin, later colonists began complaining about how hard it was to get around. (Eventually, of course, they stripped New England almost bare of trees.) When Europeans moved west, they were preceded by two waves: one of disease, the other of ecological disturbance. The former crested with fearsome rapidity; the latter sometimes took more than a century to quiet down. Far from destroying pristine wilderness, European settlers bloodily *created* it. By 1800 the hemisphere was chockablock with new wilderness. If "forest primeval" means a woodland unsullied by the human presence, William Denevan has written, there was much more of it in the late eighteenth century than in the early sixteenth.

Cronon's *Changes in the Land: Indians, Colonists, and the Ecology of New England* (1983) belongs on the same shelf as works by Crosby and Dobyns. But it was not until one of his articles was excerpted in *The New York Times* in 1995 that people outside the social sciences began to understand the implications of this view of Indian history. Environmentalists and ecologists vigorously attacked the anti-wilderness scenario, which they described as infected by postmodern philosophy. A small academic brouhaha ensued, complete with hundreds of footnotes. It precipitated *Reinventing Nature?* (1995), one of the few academic critiques of postmodernist philosophy written largely by biologists. *The Great New Wilderness Debate* (1998), another lengthy book on the subject, was edited by two philosophers who earnestly identified themselves as "Euro-American men [whose] cultural legacy is patriarchal Western civilization in its current postcolonial, globally hegemonic form."

It is easy to tweak academics for opaque, self-protective language like this. Nonetheless, their concerns were quite justified. Crediting Indians with the role of keystone species has implications for the way the current Euro-American members of that keystone species manage the forests, watersheds, and endangered species of America. Because a third of the United States is owned by the federal government, the issue inevitably has political ramifications. In Amazonia, fabled storehouse of biodiversity, the stakes are global.

Guided by the pristine myth, mainstream environmentalists want to preserve as much of the world's land as possible in a putatively intact state. But "intact," if the new research is correct, means "run by human beings for human purposes." Environmentalists dislike this, because it seems to mean that anything goes. In a sense they are correct. Native Americans managed the continent as they saw fit. Modern nations must do the same. If they want to return as much of the landscape as possible to its
1491 state, they will have to find it within themselves to create the world's largest garden.
This article available online at: http://www.theatlantic.com/magazine/archive/2002/03/1491/302445/

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Conceptualizing the Anthropocene

The Anthropocene

By Elizabeth Kolbert

The path leads up a hill, across a fast-moving stream, back across the stream, and then past the carcass of a sheep. In my view it's raining, but here in the Southern Uplands of Scotland, I'm told, this counts as only a light drizzle, or smirr. Just beyond the final switchback, there's a waterfall, half shrouded in mist, and an outcropping of jagged rock. The rock has bands that run vertically, like a layer cake that's been tipped on its side. My guide, Jan Zalasiewicz, a British stratigrapher, points to a wide stripe of gray. "Bad things happened in here," he says.

The stripe was laid down some 445 million years ago, as sediments slowly piled up on the bottom of an ancient ocean. In those days life was still confined mostly to the water, and it was undergoing a crisis. Between one edge of the three-foot-thick gray band and the other, some 80 percent of marine species died out, many of them the sorts of creatures, like graptolites, that no longer exist. The extinction event, known as the end-Ordovician, was one of the five biggest of the past half billion years. It coincided with extreme changes in climate, in global sea levels, and in ocean chemistry—all caused, perhaps, by a supercontinent drifting over the South Pole.

Stratigraphers like Zalasiewicz are, as a rule, hard to impress. Their job is to piece together Earth's history from clues that can be coaxed out of layers of rock millions of years after the fact. They take the long view—the extremely long view—of events, only the most violent of which are likely to leave behind clear, lasting signals. It's those events that mark the crucial episodes in the planet's 4.5-billion-year story, the turning points that divide it into comprehensible chapters.

So it's disconcerting to learn that many stratigraphers have come to believe that *we* are such an event—that human beings have so altered the planet in just the past century or two that we've ushered in a new epoch: the Anthropocene. Standing in the smirr, I ask Zalasiewicz what he thinks this epoch will look like to the geologists of the distant future, whoever or whatever they may be. Will the transition be a moderate one, like dozens of others that appear in the record, or will it show up as a sharp band in which very bad things happened—like the mass extinction at the end of the Ordovician? That, Zalasiewicz says, is what we are in the process of determining.

The word "Anthropocene" was coined by Dutch chemist Paul Crutzen about a decade ago. One day Crutzen, who shared a Nobel Prize for discovering the effects of ozone-depleting compounds, was sitting at a scientific conference. The conference chairman kept referring to the Holocene, the epoch that began at the end of the last ice age, 11,500 years ago, and that—officially, at least—continues to this day.

"'Let's stop it,'" Crutzen recalls blurting out. "'We are no longer in the Holocene. We are in the Anthropocene.' Well, it was quiet in the room for a while." When the group took a coffee break, the Anthropocene was the main topic of conversation. Someone suggested that Crutzen copyright the word.

Way back in the 1870s, an Italian geologist named Antonio Stoppani proposed that people had introduced a new era, which he labeled the anthropozoic. Stoppani's proposal was ignored; other scientists found it unscientific. The Anthropocene, by contrast, struck a chord. Human impacts on the world have become a lot more obvious since Stoppani's day, in part because the size of the population has roughly quadrupled, to nearly seven billion. "The pattern of human population growth in the twentieth century was more bacterial than primate," biologist E. O. Wilson has written. Wilson calculates that human biomass is already a hundred times larger than that of any other large animal species that has ever walked the Earth.

In 2002, when Crutzen wrote up the Anthropocene idea in the journal *Nature*, the concept was immediately picked up by researchers working in a wide range of disciplines. Soon it began to appear regularly in the scientific press. "Global Analysis of River Systems: From Earth System Controls to Anthropocene Syndromes" ran the title of one 2003 paper. "Soils and Sediments in the Anthropocene" was the headline of another, published in 2004.

At first most of the scientists using the new geologic term were not geologists. Zalasiewicz, who is one, found the discussions intriguing. "I noticed that Crutzen's term was appearing in the serious literature, without quotation marks and without a sense of irony," he says. In 2007 Zalasiewicz was serving as chairman of the Geological Society of London's Stratigraphy Commission. At a meeting he decided to ask his fellow stratigraphers what they thought of the Anthropocene. Twenty-one of 22 thought the concept had merit.

The group agreed to look at it as a formal problem in geology. Would the Anthropocene satisfy the criteria used for naming a new epoch? In geologic parlance, epochs are relatively short time spans, though they can extend for tens of millions of years. (Periods, such as the Ordovician and the Cretaceous, last much longer, and eras, like the Mesozoic, longer still.) The boundaries between epochs are defined by changes preserved in sedimentary rocks—the emergence of one type of commonly fossilized organism, say, or the disappearance of another.

The rock record of the present doesn't exist yet, of course. So the question was: When it does, will human impacts show up as "stratigraphically significant"? The answer, Zalasiewicz's group decided, is yes—though not necessarily for the reasons you'd expect.

Probably the most obvious way humans are altering the planet is by building cities, which are essentially vast stretches of man-made materials—steel, glass, concrete, and brick. But it turns out most cities are not good candidates for long-term preservation, for the simple reason that they're built on land, and on land the forces of erosion tend to win out over those of sedimentation. From a geologic perspective, the most plainly visible human effects on the landscape today "may in some ways be the most transient," Zalasiewicz has observed.

Humans have also transformed the world through farming; something like 38 percent of the planet's ice-free land is now devoted to agriculture. Here again, some of the effects that seem most significant today will leave behind only subtle traces at best.

Fertilizer factories, for example, now fix more nitrogen from the air, converting it to a biologically usable form, than all the plants and microbes on land; the runoff from fertilized fields is triggering life-throttling blooms of algae at river mouths all over the world. But this global perturbation of the nitrogen cycle will be hard to detect, because synthesized nitrogen is just like its natural equivalent. Future geologists are more likely to grasp the scale of 21st-century industrial agriculture from the pollen record—from the monochrome stretches of corn, wheat, and soy pollen that will have replaced the varied record left behind by rain forests or prairies.

The leveling of the world's forests will send at least two coded signals to future stratigraphers, though deciphering the first may be tricky. Massive amounts of soil eroding off denuded land are increasing sedimentation in some parts of the world—but at the same time the dams we've built on most of the world's major rivers are holding back sediment that would otherwise be washed to sea. The second signal of deforestation should come through clearer. Loss of forest habitat is a major cause of extinctions, which are now happening at a rate hundreds or even thousands of times higher than during most of the past half billion years. If current trends continue, the rate may soon be tens of thousands of times higher.

Probably the most significant change, from a geologic perspective, is one that's invisible to us—the change in the composition of the atmosphere. Carbon dioxide emissions are colorless, odorless, and in an immediate sense, harmless. But their warming effects could easily push global temperatures to levels that have not been seen for millions of years. Some plants and animals are already shifting their ranges toward the Poles, and those shifts will leave traces in the fossil record. Some species will not survive the warming at all. Meanwhile rising temperatures could eventually raise sea levels 20 feet or more.

Long after our cars, cities, and factories have turned to dust, the consequences of burning billions of tons' worth of coal and oil are likely to be clearly discernible. As carbon dioxide warms the planet, it also seeps into the oceans and acidifies them. Sometime this century they may become acidified to the point that corals can no longer construct reefs, which would register in the geologic record as a "reef gap." Reef gaps have marked each of the past five major mass extinctions. The most recent one, which is believed to have been caused by the impact of an asteroid, took place 65 million years ago, at the end of the Cretaceous period; it eliminated not just the dinosaurs, but also the plesiosaurs, pterosaurs, and ammonites. The scale of what's happening now to the oceans is, by many accounts, unmatched since then. To future geologists, Zalasiewicz says, our impact may look as sudden and profound as that of an asteroid.

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The Anthropocene in Perspective

Was the World Made for Man?

Mark Twain
1903

“Alfred Russell Wallace's revival of the theory that this earth is at the center of the stellar universe, and is the only habitable globe, has aroused great interest in the world." -- Literary Digest

"For ourselves we do thoroughly believe that man, as he lives just here on this tiny earth, is in essence and possibilities the most sublime existence in all the range of non-divine being -- the chief love and delight of God." -- Chicago "Interior" (Presb.)

I seem to be the only scientist and theologian still remaining to be heard from on this important matter of whether the world was made for man or not. I feel that it is time for me to speak.

I stand almost with the others. They believe the world was made for man, I believe it likely that it was made for man; they think there is proof, astronomical mainly, that it was made for man, I think there is evidence only, not proof, that it was made for him. It is too early, yet, to arrange the verdict, the returns are not all in. When they are all in, I think they will show that the world was made for man; but we must not hurry, we must patiently wait till they are all in.

Now as far as we have got, astronomy is on our side. Mr. Wallace has clearly shown this. He has clearly shown two things: that the world was made for man, and that the universe was made for the world -- to steady it, you know. The astronomy part is settled, and cannot be challenged.

We come now to the geological part. This is the one where the evidence is not all in, yet. It is coming in, hourly, daily, coming in all the time, but naturally it comes with geological carefulness and deliberation, and we must not be impatient, we must not get excited, we must be calm, and wait. To lose our tranquility will not hurry geology; nothing hurries geology.

It takes a long time to prepare a world for man, such a thing is not done in a day. Some of the great scientists, carefully deciphering the evidences furnished by geology, have arrived at the conviction that our world is prodigiously old, and they may be right, but Lord Kelvin is not of their opinion. He takes a cautious, conservative view, in order to be on the safe side, and feels sure it is not so old as they think. As Lord Kelvin is the highest authority in science now living, I think we must yield to him and accept his view. He does not concede that the world is more than a hundred million years old. He believes it is that old, but not older. Lyell believed that our race was introduced into the world 31,000 years ago, Herbert Spencer makes it 32,000. Lord Kelvin agrees with Spencer.

Very well. According to Kelvin's figures it took 99,968,000 years to prepare the world for man, impatient as the Creator doubtless was to see him and admire him. But a large enterprise like this has to be conducted warily, painstakingly, logically. It was foreseen that man would have to have the oyster. Therefore the first preparation was made for the oyster. Very well, you cannot make an oyster out of whole cloth, you must make the oyster's ancestor first. This is not done in a day. You must make a vast variety of invertebrates, to start with -- belemnites, trilobites, jebusites, amalekites, and that sort of fry, and put them to soak in a primary sea, and wait and see what will happen. Some will be a disappointments - the belemnites, the ammonites and such; they will be failures, they will die out and become extinct, in the course of the 19,000,000 years covered by the experiment, but all is not lost, for the amalekites will fetch the home-stake; they will develop gradually into encrinites, and stalactites, and blatherskites, and one thing and another as the mighty ages creep on and the Archaean and the Cambrian Periods pile their lofty crags in the primordial seas, and at last the first grand stage in the preparation of the world for man stands completed, the Oyster is done. An oyster has hardly any more reasoning power than a scientist has; and so it is reasonably certain that this one jumped to the conclusion that the nineteen-million years was a preparation for him; but that would be just like an oyster, which is the most conceited animal there is, except man. And anyway, this one could not know, at that early date, that he was only an incident in a scheme, and that there was some more to the scheme, yet.

The oyster being achieved, the next thing to be arranged for in the preparation of the world for man, was fish. Fish, and coal to fry it with. So the Old Silurian seas were opened up to breed the fish in, and at the same time the great work of building Old Red Sandstone mountains 80,000 feet high to cold-storage their fossils in was begun. This latter was quite indispensable, for there would be no end of failures again, no end of extinctions -- millions of them -- and it would be cheaper and less trouble to can them in the rocks than keep tally of them in a book. One does not build the coal beds and 80,000 feet of perpendicular Old Red Sandstone in a brief time -- no, it took twenty million years. In the first place, a coal bed is a slow and troublesome and tiresome thing to construct. You have to grow prodigious forests of tree-ferns and reeds and calamites and such things in a marshy region; then you have, to sink them under out of sight and let them rot; then you have to turn the streams on them, so as to bury them under several feet of sediment, and the sediment must have time to harden and turn to rock; next you must grow another forest on top, then sink it and put on another layer of sediment and harden it; then more forest and more rock, layer upon layer, three miles deep -- ah, indeed it is a sickening slow job to build a coal-measure and do it right!

So the millions of years drag on; and meantime the fish-culture is lazying along and frazzling out in a way to make a person tired. You have developed ten thousand kinds of fishes from the oyster; and come to look, you have raised nothing but fossils, nothing but extinctions. There is nothing left alive and progressive but a ganoid or two and perhaps half a dozen asteroids. Even the cat wouldn't eat such. Still, it is no great matter; there is plenty of time, yet, and they will develop into something tasty before man is ready for them. Even a ganoid can be depended on for that, when he is not going to be called on for sixty million years.

The Palaeozoic time-limit having now been reached, it was necessary to begin the next stage in the preparation of the world for man, by opening up the Mesozoic Age and instituting some reptiles. For man would need reptiles. Not to eat, but to develop himself from. This being the most important detail of the scheme, a spacious liberality of time was set apart for it -- thirty million years. What wonders followed! From the remaining ganoids and asteroids and alkaloids were developed by slow and steady and pains-taking culture those stupendous saurians that used to prowl about the steamy world in those remote ages, with their snaky heads reared forty feet in the air and sixty feet of body and tail racing and thrashing after. All gone, now, alas -- all extinct, except the little handful of Arkansawrians left stranded and lonely with us here upon this far-flung verge and fringe of time.

Yes, it took thirty million years and twenty million reptiles to get one that would stick long enough to develop into something else and let the scheme proceed to the next step.

Then the Pterodactyl burst upon the world in all his impressive solemnity and grandeur, and all Nature recognized that the Cainozoic threshold was crossed and a new Period open for business, a new stage begun in the preparation of the globe for man. It may be that the Pterodactyl thought the thirty million years had been intended as a preparation for himself, for there was nothing too foolish for a Pterodactyl to imagine, but he was in error, the preparation was for man, Without doubt the Pterodactyl attracted great attention, for even the least observant could see that there was the making of a bird in him. And so it turned out. Also the makings of a mammal, in time. One thing we have to say to his credit, that in the matter of picturesqueness he was the triumph of his Period; he wore wings and had teeth, and was a starchy and wonderful mixture altogether, a kind of long-distance premonitory symptom of Kipling's marine:

'E isn't one O'the reg'lar Line,
nor 'e isn't one of the crew,
'E's a kind of a giddy harumfrodite [hermaphrodite] --
soldier an' sailor too!

From this time onward for nearly another thirty million years the preparation moved briskly. From the Pterodactyl was developed the bird; from the bird the kangaroo, from the kangaroo the other marsupials; from these the mastodon, the megatherium, the giant sloth, the Irish elk, and all that crowd that you make useful and instructive fossils out of -- then came the first great Ice Sheet, and they all retreated before it and crossed over the bridge at Behring's strait and wandered around over Europe and Asia and died. All except a few, to carry on the preparation with. Six Glacial Periods with two million years between Periods chased these poor orphans up and down and about the earth, from weather to weather -- from tropic swelter at the poles to Arctic frost at the equator and back again and to and fro, they never knowing what kind of weather was going to turn up next; and if ever they settled down anywhere the whole continent suddenly sank under them without the least notice and they had to trade places with the fishes and scramble off to where the seas had been, and scarcely a dry rag on them; and when there was nothing else doing a volcano would let go and fire them out from wherever they had located. They led this unsettled and irritating life for twenty-five million years, half the time afloat, half the time aground, and always wondering what it was all for, they never suspecting, of course, that it was a preparation for man and had to be done just so or it wouldn't be any proper and harmonious place for him when he arrived.

And at last came the monkey, and anybody could see that man wasn't far off, now. And in truth that was so. The monkey went on developing for close upon 5,000,000 years, and then turned into a man - to all appearances.

Such is the history of it. Man has been here 32,000 years. That it took a hundred million years to prepare the world for him is proof that that is what it was done for. I suppose it is. I dunno. If the Eiffel tower were now representing the world's age, the skin of paint on the pinnacle-knob at its summit would represent man's share of that age; and anybody would perceive that that skin was what the tower was built for. I reckon they would, I dunno.

Welcome to the Anthropocene

See also: http://www.anthropocene.info/en/home htttp://www.anthropocene.info/en/home

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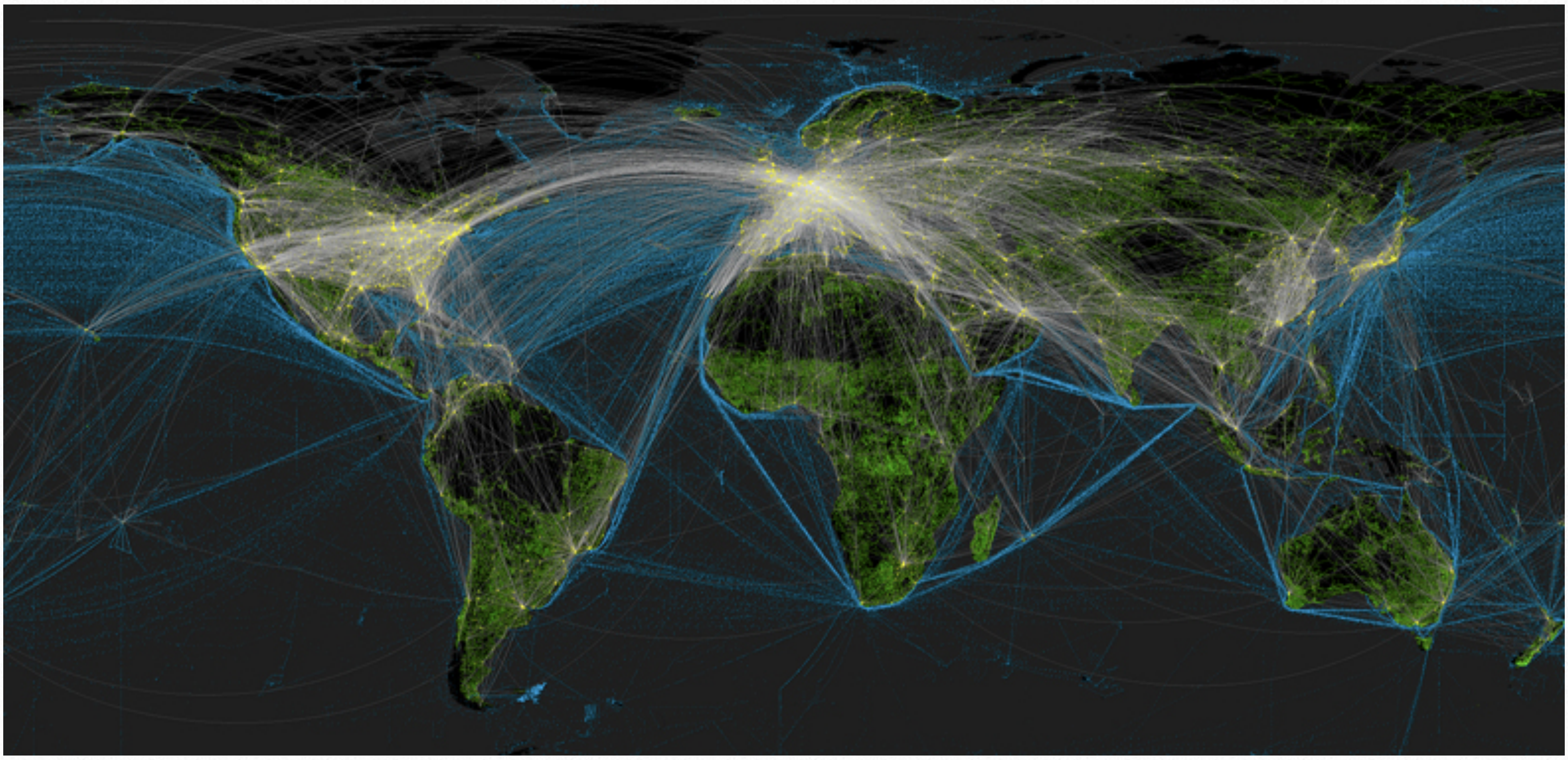
Where are we now?



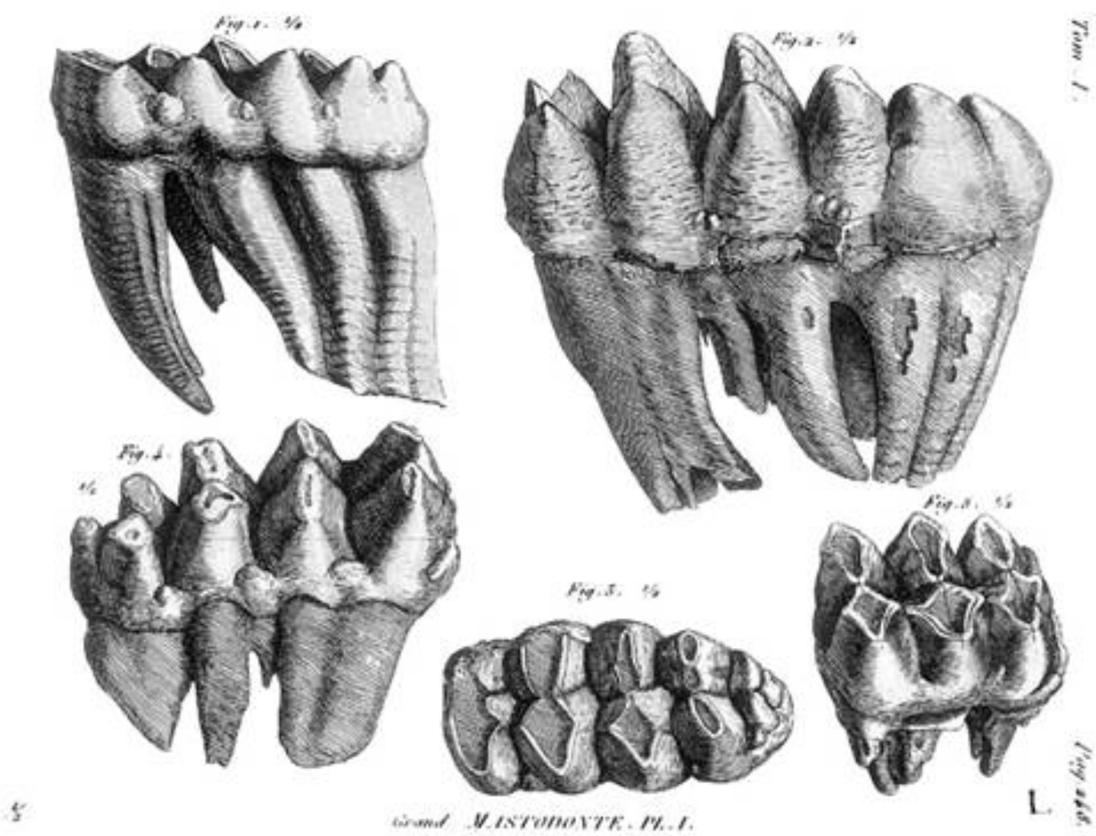
http://globaia.org/portfolio/cartography-of-the-anthropocene/

ANNALS OF EXTINCTION PART ONE

THE LOST WORLD

The mastodon's molars.

BY ELIZABETH KOLBERT



Cuvier's proof of extinction, of "a world previous to ours," was a sensational event.

On April 4, 1796—or, according to the French Revolutionary calendar in use at the time, 15 Germinal, Year IV—Jean-Léopold-Nicholas-Frédéric Cuvier, known, after a brother who had died, simply as Georges, delivered his first public lecture at the National Institute of Science and Arts, in Paris. Cuvier, who was twenty-six, had arrived in the city a year earlier, shortly after the end of the Reign of Terror. He had wide-set gray eyes, a prominent nose, and a temperament that a friend compared to the exterior of the earth—generally cool, but capable of violent tremors and eruptions. Cuvier had grown up in a small town on the Swiss border and had almost no connections in the capital. Nevertheless, he had managed to secure a prestigious research position there, thanks to the passing of the ancien régime, on the one hand, and his own sublime self-regard, on the other. An older colleague later described him as popping up in the city "like a mushroom."

For his inaugural lecture, Cuvier decided to speak about elephants. Although he left behind no record to explain his choice, it's likely that it had to do with loot. France was in the midst of the military campaigns that would lead to the Napoleonic Wars, and had recently occupied Belgium and the Netherlands. Booty, in the form of art, jewels, seeds, machinery, and minerals, was streaming into Paris. As the historian of science Martin J. S. Rudwick relates, in "Bursting the Limits of Time" (2005), a hundred and fifty crates' worth was delivered to the city's National Museum of Natural History. Included among the rocks and dried plants were two elephant skulls, one from Ceylon—now Sri Lanka—and the other from the Cape of Good Hope, in present-day South Africa.

By this point, Europe was well acquainted with elephants; occasionally one of the animals had been brought to the Continent as a royal gift, or to travel with a fair. (One touring elephant, known as Hansken, was immortalized by Rembrandt.) Europeans knew that there were elephants in Africa, which were considered to be dangerous, and elephants in Asia, which were said to be more docile. Still, elephants were regarded as elephants, much as dogs were dogs, some gentle and others ferocious. Cuvier, in his first few months in Paris, had examined with care the plundered skulls and had reached his own conclusion. Asian and African elephants, he told his audience, represented two distinct species.

"It is clear that the elephant from Ceylon differs more from that of Africa than the horse from the ass or the goat from the sheep," he declared. Among the animals' many distinguishing characteristics were their teeth. The elephant from Ceylon had molars with wavy ridges on the surface, "like festooned ribbons," while the elephant from the Cape of Good Hope had teeth with ridges arranged in the shape of diamonds. Looking at live animals would not have revealed this difference, as who would have the temerity to peer at an elephant's molars? "It is to anatomy alone that zoology owes this interesting discovery," Cuvier said.

Having successfully sliced the elephant in two, Cuvier continued with his dissection. Over the decades, the museum had acquired a variety of old bones that appeared elephantine. These included a three-and-a-half-foot-long femur, a tusk the size of a jousting lance, and several teeth that weighed more than five pounds each. Some of the bones came from Siberia, others from North America. Cuvier had studied these old bones as well. His conclusions, once again, were unequivocal. The bones were the fragmentary remains of two new species, which differed from both African and Asian elephants "as much as, or more than, the dog differs from the jackal." Moreover—and here one imagines a hush falling over his audience—both creatures had vanished from the face of the earth. Cuvier referred to the first lost species as a mammoth, and the second as an "Ohio animal." A decade later, he would invent a new name for the beast from Ohio; he would call it a mastodon.

"What has become of these two enormous animals of which one no

COURTESY MUSÉUM NATIONAL D'HISTOIRE NATURELLE longer finds any living traces?" Cuvier asked his audience. The question was more than rhetorical. Just a few months earlier, Cuvier had received sketches of a skeleton that had been discovered in Argentina. The skeleton was twelve feet long and six feet high; the sketches showed it to have sharp claws, flattish feet, and a short muzzle. On the basis of the sketches, Cuvier had identified its owner—correctly—as an oversized sloth. He named it Megatherium, meaning "great beast." Though he had never been to Argentina, or, for that matter, anywhere farther than Stuttgart, Cuvier was convinced that the Megatherium was no longer to be found lumbering through the jungles of South America. It, too, had disappeared. Like the mammoth's and the mastodon's, its bones hinted at events both strange and terrible. They "seem to me," Cuvier said, "to prove the existence of a world previous to ours, destroyed by some kind of catastrophe."

Extinction may be the first scientific idea that children today have to grapple with. We give one-year-olds dinosaurs to play with, and two-year-olds understand, in a vague sort of way, at least, that these small plastic creatures represent very large animals that once existed in the flesh. If they're quick learners, kids still in diapers can explain that there were once many kinds of dinosaurs and that they lived long ago. (My own sons, as toddlers, used to spend hours over a set of dinosaurs that could be arranged on a plastic mat depicting a forest from the Cretaceous. The scene featured a lava-spewing volcano, and when you pressed the mat in the right spot it emitted a delightfully terrifying roar.) All of which is to say that extinction strikes us as an extremely obvious idea. It isn't.

Aristotle wrote a ten-book "History of Animals" without considering the possibility that animals actually had a history. Pliny's "Natural History" includes descriptions of animals that are real and animals that are fabulous, but no descriptions of animals that are extinct. The idea did not crop up during the Middle Ages or during the Renaissance, when the word "fossil" was used to refer to anything dug up from the ground (hence the term "fossil fuel"). During the Enlightenment, the prevailing view was that every species was a link in a great, unbreakable "chain of being." As Alexander Pope put it in his "Essay on Man":

> All are but parts of one stupendous whole,
> Whose body nature is, and God the soul.

When Carl Linnaeus introduced his system of binomial nomenclature, he made no distinction between the living and the dead, because, in his view, none was required. The tenth edition of his "Systema Naturae," published in 1758, lists sixty-three species of scarab beetle, thirty-five species of cone snail, and fifteen species of flat fish. And yet in the "Systema Naturae" there is really only one kind of animal—those which exist.

This view persisted despite a growing body of evidence to the contrary. Cabinets of curiosity in London, Paris, and Berlin were filled with traces of strange marine creatures that no one had ever seen—the remains of what would now be identified as trilobites, belemnites, and ammonites. Some of the last were so large that their fossilized shells approached the size of wagon wheels. But the seas were vast and mostly unexplored, and so it was assumed that the creatures must be out there somewhere.

With his lecture on "the species of elephants, both living and fossil," Cuvier finally put an end to this way of thinking. Much as Charles Darwin is often credited with having come up with the theory of evolution—his real insight, of course, involved finding a mechanism for evolution—so Cuvier can be said to have theorized extinction.

Darwin's story has been recited (and re-recited) countless times by now. Entire books have been devoted to the few months he spent in Australia; to his mysterious and quite possibly psychosomatic illness; to the death of his oldest daughter; and to his decade-long study of barnacles. (This last subject is one that Darwin himself seems to have found tedious.) In 2009, when the two-hundredth anniversary of Darwin's birth rolled around, the occasion was marked by scores of events, including an "evolution festival" in Vancouver, an uninterrupted reading of "On the Origin of Species" in Barcelona, and the construction of a massive Darwin doll for the Carnival parade in Recife. That same year, a full-length bio-pic, starring Jennifer Connelly as Darwin's wife (and first cousin), Emma, was released.

Cuvier, though, is very nearly forgotten. Many of his papers have still not been translated into English, and in studies of professional paleontology Cuvier is routinely slighted, even as he is acknowledged to be the founder of the discipline. Unless the situation changes dramatically, the two-hundred-and-fiftieth anniversary of his birth, in 2019, will pass without notice.

Darwin's work is inconceivable without Cuvier's discoveries. And yet Cuvier's obscurity is directly linked to Darwin's fame. Darwin's theory of extinction—that it was a routine side effect of evolution—contradicted Cuvier's, which held that species died out as a result of catastrophes, or, as he also put it, "revolutions on the surface of the earth." Darwin's view prevailed, Cuvier's was discredited, and for more than a century Cuvier was ignored. More recent discoveries, however, have tended to support the theories of Cuvier's that were most thoroughly vilified. Very occasionally, it turns out, the earth has indeed been wracked by catastrophe and, much as Cuvier imagined, "living organisms without number" have been their victims. This vindication of Cuvier would be of interest mainly to paleontologists and intellectual historians were it not for the fact that many scientists believe we are in the midst of such an event right now.

"First thing, Toby—just bend your knees a little and get rid of the cigarette."

Since Cuvier's day, the National Museum of Natural History has grown into a sprawling institution, with outposts all over France. Its main buildings, though, are still in Paris, on the site of the old royal gardens in the Fifth Arrondissement. Cuvier worked at the museum for most of his life, and lived there, too, in a large stucco house that's been converted into office space. Next door to the house, there's a restaurant, and next to that a menagerie, where, on the day I visited, some wallabies were sunning themselves on the grass. Across the gardens, a large hall houses the museum's paleontology collection.

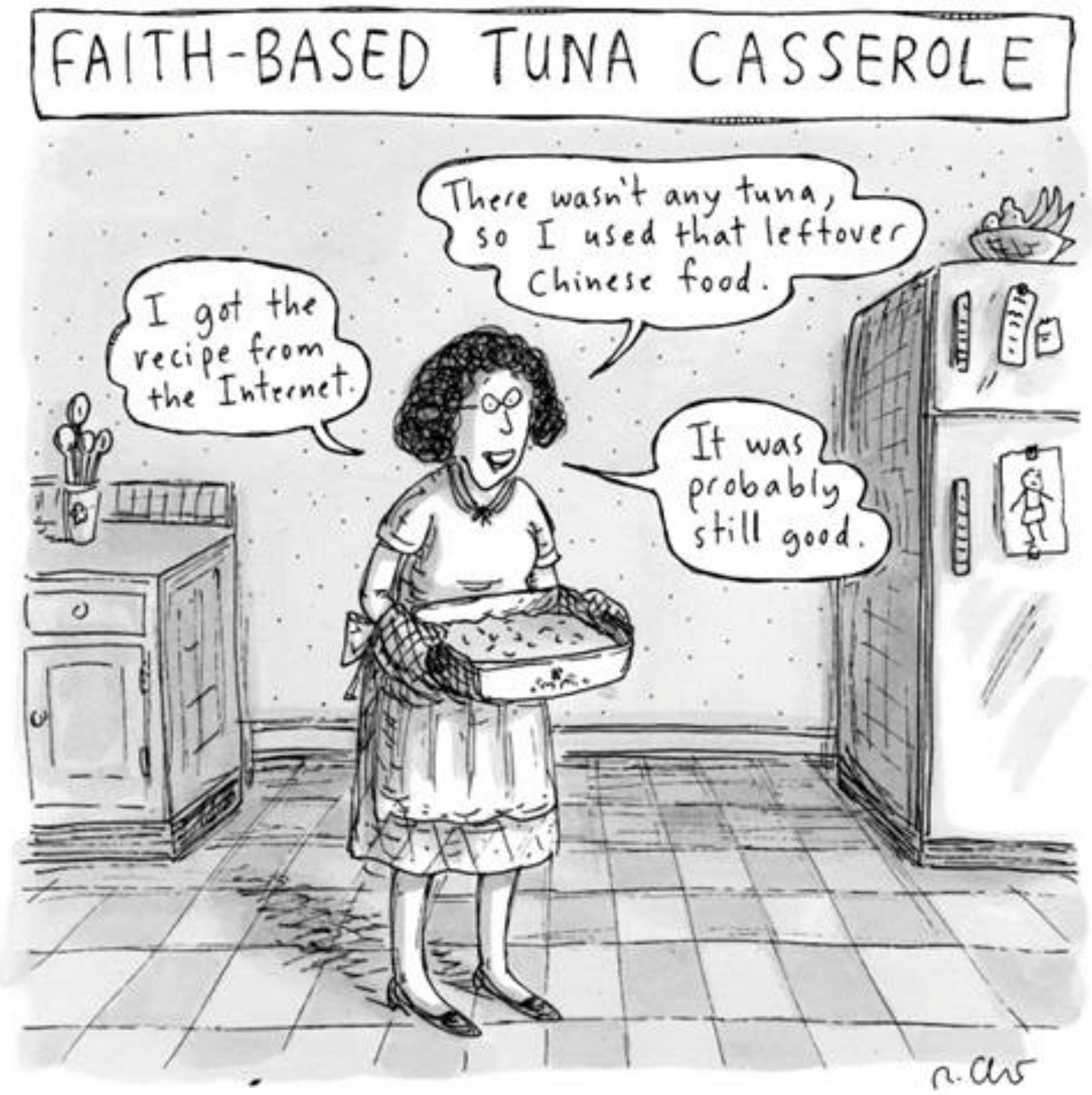
Pascal Tassy is a professor at the museum who specializes in proboscideans, the group that includes elephants and their lost cousins—mammoths, mastodons, and gomphotheres, to name just a few. He'd promised to show me the bones that Cuvier had examined when he came up with the theory of extinction. I found Tassy in his dimly lit office, in the basement under the paleontology hall, sitting amid a mortuary's worth of old skulls. The walls of the office were decorated with covers from old Tintin comic books. Tassy told me he decided to become a paleontologist when he was seven, after reading a Tintin adventure about a dig.

We chatted about proboscideans for a while. "They're a fascinating group," he told me. "For instance, the trunk, which is a change of anatomy in the facial area that is truly extraordinary. It evolved separately five times. Two times—yes, that's surprising. But it happened *five* times, independently! We are forced to accept this by looking at the fossils." So far, Tassy said, some hundred and seventy proboscidean species have been identified, going back some fifty-five million years. "And this is far from complete, I am sure."

We headed upstairs, to an annex attached to the back of the paleontology hall like a caboose. Tassy unlocked a small room crowded with metal cabinets. Just inside the door, partly wrapped in plastic, stood something resembling a hairy umbrella stand. This, he explained, was the leg of a woolly mammoth, which had been found, frozen and desiccated, on an island off Siberia. When I looked at it more closely, I could see that the skin of the leg had been stitched together, like a moccasin. The hair was a very dark brown, and seemed, even after more than ten thousand years, to be almost perfectly preserved.

Tassy opened one of the metal cabinets and placed its contents on a wooden table. These were some of the mastodon teeth that Cuvier had handled. The teeth had been found in the Ohio River Valley, in 1739, by French soldiers, and, though they were there to fight a war, the soldiers had lugged the teeth down the Mississippi and put them on a boat to Paris.

"This is the 'Mona Lisa' of paleontology," Tassy said, pointing to the largest of the group. "The beginning of everything. It's incredible, because Cuvier himself made the drawing of this tooth. So he looked at it very carefully." I picked it up in both hands. It was indeed a remarkable object. It was around eight inches long and four across—about the size of a brick, and nearly as heavy. The cusps—four sets—were pointy, and the enamel was still largely intact. The roots, as thick as



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ropes, formed a solid mass the color of mahogany.

What particularly intrigued Cuvier about the mastodon teeth—and perplexed his predecessors—was that although they'd been found alongside a giant tusk, they didn't look anything like elephant teeth. Instead, they looked as though they could have belonged to an enormous human. (A mastodon molar that was sent to London in another eighteenth-century shipment was labelled "Tooth of a Giant.") In evolutionary terms, the explanation for this is simple: about thirty million years ago, the proboscidean line that would lead to mastodons split off from the line that would lead to elephants and also mammoths. The latter would eventually develop its more sophisticated teeth, which have ridges on the surface, rather than cusps. (This arrangement is a lot tougher, and it allows elephants—and used to allow mammoths—to consume an unusually abrasive diet.)

Mastodons, meanwhile, retained their relatively primitive molars (as did humans) and just kept chomping away. Of course, as Tassy pointed out, the evolutionary perspective is precisely what Cuvier lacked, which in some ways makes his achievements that much more impressive.

"Sure, he made errors," Tassy said. "But his technical works—most of them are splendid. He was a real fantastic anatomist."

After we had examined the teeth awhile longer, Tassy took me up to the paleontology hall. Just beyond the entrance, a giant femur, also sent from the Ohio River Valley to Paris, was displayed, mounted on a pedestal. It was as wide around as a fence post. French schoolchildren were streaming past us, yelling excitedly. Tassy had a large ring of keys, which he used to open various drawers underneath the glass display cases. He showed me a mammoth tooth that had been examined by Cuvier, and bits of various other extinct species that Cuvier had been the first to identify. Then we looked at one of the world's most famous fossils, known as the Maastricht animal—an enormous pointy jaw studded with shark-like teeth. In the eighteenth century, the Maastricht fossil was thought by some to belong to a strange crocodile and by others to be from a snaggletoothed whale. Cuvier attributed it, yet again correctly, to a marine reptile. (The creature was later dubbed a mosasaur.)

Around lunchtime, I walked Tassy back to his office and then wandered through the gardens to the restaurant next to Cuvier's old house. Because it seemed like the thing to do, I ordered the Menu Cuvier—your choice of entrée plus dessert. As I was working my way through the second course—a cream-filled tart—I began to feel uncomfortably full. I was reminded of a description I had read of the anatomist's anatomy. During the Revolution, Cuvier was thin. In the years he lived on the museum grounds, he grew stouter and stouter, until, toward the end of his life, he became enormously fat.

With his lecture on "the species of elephants, both living and fossil," Cuvier had succeeded in establishing extinction as a fact. But his most extravagant assertion—that there had existed a whole lost world, filled with lost species—remained just that. If there had indeed been such a world, then it ought to be possible to find traces of other extinct animals. So Cuvier set out to find them.

Paris in the seventeen-nineties was a fine place to be a paleontologist. The hills to the north of the city were riddled with quarries that were actively producing gypsum, the main ingredient of plaster of Paris. (The capital grew so quickly over so many mines that cave-ins were a major concern.) Not infrequently, quarriers came upon weird bones, which were prized by collectors even though they had no real idea what they were collecting. With the help of one such enthusiast, Cuvier soon assembled the pieces of another extinct animal, which he described as *l'animal moyen de Montmartre*—"the medium-sized animal from Montmartre."

By 1800, four years after the elephant paper, Cuvier's fossil zoo had expanded to include twenty-three species that he deemed to be extinct. Among these were a pygmy hippopotamus, whose remains he found in a storeroom at the Paris museum; an elk with enormous antlers, whose bones had been found in Ireland; and a large bear—what now would be known as a cave bear—from Germany. The Montmartre animal had, by this point, divided, or multiplied, into six separate species. (Even today, little is known about these species except that they were ungulates and lived some thirty to forty million years ago.) "If so many lost species have been restored in so little time, how many must be supposed to exist still in the depths of the earth?" Cuvier asked.

Cuvier had a showman's flair and, long before the museum employed public-relations professionals, knew how to grab attention. ("He was a man who could have been a star on television today," Tassy told me.) At one point, the gypsum quarries around Paris yielded a fossil of a rabbit-size creature with a narrow body and a squarish head. Cuvier hypothesized, based on the shape of its teeth, that the fossil belonged to a marsupial. This was a bold claim, as there were no known marsupials in the Old World. To heighten the drama, Cuvier announced that he would put his identification to a public test. Marsupials have a distinctive pair of bones, now known as epipubic bones, that extend from their pelvis. Though these bones were not visible in the fossil as it was presented to Cuvier, he predicted that, if he scratched around, the missing bones would be revealed. He invited Paris's scientific élite to gather and watch as he picked away at the fossil with a fine needle. Voilà, the bones appeared. (A cast of the marsupial fossil is on display in Paris in the paleontology hall, but the original is deemed too valuable to be exhibited and is kept in a special vault.)

Cuvier staged a similar bit of paleontological performance art during a trip to the Netherlands. In a museum in Haarlem, he examined a specimen that consisted of a large semicircular skull attached to part of a spinal column. The fossil, three feet long, had been discovered nearly a century earlier and had been attributed—rather curiously, given the shape of the head—to a human. (It had even been assigned a scientific name: *Homo diluvii testis*, or "man who was witness to the Flood.") To rebut this identification, Cuvier first found an ordinary salamander skeleton. Then, as Rudwick relates it, he began chipping away at the rock around the deluge man's spine. When he uncovered the fossil animal's forelimbs, they were, just as he had predicted, shaped like a salamander's. The creature was not an antediluvian human but something far weirder: a giant amphibian.

The more extinct species Cuvier turned up, the more the nature of the beasts seemed to change. Cave bears, giant sloths, even giant salamanders—all these bore some relation to species that were still alive. But what to make of a bizarre fossil that had been found in a limestone formation in Bavaria? Cuvier received an engraving of this fossil from one of his many correspondents. It showed a tangle of bones, including what looked to be extremely long arms, skinny fingers, and a narrow beak. The first naturalist to examine it speculated that its owner had been a sea animal and had used its elongated arms as paddles. Cuvier, on the basis of the engraving, determined—shockingly—that the animal was actually a flying reptile. He called it a *ptero-dactyle*, meaning "wing-fingered."

Cuvier's proof of extinction—of "a world previous to ours"—was a sensational event, and news of it soon spread across the Atlantic. When a nearly complete giant skeleton was unearthed by some farmhands in Newburgh, New York, it was recognized as a find of great significance. Vice-President Thomas Jefferson made several attempts to get his hands on the bones. He failed. But a friend, the artist Charles Willson Peale, who'd recently established the nation's first natural-history museum, in Philadelphia, succeeded.

Peale, perhaps an even more accomplished showman than Cuvier, spent months fitting together the bones he acquired from Newburgh, fashioning the missing pieces out of wood and papier-mâché. He presented the skeleton to the public on Christmas Eve, 1801. To publicize the exhibition, Peale had his black servant, Moses Williams, don an Indian headdress and ride through the streets of Philadelphia on a white horse. The reconstructed beast stood eleven feet high at the shoulder and more than seventeen feet long from tusks to tail, a somewhat exaggerated size. Visitors were charged fifty cents—quite a considerable sum at the time—for a viewing. The beast, an American mastodon, at this point still lacked an agreed-upon name, and was variously referred to as an *incognitum*, an Ohio animal, and, most confusing of all, a mammoth. It became America's first blockbuster exhibit, and set off a wave of "mammoth fever." The town of Cheshire, Massachusetts, produced a twelve-hundred-and-thirty-pound "mammoth cheese"; a Philadelphia baker produced a "mammoth bread"; and the newspapers reported on a "mammoth parsnip," a "mammoth peach tree," and a mammoth eater, who "swallowed 42 eggs in ten minutes." Peale also managed to piece together a second mastodon, out of additional bones found in Newburgh and a nearby town in the Hudson Valley. After a celebratory dinner held underneath the animal's capacious rib cage, he dispatched this second skeleton to Europe with two of his sons, Rembrandt and Rubens. The skeleton was exhibited for several months in London, during which time the younger Peales decided that the animal's tusks must have pointed downward, like a walrus's. Their plan was to take the skeleton on to Paris and sell it to Cuvier. But while they were in London war broke out between Britain and France, making travel between the two countries impossible.

Cuvier finally gave the *mastodonte* its name in a paper published in Paris in 1806. The peculiar designation comes from the Greek, meaning "breast tooth"; the cusps on the animal's molars apparently reminded him of nipples.

Despite the ongoing hostilities between the British and the French, Cuvier managed to obtain detailed drawings of the skeleton that Peale's sons had taken to London, and these gave him a much better picture of the animal's anatomy. He realized that the mastodon was far more distant from modern elephants than the mammoth was, and assigned it to a new genus. (Today, mastodons are given not only their own genus but their own family.) In addition to the American mastodon, Cuvier identified four other mastodon species, all "equally strange" to the earth today. Peale didn't learn of Cuvier's new name until 1809, and when he did he immediately seized on it. He wrote to Jefferson proposing a "christening" for the mastodon skeleton in his Philadelphia museum. Jefferson was lukewarm about the name Cuvier had come up with—it "may be as good as any other," he replied—and didn't deign to respond to the idea of a christening.

In 1812, Cuvier published a four-volume compendium of his work on fossil animals—"Recherches sur les Ossemens Fossiles de Quadrupèdes." Before he began his "researches," there had been zero vertebrates classified as extinct. Thanks for the most part to his own efforts, there were now at least forty-nine.

As Cuvier's list grew, so did his renown. Few naturalists dared to announce their findings in public until he had vetted them. "Is not Cuvier the greatest poet of our century?" Balzac asked. "Our immortal naturalist has reconstructed worlds from a whitened bone; rebuilt, like Cadmus, cities from a tooth." Cuvier was honored by Napoleon and, once the Napoleonic Wars finally ended, was invited to Britain, where he was presented at court.

The English were eager converts to Cuvier's project. In the early years of the nineteenth century, fossil collecting became so popular among the upper classes that a whole new vocation sprang up. A "fossilist" was someone who made a living hunting up specimens for rich patrons. The year Cuvier published his "Recherches," one such fossilist, a young woman named Mary Anning, discovered a particularly outlandish specimen. The creature's skull, found in the limestone cliffs of Dorset, was nearly four feet long, with a jaw shaped like a pair of needle-nose pliers. Its eye sockets, peculiarly large, were covered with bony plates.

The fossil ended up in London at the Egyptian Hall, a privately owned museum not unlike Peale's. It was put on exhibit as a fish and then as a relative of a platypus before being recognized as a new kind of reptile—an ichthyosaur, or "fish-lizard." A few years later, other specimens collected by Anning yielded pieces of another, even wilder creature, dubbed a plesiosaur, or "almost-lizard." Oxford's geology expert, the Reverend William Buckland, described the plesiosaur as having a lizardlike head joined to a neck "resembling the body of a Serpent," the "ribs of a Chameleon, and the paddles of a Whale." Apprised of the find, Cuvier found the account of the plesiosaur so outrageous that he questioned whether the specimen had been doctored. When Anning uncovered another, nearly complete plesiosaur fossil, Cuvier had to acknowledge that he'd been wrong. "One shouldn't anticipate anything more monstrous to emerge," he wrote to one of his British correspondents. During Cuvier's trip to England, he visited Oxford, where Buckland showed him yet another astonishing fossil—an enormous jaw with one curved tooth sticking up out of it like a scimitar. Cuvier recognized this animal, too, as some sort of lizard. A couple of decades later, the jaw was identified as belonging to a dinosaur.

The study of stratigraphy was in its infancy at this point, but it was already understood that different layers of rocks had been formed during different periods. The plesiosaur, the ichthyosaur, and the as yet unnamed dinosaur had all been found in limestone deposits that were attributed to what was then called the Secondary and is now known as the Mesozoic era. So, too, had the *pterodactyle* and the Maastricht animal. This pattern led Cuvier to another extraordinary insight about the history of life: it had a direction. Lost species whose remains could be found near the surface of the earth, like mastodons and cave bears, belonged to orders of creatures that were still alive. Dig back further and one found creatures, like the animals from Montmartre, that had no obvious modern counterparts. Keep digging, and mammals disappeared altogether from the fossil record. Eventually, one reached not just a world previous to ours but a world previous to that, dominated by giant reptiles.

Cuvier's ideas about this history of life—that it was long, mutable, and full of fantastic creatures that no longer existed—would seem to have made him a natural advocate for evolution. But he opposed the concept of evolution, or *transformisme*, as it was known in Paris at the time, and he tried—generally, it seems, successfully—to humiliate any colleagues who advanced the theory. Curiously, it was the same skills that led him to discover extinction that made evolution appear to him preposterous, an affair as unlikely as alchemy.

As Cuvier liked to point out, he put his faith in anatomy; this was what had allowed him to distinguish the bones of a mammoth from those of an elephant and to recognize as a giant salamander what others took to be a man. At the heart of his understanding of anatomy was a notion that he termed "correlation of parts." By this, he meant that the components of an animal all fit together and are optimally designed for its particular way of life; thus, a carnivore will have an intestinal system suited to digesting flesh. Its jaws will be "constructed for devouring prey; the claws, for seizing and tearing it; the teeth, for cutting and dividing its flesh; the entire system of its locomotive organs, for pursuing and catching it; its sense organs for detecting it from afar."

Conversely, an animal with hooves must be an herbivore, since it has "no means of seizing prey." It will have "teeth with a flat crown, to grind seeds and grasses," and a jaw capable of lateral motion. Were any one of these parts to be altered, the functional integrity of the whole would be destroyed. An animal that was born with, say, teeth or sense organs that were somehow different from its parents' would not be able to survive, let alone give rise to an entirely new kind of creature.

In Cuvier's day, the most prominent proponent of *transformisme* was his senior colleague at the National Museum of Natural History, Jean-Baptiste Lamarck. According to Lamarck, there was a force—the "power of life"—that pushed organisms to become increasingly complex. At the same time, animals and also plants often had to cope with changes in their environment. They did so by adjusting their habits; these new habits, in turn, produced physical modifications that were then passed down to their offspring. Birds that sought prey in lakes spread out their toes when they hit the water, and eventually developed webbed feet and became ducks. Moles, having moved underground, stopped using their sight, and so over generations their eyes became small and weak. Lamarck adamantly opposed Cuvier's idea of extinction; there was no process he could imagine that was capable of wiping an organism out entirely. (Interestingly, the only exception he entertained was humanity, which, Lamarck allowed, might be able to exterminate certain large and slow-to-reproduce animals.) What Cuvier interpreted as *espèces perdues* Lamarck claimed were simply those that had been most completely transformed.

The notion that animals could change their body types when convenient Cuvier found absurd. He lampooned the idea that "ducks by dint of diving became pikes; pikes by dint of happening upon dry land changed into ducks; hens searching for their food at the water's edge, and striving not to get their thighs wet, succeeded so well in elongating their legs that they became herons or storks." He discovered what was, to his mind at least, definitive proof against *transformisme* in a collection of mummies.

When Napoleon invaded Egypt, the French, as usual, seized whatever interested them. Among the crates of loot shipped back to Paris was an embalmed cat. Cuvier examined the mummy, looking for signs of transformation. He found none. The ancient Egyptian cat was, anatomically speaking, indistinguishable from a Parisian alley cat. This proved that species were fixed. Lamarck objected that the few thousand years that had elapsed since the Egyptian cat was embalmed represented "an infinitely small duration" relative to the vastness of time.

"I know that some naturalists rely a lot on the thousands of centuries that they pile up with a stroke of the pen," Cuvier responded dismissively. Eventually, he was called upon to compose a eulogy for Lamarck, which he did very much in the spirit of burying rather than praising. Lamarck, according to Cuvier, was a fantasist. Like the "enchanted palaces of our old romances," his theories were built on "imaginary foundations," so that, while they might "amuse the imagination of a poet," they could not "for a moment bear the examination of anyone who has dissected a hand, a viscus, or even a feather."

Having dismissed *transformisme*, Cuvier was left with a gaping hole. He had no account of how new organisms could appear, or any explanation for

"I'm not Santa, kid—I'm just an overweight hipster with a bag full of dumpster garbage."

how the world could have come to be populated by different groups of animals at different times. This doesn't seem to have bothered him. His interest, after all, was not in the origin of species but in their demise.

The very first time he spoke about the subject, Cuvier intimated that he knew the driving force behind extinction, if not the exact mechanism. In his lecture on elephants, he proposed that the mastodon, the mammoth, and the Megatherium had all been wiped out "by some kind of catastrophe." Cuvier hesitated to speculate about the precise nature of the calamity—"It is not for us to involve ourselves in the vast field of conjectures that these questions open up"—but, at that point, he seems to have believed that one disaster would have sufficed.

Later, as his list of extinct species grew, his position changed. There had, he decided, been multiple cataclysms. "Life on earth has often been disturbed by terrible events," he wrote. "Living organisms without number have been the victims of these catastrophes."

Like his view of *transformisme*, Cuvier's belief in cataclysm fit with—indeed, could be said to follow from—his convictions about anatomy. Since animals were functional units, ideally suited to their circumstances, there was no reason, in the ordinary course of events, that they should die out. Not even the most devastating events known to occur in the contemporary world—volcanic eruptions, say, or forest fires—were sufficient to explain extinction; confronted with such changes, organisms simply moved on and survived. The changes that had caused extinctions must therefore have been of a much greater magnitude—so great that animals had been unable to cope with them. That such extreme events had never been observed by him or any other naturalist was another indication of nature's mutability: in the past, it had operated differently—more intensely and more savagely—than it did at present.

"The thread of operations is broken," Cuvier wrote. "Nature has changed course, and none of the agents she employs today would have been sufficient to produce her former works." Cuvier spent several years studying the rock formations around Paris—together with a mineralogist friend, he produced the first stratigraphic map of the Paris Basin—and here, too, he saw signs of cataclysmic change. The rocks showed that, at various points, the region had been submerged. The shifts from one environment to another—from marine to terrestrial, or, at some points, from marine to freshwater—had, Cuvier decided, "not been slow at all"; rather, they had been brought about by those sudden "revolutions" on the surface of the earth. The latest of these revolutions must have occurred relatively recently, for traces of it were still everywhere apparent. This event, Cuvier believed, lay just beyond the edge of recorded history; he observed that many ancient myths and texts, including the Old Testament, allude to some sort of crisis—usually a deluge—that preceded the present order.

Cuvier's ideas about a globe wracked periodically by cataclysm proved to be nearly as influential as his original discoveries. His major essay on the subject, which was published in Paris in 1812, was almost immediately reprinted in English and exported to America. It also appeared in German, Swedish, Italian, and Russian. But a good deal was lost, or, at least, misinterpreted in translation. Cuvier's essay was pointedly secular. He cited the Bible as merely one of many ancient texts, alongside the Hindu Vedas and the Shujing. This sort of ecumenism was unacceptable to the Anglican clergy who made up the faculty at institutions like Oxford, and when the essay was translated into English it was construed by Buckland and others as offering proof of Noah's flood.

By now, the empirical grounds of Cuvier's theory have largely been disproved. The physical evidence that convinced him of a "revolution" just prior to recorded history (and that the English interpreted as proof of the Deluge) was in reality debris left behind by the last glaciation. The stratigraphy of the Paris Basin reflects not sudden "irruptions" of water but, rather, gradual changes in sea level and the effects of plate tectonics. On all these matters, Cuvier was, we now know, wrong.

Yet his wildest-sounding claims have turned out to be surprisingly accurate. Cataclysms happen. Nature does, on occasion, "change course," and at such moments it is as if the "thread of operations" has been broken. The contemporary term for these cataclysms is "mass extinctions," and the geological record suggests that, in the past half billion years, there have been five major ones and a dozen or more lesser ones. In the most severe of the so-called Big Five, at the end of the Permian period, some two hundred and fifty million years ago, something like ninety per cent of all species died off, and multicellular life came perilously close to being obliterated altogether. In the most recent, at the end of the Cretaceous, the dinosaurs were wiped out, along with the mosasaurs, the pterosaurs, the plesiosaurs, the ammonites, and two-thirds of all families of mammals, all in what, geologically speaking, amounted to an instant.

Meanwhile, as far as the American mastodon is concerned, Cuvier was to an almost uncanny extent correct. He decided that the beast had disappeared five or six thousand years ago, in the same "revolution" that had killed off the mammoth and the Megatherium. Actually, the American mastodon vanished around thirteen thousand years ago, in a wave of disappearances that has become known as the megafauna extinction. This wave coincided with the spread of modern humans, and, increasingly, is understood to have been a result of it. Humans are now so rapidly transforming the planet—changing the atmosphere, altering the chemistry of the oceans, reshuffling the biosphere—that many scientists argue that we've entered a whole new geological epoch: the Anthropocene. In this sense, the crisis that Cuvier discerned just beyond the edge of recorded history was us. ♦

(This is the first part of a two-part article.)

From the San Diego Union-Tribune.

Fibromyalgia is a complicated and often debilitating chronic pain condition that afflicts an estimated 6 million Americans. It is largely misunderstood because it affects the central nervous system, but symptoms can include joint and muscle pain, sleep disruption, mood disorder and decreased physician function.

Talk about empathy.

ANNALS OF EXTINCTION PART TWO

THE LOST WORLD

Fossils of the future.

BY ELIZABETH KOLBERT

The Geological Society of London, known to its members as the Geol Soc (pronounced "gee-ahl sock"), was founded in 1807, over dinner in a Covent Garden tavern. Geology was at that point a brand-new science, a circumstance reflected in the society's goals, which were to stimulate "zeal" for the discipline and to induce participants "to adopt one nomenclature." There followed long, often spirited debates on matters such as where to fix the borders of the Devonian period. "Though I don't much care for geology," one visitor to the society's early meetings noted, "I do like to see the fellows fight."

The Geol Soc is now headquartered in a stone mansion not far from Piccadilly Circus. On the outside, the style of the mansion is Palladian; inside, it leans more toward mid-century public library. Much of the place is wrapped in plastic, owing to a construction project that never quite seems to reach completion. Near the reception desk, behind a green velvet curtain, hangs a copy of the first geological map of Britain, which was published in 1815 by William Smith. (Smith's British biographer has called the map "one of the classics of English science"; his American counterpart has pronounced it "the map that changed the world.") At the top of the stairs, there's a reading room with a brass chandelier, a few armchairs, some scuffed tables, and a broken coffee machine.

On a sunny morning not long ago, Jan Zalasiewicz, a stratigrapher and longtime society member, was sitting in the reading room, wishing the coffee machine were functional so that he could make a cup of tea. Zalasiewicz is a slight, almost elfin man with shaggy graying hair and narrow blue eyes. He had come down to London that morning from his home, in Nottinghamshire, to give a visitor a tour. His perspective on the Geol Soc, and on the city more generally, was, he had to admit, idiosyncratic.

"This building has never been considered as a rock before," he observed. "But it is just as much made of geology as anything you would find out in the field.

"Clearly, very few of these objects will survive Pompeii style," he went on, gesturing, with a faraway look in his eyes, toward the chairs, the tables, the magazine racks, and the coffee machine. "But they won't simply disappear. They'll break down into rubble, and the rubble will be washed away. But even the rubble that's been washed away will have its own character, its own signal." He swivelled to take in the windows (mostly silica) and the panelling (made of wood). "Potentially, everything here is fossilizable," he said.

Walter White-like, Zalasiewicz leads a double life. By day, he's an expert on a group of ancient marine organisms known as graptolites. Zalasiewicz deeply admires graptolites, which thrived and diversified in the early Paleozoic, some five hundred million years ago, only to be very nearly wiped out in a catastrophic extinction event. Present him with a fossilized graptolite and he can tell you at a glance which biozone of the Silurian period it belongs to.

In his off-hours, Zalasiewicz is a provocateur, or, to be more British about it, "a scientific hooligan." He has more or less invented a new discipline, which might be called the stratigraphy of the future. It is based on a simple, if disturbing, premise: humans are so radically refashioning the planet—levelling so many forests, eliminating so many creatures that once occupied those forests, transporting so many other creatures around the globe, and burning through such vast quantities of fossil fuels to keep the whole enterprise going—that we may well end up producing a catas-

Graptolites indicate a major die-off. What will the fossils of our own day reveal?

COURTESY JAN A. ZALASIEWICZ

trophe comparable in scale to the one that laid waste to the graptolites. Already, Zalasiewicz is convinced, the geology of the planet has been permanently altered. The signal that will be left behind by our cities, our carbon emissions, and our potentially fossilizable detritus is strong enough, he maintains, that even a moderately competent stratigrapher, at a distance of a hundred million years or so, should be able to tell that something extraordinary happened in what to us represents the present. "We have already left a record that is now indelible," he has written.

In recognition of the ways that, collectively, we are all world-changers, Zalasiewicz believes that an adjustment in nomenclature is called for. Officially, our epoch is the Holocene, but Zalasiewicz believes it would probably be more accurate to say that we have entered the Anthropocene. He is trying to persuade his colleagues to formally consider this new term. He hopes to bring the matter to a vote of the International Commission on Stratigraphy in 2016. If he has his way, every geology textbook in the world will instantly become obsolete.

The path led up a hill, across a stream, back across the stream, and past the carcass of a sheep, which looked deflated, like a lost balloon. The hill was bright green, but treeless; generations of the sheep's relatives had kept anything from growing much above muzzle height. As far as I was concerned, it was raining. But in the Southern Uplands of Scotland, I was told, this counted only as a light drizzle, or smirr.

Zalasiewicz and I and two of his colleagues from the British Geological Survey had driven for more than five hours to get to the Uplands from the Survey's headquarters, near Nottingham. We were hiking to a spot called Dob's Linn, where, according to an old ballad, the Devil himself was pushed over a precipice by a pious shepherd named Dob. By the time we reached the cliff, the smirr seemed to be smirring harder. There was a view over a waterfall, which crashed down into a narrow valley. A few yards farther up the path loomed a jagged outcropping of rock. It was striped vertically, like a referee's jersey, in bands of light and dark. Zalasiewicz set his rucksack down on the soggy ground and adjusted his red rain jacket. He pointed to one of the dark-colored stripes. "Bad things happened in here," he told me.

Much as Civil War buffs visit Gettysburg, stratigraphers are drawn to Dob's Linn. It's one of those rare places where, owing to an accident of plate tectonics, a major turning point in life's history is visible right on the surface of the earth. In this case, the event is the end-Ordovician extinction, which occurred some four hundred and forty million years ago. In addition to nearly knocking out the graptolites, it killed off something like eighty per cent of the planet's species. ("Had the list of survivors been one jot different," Richard Fortey, a British paleontologist and a recent president of the Geol Soc, has observed, "then so would the world today.") Not coincidentally, Dob's Linn is also a great place to find graptolites.

To the naked eye, graptolite fossils look a bit like scratches and a bit like hieroglyphics. ("Graptolite" comes from the Greek, meaning "written rock"; the term was coined by Linnaeus, who dismissed graptolites as mineral encrustations trying to pass themselves off as the remnants of animals.) Viewed through a hand lens, they often prove to have lovely, evocative shapes; one species suggests a feather, another a lyre, a third the frond of a fern. Graptolites were colonial animals. Each one, known as a zooid, built itself a tiny, tubular shelter, known as a theca, that was attached to its neighbor's, like a row house. A single graptolite fossil thus represents a whole community, which drifted or, more probably, swam along as a single entity, feeding off even smaller plankton. Zalasiewicz lent me a hammer, and one of the graptolites I hacked out of the rock face had been preserved with peculiar clarity. It was shaped like a set of false eyelashes, but very small, as if for a Barbie. Zalasiewicz told me—doubtless exaggerating—that I had found a "museum-quality specimen." I pocketed it.

Graptolites had a habit—endearing from a stratigrapher's point of view—of speciating, spreading out, and dying off, all in relatively short order. Zalasiewicz likened them to Natasha, the tender heroine of "War and Peace." They were, he told me, "delicate, nervous, and very

"You can't compete with a retired pharmacist."

• •

sensitive to things around them." This makes them useful "index fossils"—successive species can be used to identify successive layers of rock.

Once Zalasiewicz showed me what to look for at Dob's Linn, I, too, could see that "bad things" happened here. The dark stripes were shale; in them, graptolites were plentiful and varied. This indicated that there was nothing alive to consume the animals once they'd died and sunk to the seafloor. Soon, I'd collected so many that the pockets of my jacket were sagging. Many of the fossils were variations on the letter "V," with two arms branching away from a central node. Some looked like zippers, others like wishbones. Still others had arms growing off their arms, like tiny trees.

The lighter stone—also shale—was barren, with barely a graptolite to be found in it. Paradoxically, this was a sign of a healthy ocean floor, with lots of scavengers living in the muck. The transition from one state to another—from gray stone to black, from no graptolites to many—appears to have occurred suddenly and, according to Zalasiewicz, *did* occur suddenly. "The change here from gray to black marks a tipping point, if you like, from a habitable seafloor to an uninhabitable one," Zalasiewicz said. "And one might have seen that in the span of a human lifetime." He described this transition as "Cuvierian."

Zalasiewicz's colleagues from the British Geological Survey, Dan Condon and Ian Millar, had come to Dob's Linn to collect samples from the various stripes. (Zalasiewicz also worked for many years at the B.G.S.; he now teaches at the University of Leicester.) The samples, they hoped, would contain tiny crystals of zircon, which, after some complicated chemical manipulations, would allow them to date the layers of rock quite precisely. Millar, who grew up in Scotland, at first claimed to be undaunted by the smirr. But after a while even he admitted that it was pouring. Rivulets of mud were cascading down the face of the outcropping, compromising the samples. It was decided that we would have to come back the following day. The geologists packed up their gear and we squished back down the trail to the car. Zalasiewicz had made reservations at a bed-and-breakfast in the nearby town of Moffat. The town's attractions, I had read, included Britain's narrowest hotel and a bronze sheep.

The idea that the world can change suddenly and drastically—"in the span of a human lifetime"—is very old and, at the same time, very new. To the early members of the Geol Soc, the role of catastrophe in the earth's history was self-evident. These men—and they were, of course, all men—had read the great nineteenth-century French naturalist Georges Cuvier, who interpreted the fossil record as a chronicle of recurring tragedy. (When the Napoleonic Wars ended, in 1815, Cuvier was made an honorary Geol Soc member.)

"Life on earth has often been disturbed by terrible events," Cuvier wrote. "Living organisms without number have been the victims of these catastrophes."

Cuvier's view of life was challenged by Charles Lyell, another of the nineteenth century's most influential naturalists. According to Lyell, who served as the Geol Soc's fourteenth president and also as its twenty-first, the earth was capable of changing only very gradually. The way to understand the distant past was to look at the present. Since no one had ever seen the kind of cataclysm that Cuvier invoked, it was unscientific, or, to use Lyell's term, "unphilosophical," to imagine that such events took place. If it appeared from the fossil record that the world had changed abruptly, Lyell maintained, this just went to show how little the record was to be trusted.

Among the early converts to Lyell's view was Charles Darwin. In "On the Origin of Species," Darwin acknowledged that there were points in the earth's history when it appeared that "whole families or orders" had suddenly been exterminated. But, like Lyell, he took this as evidence that "wide intervals of time" were unaccounted for. Had the evidence of these intervals not been lost, it would have shown "much slow extermination." He wrote, "So profound is our ignorance, and so high our presumption, that we marvel when we hear of the extinction of an organic being; and as we do not see the cause, we invoke cataclysms to desolate the world!"

Such was Lyell and Darwin's influence that for more than a century, even as it became increasingly clear that "whole families or orders" had indeed at various points suddenly been eliminated, geologists eschewed any account of these episodes that might be construed as Cuvierian. This reluctance extended into the nineteen-eighties, when it was proposed that an asteroid plowing into the earth at the end of the Cretaceous period, sixty-five million years ago, was what had done in the dinosaurs, along with the plesiosaurs, the mosasaurs, the pterosaurs, the ammonites, most birds, and a significant proportion of mammals. The impact hypothesis was resisted until the nineteen-nineties, when the existence of a huge impact crater formed precisely at the end of the Cretaceous was confirmed. The crater lies off the Yucatán Peninsula, buried under half a mile of newer sediment.

While the discovery of the impact crater didn't exactly invalidate Lyell and Darwin's model, it revealed their dismissal of catastrophe to have been itself "unphilosophical." Life on earth *has* been "disturbed by terrible events," and "living organisms without number" have been their victims. What is sometimes called "neocatastrophism," but is mostly now just considered mainstream geology, holds that the world changes only very slowly, except when it doesn't.

As best as can be determined, the rate of change today is as fast as it's been at any time since the asteroid impact. This is why Zalasiewicz believes that the stratigraphers of the future should have a relatively easy time of it, even though who or what was responsible for the sudden alteration of the planet may not immediately be clear. At one point, he mused, "It may take them a little while to sort out whether we were the drivers of this, or if the cats or the dogs or the sheep were."

After everyone had changed into dry clothes, we met in the sitting room of the B. and B. for tea. Zalasiewicz had brought along several papers he had recently published on graptolites. Settling back in their chairs, Condon and Millar rolled their eyes. Zalasiewicz ignored them, patiently explaining to me the import of his latest monograph, "Graptolites in British Stratigraphy," which ran to sixty-six pages and included illustrations of more than six hundred and fifty species. In the monograph, the effects of the extinction event showed up more systematically, if also less vividly, than on the rain-slicked hillside. Until the end of the Ordovician, V-shaped graptolites were common. These included species like the *Dicranograptus ziczac*, whose tiny cups were arranged along arms that curled away and then toward each other, like tusks; and *Amphigraptus divergens*, which was shaped like a bat in flight. Only a handful of graptolite species survived the end-Ordovician extinction, which, it's now believed, was caused by the sudden glaciation of the supercontinent Gondwana. (No one is entirely sure what caused this glaciation.) Eventually, the surviving graptolites diversified and repopulated the seas of the Silurian. But Silurian graptolites had a streamlined body plan, more like a stick than like a set of branches. The V shape had been lost, never to reappear. Here, writ very, very small, was the fate of the dinosaurs, the pterosaurs, and the ammonites—a once highly successful form now relegated to oblivion.

That evening, when everyone had had enough of tea and graptolites, we went out to the pub on the ground floor of Britain's narrowest hotel, which is twenty feet across. After a pint or two, the conversation turned to another one of Zalasiewicz's favorite subjects: giant rats. Zalasiewicz pointed out that rats have followed humans to just about every corner of the globe, and it is his professional opinion that one day they will take over the earth.

"Some number will probably stay rat-size and rat-shaped," he told me. "But others may well shrink or expand. Particularly if there's been epidemic extinction and ecospace opens up, rats may be best placed to take advantage of that. And we know that change in size can take place fairly quickly." I recalled once watching a rat drag a pizza crust along the tracks at an Upper West Side subway station. I imagined it waddling through a deserted tunnel, blown up to the size of a Doberman.

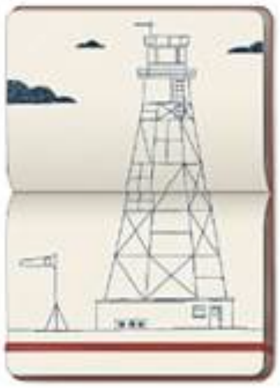
Though the connection might seem tenuous, Zalasiewicz's interest in giant rats represents a logical extension of his interest in graptolites. When he studies the Ordovician and the Silurian, he's trying to reconstruct the distant past on the basis of the fragmentary clues that remain—fossils, isotopes of carbon, layers of sedimentary rock. When he contemplates the future, he's trying to imagine what will remain of the present once the contemporary world has been reduced to fragments—fossils, isotopes of carbon, layers of sedimentary rock. One of the many aspects of the Anthropocene that he believes will leave a permanent mark is a reshuffling of the biosphere.

Often purposefully and just as often not, people have transported living things around the globe, importing the flora and fauna of Asia to the Americas and of the Americas to Europe and of Europe to Australia. Rats have consistently been in the vanguard of these movements, and they have left their bones scattered everywhere, including on islands so remote that humans never bothered to settle them. The Pacific rat, *Rattus exulans*, a native of Southeast Asia, travelled with Polynesian seafarers to, among many other places, Hawaii, Fiji, Tahiti, Tonga, Samoa, Easter Island, and New Zealand. Encountering few predators, stowaway *Rattus exulans* multiplied into what Richard Holdaway, a New Zealand paleontologist, has described as "a grey tide" that turned "everything edible into rat protein." (A recent study in the *Journal of Archaeological Science* concluded that it wasn't humans who deforested Easter Island; rather, it was the rats that came along for the ride and then bred unchecked. The native palms couldn't produce seeds fast enough to keep up with their appetite.)

When Europeans arrived in the Americas, and then continued west to the islands that the Polynesians had settled, they brought with them the even more adaptable Norway rat, *Rattus norvegicus*. In many places, Norway rats, which are actually from China, outcompeted the earlier rat invaders and ravaged whatever bird and reptile populations the Pacific rats had missed. Rats thus might be said to have created their own "ecospace," which their progeny seem well positioned to dominate. The descendants of today's rats, according to Zalasiewicz, will radiate out to fill the niches that *Rattus exulans* and *Rattus norvegicus* helped empty. He imagines the rats of the future evolving into new shapes and sizes—some "smaller than shrews," others as large as elephants.

"We might," he has written, in "The Earth After Us" (2008), "include among them—for curiosity's sake and to keep our options open—a species or two of large naked rodent, living in caves, shaping rocks as primitive tools and wearing the skins of other mammals that they have killed and eaten."

Meanwhile, whatever the future holds for rats, the extinction event that they are helping to bring about will leave its own mark. Many evolutionary lineages have recently come to an end; many, many more are likely soon to follow. Extinction rates today are hundreds of times higher—for some groups, such as amphibians and freshwater mollusks, perhaps thousands, or even tens of thousands, of times higher—than they've been since mammals took over the "ecospace" emptied by the dinosaurs. For reasons of geological history, the current extinction event is often referred to as the "sixth extinction." (By this accounting, the event recorded in the rocks at Dob's Linn is the first of the five major mass extinctions that have occurred since complex animal life evolved.) Whether the "sixth extinction" will turn out to be anywhere near as drastic as the first is impossible to know; nevertheless, it is likely to appear in the fossil record as a turning point. Climate change—itself a driver of extinction—will also leave behind geological traces, as will deforestation, industrial pollution, and monoculture farming.



Ultimately, most of our carbon emissions will end up in the oceans; this will dramatically alter the chemistry of the water, turning it more acidic. Ocean acidification is associated with some of the worst crises in biotic history, including what's known as the end-Permian extinction—the third of the so-called Big Five—which took place roughly two hundred and fifty million years ago and killed off something like ninety per cent of the species on the planet.

"Oh, ocean acidification," Zalasiewicz said when we returned to Dob's Linn the following day. "That's the big nasty one that's coming down."

In recent years, a number of names have been proposed for the new age that humans have ushered in. The noted conservation biologist Michael Soulé has suggested that, instead of the Cenozoic, we now live in the "Catastrophozoic" era. Michael Samways, an entomologist at South Africa's Stellenbosch University, has floated the term "Homogenocene." Daniel Pauly, a Canadian marine biologist, has recommended the "Myxocene," from the Greek word for "slime," and Andrew Revkin, an American journalist, has offered the "Anthrocene." (Most of these terms owe their origins, indirectly at least, to Lyell, who, back in the eighteen-thirties, coined the names Eocene, Miocene, and Pliocene.)

The word "Anthropocene" was put into circulation by Paul Crutzen, a Dutch chemist who, in 1995, shared a Nobel Prize for discovering the effects of ozone-depleting compounds. The importance of this discovery is difficult to overstate. Had it not been made—and had the chemicals continued to be widely used—the ozone "hole" that opens up every spring over Antarctica would have expanded until, eventually, it encircled the entire globe. One of Crutzen's fellow-Nobelists reportedly came home from his lab one night and said to his wife, "The work is going well, but it looks like the end of the world."

Crutzen once told me that the word "Anthropocene" came to him while he was in a meeting. The meeting's chairman kept referring to the Holocene, the "wholly recent" epoch, which began at the conclusion of the last ice age, eleven and a half thousand years ago. According to the International Commission on Stratigraphy, or I.C.S., which maintains the official geological time scale, the Holocene continues to this day.

" 'Let's stop it,' " Crutzen recalled blurting out. " 'We are no longer in the Holocene; we are in the Anthropocene.' Well, it was quiet in the room for a while." At the next coffee break, the Anthropocene was the main topic of conversation. Someone came up to Crutzen and suggested that he patent the term.

Crutzen wrote up his idea in a short essay, titled "Geology of Mankind," which ran in the journal *Nature*. "It seems appropriate to assign the term 'Anthropocene' to the present, in many ways human-dominated, geological epoch," he observed. Among the many geologic-scale changes people have effected, Crutzen cited the following:

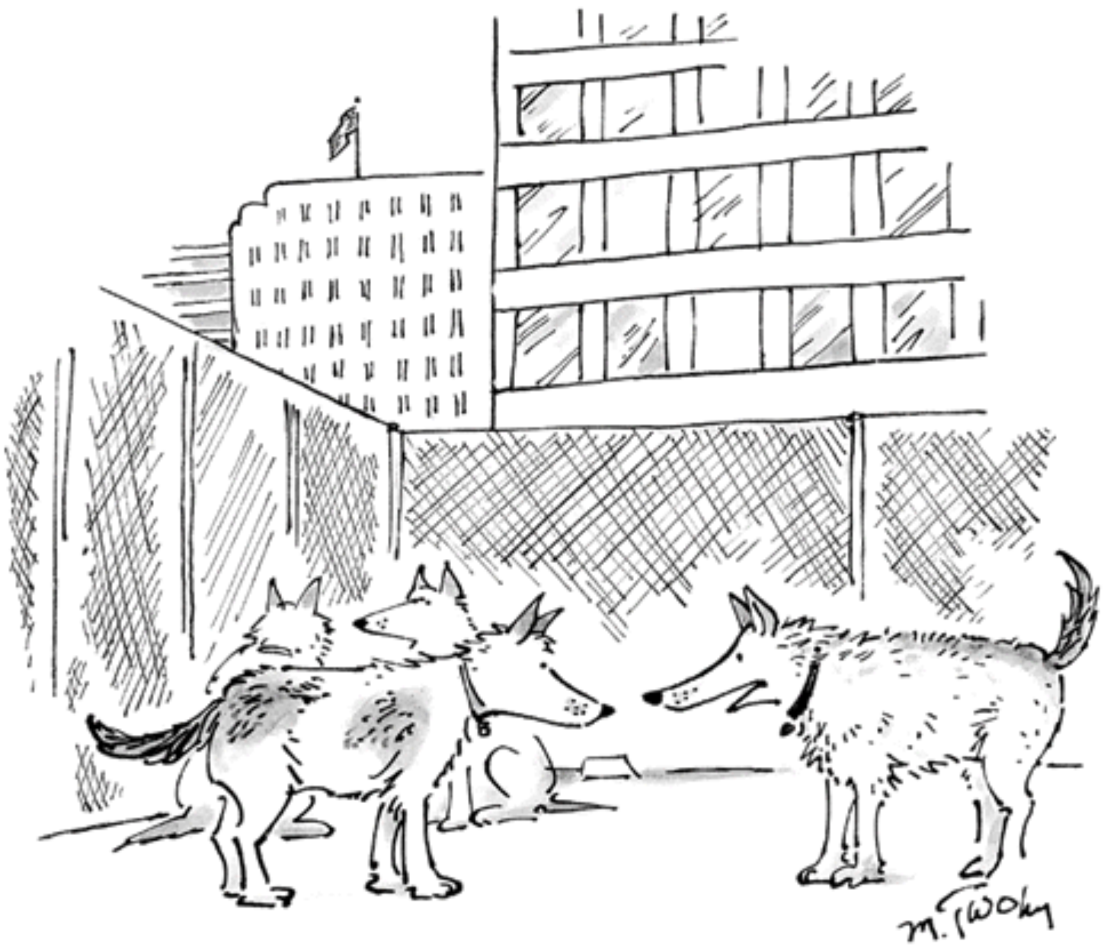
> Human activity has transformed between a third and a half of the land surface of the planet.
>
> Many of the world's major rivers have been dammed or diverted.
>
> Fertilizer plants produce more nitrogen than is fixed naturally by all terrestrial ecosystems.
>
> Humans use more than half of the world's readily accessible freshwater runoff.

Most significant, Crutzen noted, people have altered the composition of the atmosphere. Owing to a combination of fossil-fuel combustion and deforestation, the concentration of carbon dioxide in the air has risen by more than a third in the past two centuries, while the concentration of methane, an even more potent greenhouse gas, has more than doubled. Just a few more decades of emissions may bring atmospheric CO_2 to a level not seen since the mid-Miocene, fifteen million years ago. A few decades after that, it could easily reach a level not seen since the Eocene, some fifty million years ago. During the Eocene, palm trees flourished in the Antarctic, and alligators paddled around the British Isles.

"Because of these anthropogenic emissions," Crutzen wrote, the global climate is likely to "depart significantly from natural behavior for many millennia to come."

Crutzen published "Geology of Mankind" in 2002. Soon, the Anthropocene began migrating into other scientific journals. "Global Analysis of River Systems: From Earth System Controls to Anthropocene Syndromes" was the title of a 2003 article in the journal *Philosophical Transactions of the Royal Society B*. "Soils and Sediments in the Anthropocene," ran the headline of a piece, from 2004, in the *Journal of Soils and Sediments*.

Zalasiewicz noticed that most of those using the term were not trained in the fine points of stratigraphy, and he wondered how his colleagues felt about this. At the time, he was head of the Geol Soc's stratigraphy committee, and during a meeting one day he asked the members what they thought of the Anthropocene. Of the twenty-two



"Did you hear—we're being transferred from bomb-sniffing to trans fats."

stratigraphers present, twenty-one thought that the concept had merit.

"My response was it's a very interesting and powerful idea," Andy Gale, a professor at the University of Portsmouth, told me. "I felt it was worthwhile to pursue, because it's an important tool for making people think."

The group decided to approach the concept as a formal problem. Would the Anthropocene satisfy the stratigraphic criteria used for naming a new epoch? (To geologists, an epoch is a subdivision of a period, which, in turn, is a division of an era; the Holocene, for instance, is an epoch of the Quaternary, which is a period in the Cenozoic.) After a year's worth of study, the answer that the group arrived at was an unqualified yes. Among other things, the members observed in a paper summarizing their findings, the Anthropocene will be marked by a unique "biostratigraphic signal," a product of the current extinction event, on the one hand, and of the human propensity for redistributing life, on the other. This signal will be permanently inscribed, they wrote, "as future evolution will take place from surviving (and frequently anthropogenically relocated) stocks."

Or, as Zalasiewicz would have it, giant rats.

Just as in the early years of the Geol Soc, stratigraphers today spend a lot of time arguing about borders. A few years ago, after much heated discussion, members of the I.C.S. voted to move the start of the Pleistocene epoch from about 1.8 million to about 2.6 million years ago. This decision was part of a broader, and even fiercer, debate about whether to do away with the Quaternary, the period that spans both the Pleistocene and the Holocene, and fold it into the Neogene. (The elimination of the Quaternary was vigorously—and, ultimately, successfully—resisted by Quaternary stratigraphers.)

The debate over the Anthropocene's borders is complicated by the fact that the geology of the epoch is, at this point, almost entirely prospective. The way stratigraphers usually define boundaries—once they've stopped arguing about them—is by choosing a particularly fossil-rich sequence of rocks to serve as a reference. These reference sequences are colloquially known as "golden spikes"—technically, they're called Global Boundary Stratotype Sections and Points, or G.S.S.P.s—and they're scattered around the world (though a disproportionate number are in Europe). The striped rocks at Dob's Linn have been designated the golden spike for the start of the Silurian period. For the base of the Carboniferous, the golden spike is near the town of Cabrières, in southern France, and for the start of the Triassic it's in the hills of Meishan, China. (The Chinese have tried to turn this last golden spike into a tourist destination, with a manicured park and a statue of a tooth from a once common eel-like creature known as a conodont.)

Since the rocks of the Anthropocene don't yet exist, it's impossible to choose an exemplary sequence of them. To stratigraphers, then, a key, but also rather vexing, question is what could serve instead of the traditional golden spike. In 2009, the I.C.S. set up an Anthropocene Working Group to examine this and related issues; not surprisingly, Zalasiewicz was appointed chairman. At the time of our visit to London, he told me that he thought there were many possible ways that the start of the epoch could be designated. One would simply be to choose a date—1800, say, or 1950. This is how geological periods of the deep, pre-fossiliferous past are defined; what's known as the Neoproterozoic era, for example, is said to have begun precisely one billion years ago.

Another possibility would be to use nuclear fallout. The aboveground tests of the mid-twentieth century dispersed radioactive particles all around the globe. Some have half-lives of more than a thousand years; in a few cases, like uranium-236, the figure is in the tens of millions. To future geologists, the fallout will thus present a novel radioactive "spike" (assuming, that is, that the future does not hold a nuclear war). This sort of geochemical marker is used to define the end of the Cretaceous. The impact that occurred during the final seconds of the period left behind a thin layer of sediment containing anomalously high concentrations of the element iridium—the so-called "iridium spike."

Yet another possibility is to use the world's subway systems, an idea that also has precedent in deep time. Geologists refer to the outlines of burrows that creatures left behind in the sediments as "trace fossils." The start of the Cambrian period, some five hundred and forty million years ago, is defined as the point when the first complex burrows appear; these left impressions in the rocks which resemble scattered grains of rice. (No one is sure what the animals that made the burrows looked like, as their bodies have not been preserved.) London's subway system, the world's oldest, will leave behind an enormous set of trace fossils, as will New York's and Seoul's and Paris's and Dubai's.

"All the great world cities have underground systems now," Mark Williams, a stratigrapher who teaches at the University of Leicester and is a member of the Anthropocene Working Group, noted. "They're extensive, they're fairly permanent from a geological perspective, and they're a very, very good indicator of the complexity that's come to characterize the twentieth and twenty-first centuries."

Williams told me that the response to the idea of formalizing the Anthropocene had "generally been very positive." (Just in the past few months, three new academic journals focussing on the Anthropocene have been launched.) But, as is to be expected from a group that can sustain a decade-long disagreement about the status of the Quaternary, there's still plenty of dissent. Some critics argue that humans have been altering the planet for thousands of years already, so why get all worked up about it now?

"We can see that human interactions with the landscape are increasing," Philip Gibbard, a stratigrapher at Cambridge, told me. "No one disputes that. We build buildings. We build towns. We build roads. We drop plastic bags in the ocean. All that's absolutely true. But from a geological perspective—and I have to speak as a geologist, not as a generally interested person—I think what's happening now is just a logical continuation of something that began as human populations started to increase at the beginning of the Holocene.

"It is quite exciting to pursue this new idea," he added. "But I'm suspicious of it."

Other critics are skeptical of the idea for opposite reasons. They point out that human impacts on the planet are likely to become even more pronounced, and hence more stratigraphically significant, as time goes on. Thus, what's sometimes referred to in geological circles as the "event horizon" has not yet been reached.

For his part, Zalasiewicz is sympathetic to both lines of argument. Humans *have* been altering the planet for quite a while, though probably the impacts of the past were orders of magnitude more modest than they are today. And a few centuries from now the impacts of human activity may be orders of magnitude greater again. By the time people are through, Zalasiewicz told me, he wouldn't be surprised if the earth were rendered more or less unrecognizable. "One cannot exclude a P-T-type outcome," he observed, referring to the worst of the so-called Big Five, the end-Permian, or Permo-Triassic, extinction. In the meantime, though, he said, "we have to work with what we've got."

This past summer, I went with Zalasiewicz on another collecting trip, this one to Wales. Zalasiewicz has a special fondness for the country. He wrote his dissertation on the stratigraphy of northern Wales, and while finishing his research he drove around in a decommissioned postal van and lived in a camper that had been used as a chicken coop. He wanted to show me a spot near the town of Ponterwyd where he thought there should perhaps be another golden spike—in this case, marking the base of the Aeronian Stage of the Silurian. We set out from the town of Keyworth, in Nottinghamshire, where Zalasiewicz lives with his wife and teen-age son, and drove through the West Midlands. In its day, the West Midlands was the industrial heart of Britain. Now the industry is mostly gone, and people struggle to find work. "About as scary an advertisement for the Anthropocene as you can imagine" is how Zalasiewicz described the region.

When we arrived at Ponterwyd, smirr was falling, or, as the Welsh put it, piglaw. Again, there were lots of sheep and green, sheep-shorn hills, and rocks filled with fossils. Banging away at an outcropping, I soon found several graptolites. One, which Zalasiewicz identified as belonging to the species *Monograptus triangulatus*, looked like a tiny saw blade, with miniature triangular teeth. With characteristic tact, he told me that my specimen was "very lovely." I stuck it in my bag.

A few days later, I took the train back to London, and then the Tube out to Heathrow, where I was spending the night at an airport hotel. Thanks to all the graptolites I'd gathered, my suitcase was overweight, and I decided that I was going to have to deaccession some of them. I took what seemed to be the least impressive examples and headed out through the lobby, only to realize that there was nowhere to go. The hotel faced a ten-foot wall, which was made of plywood and covered with billboard-size sheets of plastic printed with photographs of trees. The photos kept repeating, so that walking along was like getting lost in a dark monoculture. Beyond the plywood wall, there was a parking lot, and beyond that an access road. I figured that the parking lot would have to do. By this point, I'd spent enough time with Zalasiewicz that the place appeared to me as a mosaic of human impacts. The lot was edged with a margin of dirt; this was filled with scraggly plants, many of them no doubt introduced species. Strewn among the weeds was the usual flotsam of travel: empty water bottles, crumpled candy wrappers, crushed soda cans, half-eaten packages of crisps. I recalled what Zalasiewicz had told me about aluminum, which is that until the late nineteenth century it did not exist on earth except in combination with other elements. So soda cans may provide yet another marker of our presence: the Dr Pepper spike.

It was a lovely evening. A half-moon hung in a purple sky crisscrossed by jet contrails. I took out my graptolites. Most I couldn't identify, but one, I thought, belonged to the species *Rhaphidograptus toernquisti*, which Zalasiewicz had described to me as among life's great success stories. *Rhaphidograptus toernquisti* managed to persist, unchanged, for some five million years. I placed my fossils in a little pile next to a discarded cigarette pack. Nearby, I noticed a plastic pouch with the word "Toxic" printed in block letters. The pouch was torn, and some ominously bright-yellow powder was leaking out of it. I tried to imagine a geologist in the year 100,000,000 A.D. stumbling onto the site. It was hard for me to picture what he (or it) would look like, but I got a certain satisfaction thinking about how puzzled he would be when he came upon my Silurian graptolites nestled amid the wreckage of the Anthropocene. ♦

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Approaching a state shift in Earth's biosphere

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Localized ecological systems are known to shift abruptly and irreversibly from one state to another when they are forced across critical thresholds. Here we review evidence that the global ecosystem as a whole can react in the same way and is approaching a planetary-scale critical transition as a result of human influence. The plausibility of a planetary-scale 'tipping point' highlights the need to improve biological forecasting by detecting early warning signs of critical transitions on global as well as local scales, and by detecting feedbacks that promote such transitions. It is also necessary to address root causes of how humans are forcing biological changes.

Humans now dominate Earth, changing it in ways that threaten its ability to sustain us and other species[1–3]. This realization has led to a growing interest in forecasting biological responses on all scales from local to global[4–7].

However, most biological forecasting now depends on projecting recent trends into the future assuming various environmental pressures[5], or on using species distribution models to predict how climatic changes may alter presently observed geographic ranges[8,9]. Present work recognizes that relying solely on such approaches will be insufficient to characterize fully the range of likely biological changes in the future, especially because complex interactions, feedbacks and their hard-to-predict effects are not taken into account[6,8–11].

Particularly important are recent demonstrations that 'critical transitions' caused by threshold effects are likely[12]. Critical transitions lead to state shifts, which abruptly override trends and produce unanticipated biotic effects. Although most previous work on threshold-induced state shifts has been theoretical or concerned with critical transitions in localized ecological systems over short time spans[12–14], planetary-scale critical transitions that operate over centuries or millennia have also been postulated[3,12,15–18]. Here we summarize evidence that such planetary-scale critical transitions have occurred previously in the biosphere, albeit rarely, and that humans are now forcing another such transition, with the potential to transform Earth rapidly and irreversibly into a state unknown in human experience.

Two conclusions emerge. First, to minimize biological surprises that would adversely impact humanity, it is essential to improve biological forecasting by anticipating critical transitions that can emerge on a planetary scale and understanding how such global forcings cause local changes. Second, as was also concluded in previous work, to prevent a global-scale state shift, or at least to guide it as best we can, it will be necessary to address the root causes of human-driven global change and to improve our management of biodiversity and ecosystem services[3,15–17,19].

Basics of state shift theory

It is now well documented that biological systems on many scales can shift rapidly from an existing state to a radically different state[12]. Biological 'states' are neither steady nor in equilibrium; rather, they are characterized by a defined range of deviations from a mean condition over a prescribed period of time. The shift from one state to another can be caused by either a 'threshold' or 'sledgehammer' effect. State shifts resulting from threshold effects can be difficult to anticipate, because the critical threshold is reached as incremental changes accumulate and the threshold value generally is not known in advance. By contrast, a state shift caused by a sledgehammer effect—for example the clearing of a forest using a bulldozer—comes as no surprise. In both cases, the state shift is relatively abrupt and leads to new mean conditions outside the range of fluctuation evident in the previous state.

Threshold-induced state shifts, or critical transitions, can result from 'fold bifurcations' and can show hysteresis[12]. The net effect is that once a critical transition occurs, it is extremely difficult or even impossible for the system to return to its previous state. Critical transitions can also result from more complex bifurcations, which have a different character from fold bifurcations but which also lead to irreversible changes[20].

Recent theoretical work suggests that state shifts due to fold bifurcations are probably preceded by general phenomena that can be characterized mathematically: a deceleration in recovery from perturbations ('critical slowing down'), an increase in variance in the pattern of within-state fluctuations, an increase in autocorrelation between fluctuations, an increase in asymmetry of fluctuations and rapid back-and-forth shifts ('flickering') between states[12,14,18]. These phenomena can theoretically be

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assessed within any temporally and spatially bounded system. Although such assessment is not yet straightforward[12,18,20], critical transitions and in some cases their warning signs have become evident in diverse biological investigations[21], for example in assessing the dynamics of disease outbreaks[22,23], populations[14] and lake ecosystems[12,13]. Impending state shifts can also sometimes be determined by parameterizing relatively simple models[20,21].

In the context of forecasting biological change, the realization that critical transitions and state shifts can occur on the global scale[3,12,15–18], as well as on smaller scales, is of great importance. One key question is how to recognize a global-scale state shift. Another is whether global-scale state shifts are the cumulative result of many smaller-scale events that originate in local systems or instead require global-level forcings that emerge on the planetary scale and then percolate downwards to cause changes in local systems. Examining past global-scale state shifts provides useful insights into both of these issues.

Hallmarks of global-scale state shifts

Earth's biosphere has undergone state shifts in the past, over various (usually very long) timescales, and therefore can do so in the future (Box 1). One of the fastest planetary state shifts, and the most recent, was the transition from the last glacial into the present interglacial condition[12,18], which occurred over millennia[24]. Glacial conditions had prevailed for ~100,000 yr. Then, within ~3,300 yr, punctuated by episodes of abrupt, decadal-scale climatic oscillations, full interglacial conditions were attained. Most of the biotic change—which included extinctions, altered diversity patterns and new community compositions—occurred within a period of 1,600 yr beginning ~12,900 yr ago. The ensuing interglacial state that we live in now has prevailed for the past ~11,000 yr.

Occurring on longer timescales are events such as at least four of the 'Big Five' mass extinctions[25], each of which represents a critical transition that spanned several tens of thousands to 2,000,000 yr and changed the course of life's evolution with respect to what had been normal for the previous tens of millions of years. Planetary state shifts can also substantially increase biodiversity, as occurred for example at the 'Cambrian explosion'[26], but such transitions require tens of millions of years, timescales that are not meaningful for forecasting biological changes that may occur over the next few human generations (Box 1).

Despite their different timescales, past critical transitions occur very quickly relative to their bracketing states: for the examples discussed here, the transitions took less than ~5% of the time the previous state had lasted (Box 1). The biotic hallmark for each state change was, during the critical transition, pronounced change in global, regional and local assemblages of species. Previously dominant species diminished or went extinct, new consumers became important both locally and globally, formerly rare organisms proliferated, food webs were modified, geographic ranges reconfigured and resulted in new biological communities, and evolution was initiated in new directions. For example, at the Cambrian explosion large, mobile predators became part of the food chain for the first time. Following the K/T extinction, mammalian herbivores replaced large archosaur herbivores. And at the last glacial–interglacial transition, megafaunal biomass switched from being dominated by many species to being dominated by *Homo sapiens* and our domesticated species[27].

All of the global-scale state shifts noted above coincided with global-scale forcings that modified the atmosphere, oceans and climate (Box 1). These examples suggest that past global-scale state shifts required global-scale forcings, which in turn initiated lower-level state changes that local controls do not override. Thus, critical aspects of biological forecasting are to understand whether present global forcings are of a magnitude sufficient to trigger a global-scale critical transition, and to ascertain the extent of lower-level state changes that these global forcings have already caused or are likely to cause.

Present global-scale forcings

Global-scale forcing mechanisms today are human population growth with attendant resource consumption[3], habitat transformation and fragmentation[3], energy production and consumption[28,29], and climate change[3,18]. All of these far exceed, in both rate and magnitude, the forcings evident at the most recent global-scale state shift, the last glacial–interglacial transition (Box 1), which is a particularly relevant benchmark for comparison given that the two global-scale forcings at that time—climate change

BOX 1

Past planetary-scale critical transitions and state shifts

Last glacial–interglacial transition[18,24]. The critical transition was a rapid warm–cold–warm fluctuation in climate between 14,300 and 11,000 yr ago, and the most pronounced biotic changes occurred between 12,900 and 11,300 yr ago[24,27,30,54].

The major biotic changes were the extinction of about half of the species of large-bodied mammals, several species of large birds and reptiles, and a few species of small animals[30]; a significant decrease in local and regional biodiversity as geographic ranges shifted individualistically, which also resulted in novel species assemblages[37,49,53,54]; and a global increase in human biomass and spread of humans to all continents[27].

The pre-transition global state was a glacial stage that lasted about 100,000 yr and the post-transition global state is an interglacial that Earth has been in for approximately 11,000 yr. The global forcings were orbitally induced, cyclic variations in solar insolation that caused rapid global warming. Direct and indirect of effects of humans probably contributed to extinctions of megafauna and subsequent ecological restructuring.

'Big Five' mass extinctions[25]. The respective critical transitions ended at ~443,000,000, ~359,000,000, ~251,000,000, ~200,000,000 and ~65,000,000 yr ago. They are each thought to have taken at most 2,000,000 yr to complete but could have been much shorter; the limitations of geological dating preclude more precision. The most recent transition (the K/T extinction, which occurred at the end of the Cretaceous period) may have been the catastrophic result of a bolide impact, and could have occurred on a timescale as short as a human lifetime.

The major biotic changes were the extinction of at least 75% of Earth's species; a major reorganization of global and local ecosystems as previously rare lifeforms gained evolutionary dominance; and the return to pre-extinction levels of biodiversity over hundreds of thousands to millions of years.

The pre- and post-transition global states lasted ~50,000,000–100,000,000 yr. We are now 65,000,000 yr into the present state on this scale, in an era known as the Cenozoic or the Age of Mammals. The global forcings all corresponded to unusual climate changes and shifts in ocean and atmospheric chemistry, especially in concentrations of carbon dioxide and, in one case, hydrogen sulphide. Intense volcanic activity seems to have been important at some extinction events. A bolide impact is well documented as a cause of the K/T event and has been postulated as a cause of some of the others.

Cambrian explosion[26,81]. The critical transition began ~540,000,000 yr ago and lasted about 30,000,000 yr.

The major biotic changes were evolutionary innovations resulting in all phyla known today; a conversion of the global ecosystem from one based almost solely on microbes to one based on complex, multicellular life; and diversity increased, but on a timescale that is far too long to be meaningful in predicting the biotic future over human generations.

The pre-transition global state lasted ~2,000,000,000 yr and was characterized by primary lifeforms consisting of prokaryotic and eukaryotic microbes. The post-transition global state is about 540,000,000 yr old and ongoing. The global forcings were the increase of atmospheric oxygen to levels sufficient for the metabolic processes required to sustain complex, multicellular life, and evolutionary innovations that included large size, predation and complex locomotion.

Figure 1 | Drivers of a potential planetary-scale critical transition. **a**, Humans locally transform and fragment landscapes. **b**, Adjacent areas still harbouring natural landscapes undergo indirect changes. **c**, Anthropogenic local state shifts accumulate to transform a high percentage of Earth's surface drastically; brown colouring indicates the approximately 40% of terrestrial ecosystems that have now been transformed to agricultural landscapes, as explained in ref. 34. **d**, Global-scale forcings emerge from accumulated local human impacts, for example dead zones in the oceans from run-off of agricultural pollutants. **e**, Changes in atmospheric and ocean chemistry from the release of greenhouse gases as fossil fuels are burned. **f–h**, Global-scale forcings emerge to cause ecological changes even in areas that are far from human population concentrations. **f**, Beetle-killed conifer forests (brown trees) triggered by seasonal changes in temperature observed over the past five decades. **g**, Reservoirs of biodiversity, such as tropical rainforests, are projected to lose many species as global climate change causes local changes in temperature and precipitation, exacerbating other threats already causing abnormally high extinction rates. In the case of amphibians, this threat is the human-facilitated spread of chytrid fungus. **h**, Glaciers on Mount Kilimanjaro, which remained large throughout the past 11,000 yr, are now melting quickly, a global trend that in many parts of the world threatens the water supplies of major population centres. As increasing human populations directly transform more and more of Earth's surface, such changes driven by emergent global-scale forcings increase drastically, in turn causing state shifts in ecosystems that are not directly used by people. Photo credits: E.A.H. and A.D.B. (**a–c**, **e–h**); NASA (**d**).

and human population growth[27,30]—are also primary forcings today. During the last glacial–interglacial transition, however, these were probably separate, yet coincidental, forcings. Today conditions are very different because global-scale forcings including (but not limited to) climate change have emerged as a direct result of human activities.

Human population growth and per-capita consumption rate underlie all of the other present drivers of global change. The growth in the human population now (~77,000,000 people per year) is three orders of magnitude higher than the average yearly growth from ~10,000–400 yr ago (~67,000 people per year), and the human population has nearly quadrupled just in the past century[31–33]. The most conservative estimates suggest that the population will grow from its present value, 7,000,000,000, to 9,000,000,000 by 2045[31] and to 9,500,000,000 by 2050[31,33].

As a result of human activities, direct local-scale forcings have accumulated to the extent that indirect, global-scale forcings of biological change have now emerged. Direct forcing includes the conversion of ~43% of Earth's land to agricultural or urban landscapes, with much of the remaining natural landscapes networked with roads[1,2,34,35]. This exceeds the physical transformation that occurred at the last global-scale critical transition, when ~30% of Earth's surface went from being covered by glacial ice to being ice free.

The indirect global-scale forcings that have emerged from human activities include drastic modification of how energy flows through the global ecosystem. An inordinate amount of energy now is routed through one species, *Homo sapiens*. Humans commandeer ~20–40% of global net primary productivity[1,2,35] (NPP) and decrease overall NPP through habitat degradation. Increasing NPP regionally through atmospheric and agricultural deposition of nutrients (for example nitrogen and phosphorus) does not make up the shortfall[2]. Second, through the release of energy formerly stored in fossil fuels, humans have substantially increased the energy ultimately available to power the global ecosystem. That addition does not offset entirely the human appropriation of NPP, because the vast majority of that 'extra' energy is used to support humans and their domesticates, the sum of which comprises large-animal biomass that is far beyond that typical of pre-industrial times[27]. A decrease in this extra energy budget, which is inevitable if alternatives do not compensate for depleted fossil fuels, is likely to impact human health and economies severely[28], and also to diminish biodiversity[27], the latter because even more NPP would have to be appropriated by humans, leaving less for other species[36].

By-products of altering the global energy budget are major modifications to the atmosphere and oceans. Burning fossil fuels has increased atmospheric CO_2 concentrations by more than a third (~35%) with respect to pre-industrial levels, with consequent climatic disruptions that include a higher rate of global warming than occurred at the last global-scale state shift[37]. Higher CO_2 concentrations have also caused the ocean rapidly to become more acidic, evident as a decrease in pH by ~0.05 in the past two decades[38]. In addition, pollutants from agricultural run-off and urban areas have radically changed how nutrients cycle through large swaths of marine areas[16].

Already observable biotic responses include vast 'dead zones' in the near-shore marine realm[39], as well as the replacement of >40% of Earth's formerly biodiverse land areas with landscapes that contain only a few species of crop plants, domestic animals and humans[3,40]. Worldwide shifts in species ranges, phenology and abundances are concordant with ongoing climate change and habitat transformation[41]. Novel communities are becoming widespread as introduced, invasive and agricultural species integrate into many ecosystems[42]. Not all community modification is leading to species reductions; on local and regional scales, plant diversity has been increasing, owing to anthropogenic introductions[42], counter to the overall trend of global species loss[5,43]. However, it is unknown whether increased diversity in such locales will persist or will eventually decrease as a result of species interactions that play out over time. Recent and projected[5,44] extinction rates of vertebrates far exceed empirically derived background rates[25]. In addition, many plants, vertebrates and invertebrates have markedly reduced their geographic ranges and abundances to the extent that they are at risk of extinction[43]. Removal of keystone species worldwide, especially large predators at upper trophic levels, has exacerbated changes caused by less direct impacts, leading to increasingly simplified and less stable ecological networks[39,45,46].

Looking towards the year 2100, models forecast that pressures on biota will continue to increase. The co-opting of resources and energy use by humans will continue to increase as the global population reaches 9,500,000,000 people (by 2050), and effects will be greatly exacerbated if per capita resource use also increases. Projections for 2100 range from a population low of 6,200,000,000 (requiring a substantial decline in fertility rates) to 10,100,000,000 (requiring continued decline of fertility in countries that still have fertility above replacement level) to 27,000,000,000 (if fertility remains at 2005–2010 levels; this population size is not thought to be supportable; ref. 31). Rapid climate change shows no signs of slowing. Modelling suggests that for ~30% of Earth, the speed at which plant species will have to migrate to keep pace with projected climate change is greater than their dispersal rate when Earth last shifted from a glacial to an interglacial climate[47], and that dispersal will be thwarted by highly fragmented landscapes. Climates found at present on 10–48% of the planet are projected to disappear within a century, and climates that contemporary organisms have never experienced are likely to cover 12–39% of Earth[48]. The mean global temperature by 2070 (or possibly a few decades earlier) will be higher than it has been since the human species evolved.

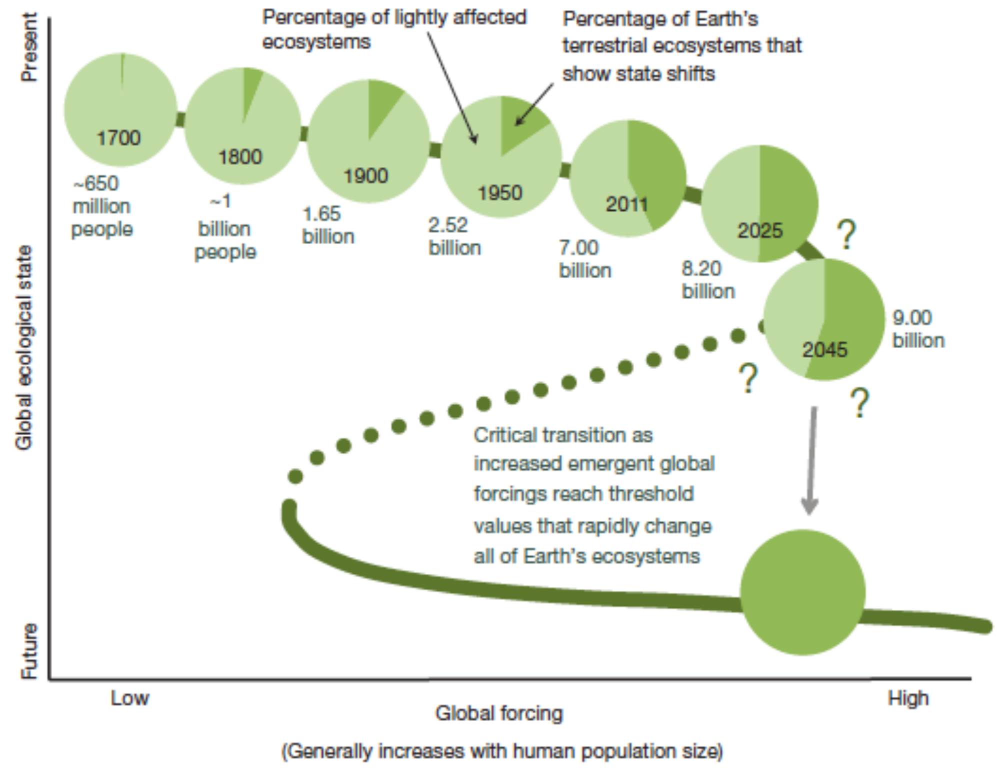

Figure 2 | Quantifying land use as one method of anticipating a planetary state shift. The trajectory of the green line represents a fold bifurcation with hysteresis[12]. At each time point, light green represents the fraction of Earth's land that probably has dynamics within the limits characteristic of the past 11,000 yr. Dark green indicates the fraction of terrestrial ecosystems that have unarguably undergone drastic state changes; these are minimum values because they count only agricultural and urban lands. The percentages of such transformed lands in 2011 come from refs 1, 34, 35, and when divided by 7,000,000,000 (the present global human population) yield a value of approximately 2.27 acres (0.92 ha) of transformed land for each person. That value was used to estimate the amount of transformed land that probably existed in the years 1800, 1900 and 1950, and which would exist in 2025 and 2045 assuming conservative population growth and that resource use does not become any more efficient. Population estimates are from refs 31–33. An estimate of 0.68 transformed acres (0.28 ha) per capita (approximately that for India today) was used for the year 1700, assuming a lesser effect on the global landscape before the industrial revolution. Question marks emphasize that at present we still do not know how much land would have to be directly transformed by humans before a planetary state shift was imminent, but landscape-scale studies and theory suggest that the critical threshold may lie between 50 and 90% (although it could be even lower owing to synergies between emergent global forcings). See the main text for further explanation. Billion, 10^9.

Expecting the unexpected

The magnitudes of both local-scale direct forcing and emergent global-scale forcing are much greater than those that characterized the last global-scale state shift, and are not expected to decline any time soon. Therefore, the plausibility of a future planetary state shift seems high, even though considerable uncertainty remains about whether it is inevitable and, if so, how far in the future it may be. The clear potential for a planetary-scale state shift greatly complicates biotic forecasting efforts, because by their nature state shifts contain surprises. Nevertheless, some general expectations can be gleaned from the natural experiments provided by past global-scale state shifts. On the timescale most relevant to biological forecasting today, biotic effects observed in the shift from the last glacial to the present interglacial (Box 1) included many extinctions[30,49–51]; drastic changes in species distributions, abundances and diversity; and the emergence of novel communities[49,50,52–54]. New patterns of gene flow triggered new evolutionary trajectories[55–58], but the time since then has not been long enough for evolution to compensate for extinctions.

At a minimum, these kinds of effects would be expected from a global-scale state shift forced by present drivers, not only in human-dominated regions but also in remote regions not now heavily occupied by humans (Fig. 1); indeed, such changes are already under way (see above[5,25,39,41–44]). Given that it takes hundreds of thousands to millions of years for evolution to build diversity back up to pre-crash levels after major extinction episodes[25], increased rates of extinction are of particular concern, especially because global and regional diversity today is generally lower than it was 20,000 yr ago as a result of the last planetary state shift[37,50,51,54,59]. This large-scale loss of diversity is not overridden by historical increases in plant species richness in many locales, owing to human-transported species homogenizing the world's biota[42]. Possible too are substantial losses of ecosystem services required to sustain the human population[60]. Still unknown is the extent to which human-caused increases in certain ecosystem services—such as growing food—balances the loss of 'natural' ecosystem services, many of which already are trending in dangerous directions as a result of overuse, pollutants and climate change[3,16]. Examples include the collapse of cod and other fisheries[45,61,62]; loss of millions of square kilometres of conifer forests due to climate-induced bark-beetle outbreaks;[63] loss of carbon sequestration by forest clearing[60]; and regional losses of agricultural productivity from desertification or detrimental land-use practices[1,35]. Although the ultimate effects of changing biodiversity and species compositions are still unknown, if critical thresholds of diminishing returns in ecosystem services were reached over large areas and at the same time global demands increased (as will happen if the population increases by 2,000,000,000 within about three decades), widespread social unrest, economic instability and loss of human life could result[64].

Towards improved biological forecasting and monitoring

In view of potential impacts on humanity, a key need in biological forecasting is the development of ways to anticipate a global critical transition, ideally in time to do something about it[65]. It is possible to imagine qualitative aspects of a planetary state shift given present human impacts (Fig. 1), but criteria that would indicate exactly how close we might be to a planetary-scale critical transition remain elusive. Three approaches should prove helpful in defining useful benchmarks and tracking progression towards them.

Tracking global-scale changes

The first approach acknowledges the fact that local-scale state changes—whether they result from sledgehammer or threshold effects—trigger critical transitions over regions larger than the directly affected area, as has been shown both empirically and theoretically[66–70]. On the landscape scale, tipping points in undisturbed patches are empirically evident when 50–90% of the surrounding patches are disturbed. Simulations indicate that critical transitions become much more likely when the probability of connection of any two nodes in a network (ecological or otherwise) drops below ~59% (refs 66–70). More generally, dense human populations, roads and infrastructure, and land transformation are known to cause ecological changes outside the areas that have actually undergone sledgehammer state changes[68]. Translating these principles to the planetary scale would imply that once a sufficient proportion of Earth's ecosystems have undergone transformation, the remainder can change rapidly (Fig. 2), especially because emergent, larger-scale forcings (for instance changes in atmospheric and ocean chemistry, nutrient and energy cycling, pollution and so on) multiply and interact to exacerbate local forcings[21] (Fig. 1). It is still unknown, however, what percentage of Earth's ecosystems actually have to be transformed to new states by the direct action of humans for rapid state changes to be triggered in remaining 'natural' systems. That percentage may be knowable only in retrospect, but, judging from landscape-scale observations and simulations[66–70], it can reasonably be expected to be as low as 50% (ref. [68]), or even lower if the interaction effects of many local ecosystem transformations cause sufficiently large global-scale forcings to emerge.

In that context, continued efforts to track global-scale changes by remote sensing and other techniques will be essential in assessing how close we are to tipping the balance towards an Earth where most ecosystems are directly altered by people. This is relatively straightforward for land and it has already been demonstrated that at least 43% of Earth's terrestrial ecosystems have undergone wholesale transformation[1,2,34,40], on average equating to ~2.27 transformed acres (0.92 ha) per capita for the present human population. Assuming that this average rate of land transformation per capita does not change, 50% of Earth's land will have undergone state shifts when the global population reaches 8,200,000,000, which is estimated to occur by the year 2025[31]. Under the same land-use assumption and according to only slightly less conservative population growth models, 70% of Earth's land could be shifted to human use (if the population reaches 11,500,000,000) by 2060[31].

Assessing the percentage change to new states in marine systems, and the direct human footprint on the oceans, is much more challenging, but available data suggest widespread effects[38,39]. More precise quantification of ecosystem state shifts in the oceans is an important task, to the extent that ocean ecosystems cover most of the planet.

Tracking local-scale changes caused by global forcings

The second approach is the direct monitoring of biological change in local study systems caused by external forcing. Such monitoring will be vital, particularly where the human footprint is thought to be small. Observing unusual changes in such areas, as has occurred recently in Yellowstone Park, USA, which has been protected since 1872[71], and in many remote watersheds[72], would indicate that larger-scale forcings[38,73] are influencing local ecological processes.

A key problem has been how to recognize 'unusual' change, because biological systems are dynamic and shifting baselines have given rise to many different definitions of 'normal', each of which can be specified as unusual within a given temporal context. However, identifying signals of a global-scale state shift in any local system demands a temporal context that includes at least a few centuries or millennia, to encompass the range of ecological variation that would be considered normal over the entire ~11,000-yr duration of the present interglacial period. Identifying unusual biotic changes on that scale has recently become possible through several different approaches, which are united by their focus on integrating spatial and temporal information (Box 2). Breakthroughs include characterizing ecosystems using taxon-independent metrics that can be tracked with palaeontological data through pre-anthropogenic times and then compared with present conditions and monitored into the future; recognizing macro-ecological patterns that indicate disturbed systems; combining phylochronologic and phylogeographic information to trace population dynamics over several millennia; and assessing the structure and stability of ecological networks using theoretical and empirical methods. Because all of these approaches benefit from time series data, long-term monitoring efforts and existing palaeontological and natural history museum collections will become particularly valuable[74].

BOX 2

Integrating spatio-temporal data on large scales to detect planetary state shifts

- Palaeontology uses historical, fossil and geological information to calibrate normal levels of fluctuation in biodiversity, species composition and abundance[80], food webs[82], ecomorphology[83], extinction[25] and so on. Recent work shows that some lightly populated ecosystems still operate within bounds that would be considered normal for the present interglacial period, but that others have been disturbed[80].
- Macroecology provides quantitative ways to identify when a particular ecosystem has unusual characteristics in such metrics as the species–area relationship, species abundance distributions, spatial aggregation patterns[84,85], the distribution of metabolic rates over individuals in a community[85,86], the inverse power-law relation between abundance and body size[87], and the distribution of linkages across species in a trophic network[88]. Recent advances in formalizing the maximum entropy (MaxEnt) theory of ecology[85,86] provide a theoretical means of accurately predicting such patterns in undisturbed ecosystems; significant departures from the predictions of MaxEnt probably indicate disturbed systems[85].
- Population biology uses life history, abundance, genetics and numerical modelling to assess population dynamics and viability. Recent advances in obtaining ancient DNA from samples several thousand years old, plus newly developed analytical models that take into account temporal (phylochronologic) as well as spatial (phylogeographic) patterning, increase power in testing whether genetic patterning on the modern landscape deviates significantly from patterns that arise on the scale of centuries to millennia[10,89].
- Ecological network theory regards ecosystems as complex networks of species connected by different interactions. Recent work identifies persistent and stabilizing characteristics of networks on different geographic and temporal scales[81,82] (both current and palaeontological), such as consumer–resource body size ratios[90], allometric scaling effects[91] and skewed distributions for connectivity[81,92,93] and interaction strengths[94–96]. Alteration in such characteristics signals perturbation of the normal network structure. Theoretical work also is revealing where information about species-specific traits such as body size[46,90,91], trophic generality[91], trophic uniqueness[97], non-trophic interactions[98] and phylogenetic information[99] may help predict when ecosystem services degrade as networks destabilize[46,100] and disassemble[97].

Synergy and feedbacks

Thresholds leading to critical transitions are often crossed when forcings are magnified by the synergistic interaction of seemingly independent processes or through feedback loops[3,16]. Given that several global-scale forcings are at work today, understanding how they may combine to magnify biological change is a key challenge[3,15–17]. For example, rapid climate change combined with highly fragmented species ranges can be expected to magnify the potential for ecosystem collapse, and wholesale landscape changes may in turn influence the biology of oceans.

Feedback loops also occur among seemingly discrete systems that operate at different levels of the biological hierarchy[6,8,37] (genotype, phenotype, populations, species distributions, species interactions and so on). The net effect is that a biological forcing applied on one scale can cause a critical transition to occur on another scale. Examples include inadvertent, anthropogenic selection for younger maturation of individual cod as a result of heavy fishing pressure[61]; population crashes due to decreased genetic diversity[75]; mismatch in the phenology of flowering and pollination resulting from interaction of genetic factors, temperature, photoperiod and/or precipitation[76]; and cascades of ecological changes triggered by the removal of top predators[62]. In most cases, these 'scale-jumping' effects, and the mechanisms that drive them, have become apparent only in hindsight, but even so they take on critical importance in revealing interaction effects that can now be incorporated into the next generation of biological forecasts.

Finally, because the global-scale ecosystem comprises many smaller-scale, spatially bounded complex systems (for instance the community within a given physiographic region), each of which overlaps and interacts with others, state shifts of the small-scale components can propagate to cause a state shift of the entire system[21]. Our understanding of complexity at this level can be increased by tracking changes within many different ecosystems in a parallel fashion, from landscape-scale studies of state-shifts[12,21] and from theoretical work that is under way[20]. Potential interactions between overlapping complex systems, however, are proving difficult to characterize mathematically, especially when the systems under study are not well known and are heterogeneous[20]. Nevertheless, one possibility emerging from such work is that long-term transient behaviours, where sudden changes in dynamics can occur after periods of relative stasis even in the absence of outside forces, may be pervasive at the ecosystem level[20], somewhat analogously to delayed metapopulation collapse as a result of extinction debt[77]. This potential 'lag-time' effect makes it all the more critical rapidly to address, where possible, global-scale forcings that can push the entire biosphere towards a critical transition.

Guiding the biotic future

Humans have already changed the biosphere substantially, so much so that some argue for recognizing the time in which we live as a new geologic epoch, the Anthropocene[3,16,78]. Comparison of the present extent of planetary change with that characterizing past global-scale state shifts, and the enormous global forcings we continue to exert, suggests that another global-scale state shift is highly plausible within decades to centuries, if it has not already been initiated.

As a result, the biological resources we take for granted at present may be subject to rapid and unpredictable transformations within a few human generations. Anticipating biological surprises on global as well as local scales, therefore, has become especially crucial to guiding the future of the global ecosystem and human societies. Guidance will require not only scientific work that foretells, and ideally helps to avoid[65], negative effects of critical transitions, but also society's willingness to incorporate expectations of biological instability[64] into strategies for maintaining human well-being.

Diminishing the range of biological surprises resulting from bottom-up (local-to-global) and top-down (global-to-local) forcings, postponing their effects and, in the optimal case, averting a planetary-scale critical transition demands global cooperation to stem current global-scale anthropogenic forcings[3,15–17,19]. This will require reducing world population growth[31] and per-capita resource use; rapidly increasing the proportion of the world's energy budget that is supplied by sources other than fossil fuels while also becoming more efficient in using fossil fuels when they provide the only option[79]; increasing the efficiency of existing means of food production and distribution instead of converting new areas[34] or relying on wild species[39] to feed people; and enhancing efforts to manage as reservoirs of biodiversity and ecosystem services, both in the terrestrial[80] and marine realms[39], the parts of Earth's surface that are not already dominated by humans. These are admittedly huge tasks, but are vital if the goal of science and society is to steer the biosphere towards conditions we desire, rather than those that are thrust upon us unwittingly.

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7

Food and its Impacts in the Anthropocene

Evolution, consequences and future of plant and animal domestication

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Domestication interests us as the most momentous change in Holocene human history. Why did it operate on so few wild species, in so few geographic areas? Why did people adopt it at all, why did they adopt it when they did, and how did it spread? The answers to these questions determined the remaking of the modern world, as farmers spread at the expense of hunter–gatherers and of other farmers.

Plant and animal domestication is the most important development in the past 13,000 years of human history. It interests all of us, scientists and non-scientists alike, because it provides most of our food today, it was prerequisite to the rise of civilization, and it transformed global demography. Because domestication ultimately yielded agents of conquest (for example, guns, germs and steel) but arose in only a few areas of the world, and in certain of those areas earlier than in others, the peoples who through biogeographic luck first acquired domesticates acquired enormous advantages over other peoples and expanded. As a result of those replacements, about 88% of all humans alive today speak some language belonging to one or another of a mere seven language families confined in the early Holocene to two small areas of Eurasia that happened to become the earliest centres of domestication — the Fertile Crescent and parts of China. Through that head start, the inhabitants of those two areas spread their languages and genes over much of the rest of the world. Those localized origins of domestication ultimately explain why this international journal of science is published in an Indo-European language rather than in Basque, Swahili, Quechua or Pitjantjatjara.

Much of this review is devoted to domestication itself: its origins, the biological changes involved, its surprising restriction to so few species, the restriction of its geographic origins to so few homelands, and its subsequent geographic expansion from those homelands. I then discuss the consequences of domestication for human societies, the origins of human infectious diseases, expansions of agricultural populations, and human evolution. After posing the unresolved questions that I would most like to see answered, I conclude by speculating about possible future domestications of plants and animals, and of ourselves. By a domesticate, I mean a species bred in captivity and thereby modified from its wild ancestors in ways making it more useful to humans who control its reproduction and (in the case of animals) its food supply. Domestication is thus distinct from mere taming of wild-born animals. Hannibal's African war elephants were, and modern Asian work elephants still are, just tamed wild individuals, not individuals of a genetically distinct population born and reared in captivity.

In 1997 I summarized available information about domestication and its consequences for human history in a book[1]. Since then, new details have continued to accumulate, and unanswered questions have come into sharper focus. Sources for statements not specifically referenced will generally be found in refs 1–9.

The past of domestication

Our 'decision' to domesticate

The question "why farm?" strikes most of us modern humans as silly. Of course it is better to grow wheat and cows than to forage for roots and snails. But in reality, that perspective is flawed by hindsight. Food production could not possibly have arisen through a conscious decision, because the world's first farmers had around them no model of farming to observe, hence they could not have known that there was a goal of domestication to strive for, and could not have guessed the consequences that domestication would bring for them. If they had actually foreseen the consequences, they would surely have outlawed the first steps towards domestication, because the archaeological and ethnographic record throughout the world shows that the transition from hunting and gathering to farming eventually resulted in more work, lower adult stature, worse nutritional condition and heavier disease burdens[10,11]. The only peoples who could make a conscious choice about becoming farmers were hunter–gatherers living adjacent to the first farming communities, and they generally disliked what they saw and rejected farming, for the good reasons just mentioned and others.

Instead, the origins of domestication involved unforeseen consequences of two sets of changes — changes in plants and animals, and changes in human behaviour. As initially recognized by Darwin[12], and elaborated by Rindos[13], many of the differences between domestic plants and their wild ancestors evolved as consequences of wild plants being selected, gathered and brought back to camp by hunter–gatherers, while the roots of animal domestication included the ubiquitous tendency of all peoples to try to tame or manage wild animals (including such unlikely candidates as ospreys, hyenas and grizzly bears). Although humans had been manipulating wild plants and animals for a long time, hunter–gatherer behaviour began to change at the end of the Pleistocene because of increasingly unpredictable climate, decreases in big-game species that were hunters' first-choice prey, and increasing human occupation of available habitats[14,15]. To decrease the risk of unpredictable variation in food supply, people broadened their diets (the so-called broad-spectrum revolution) to second- and third-choice foods, which included more small

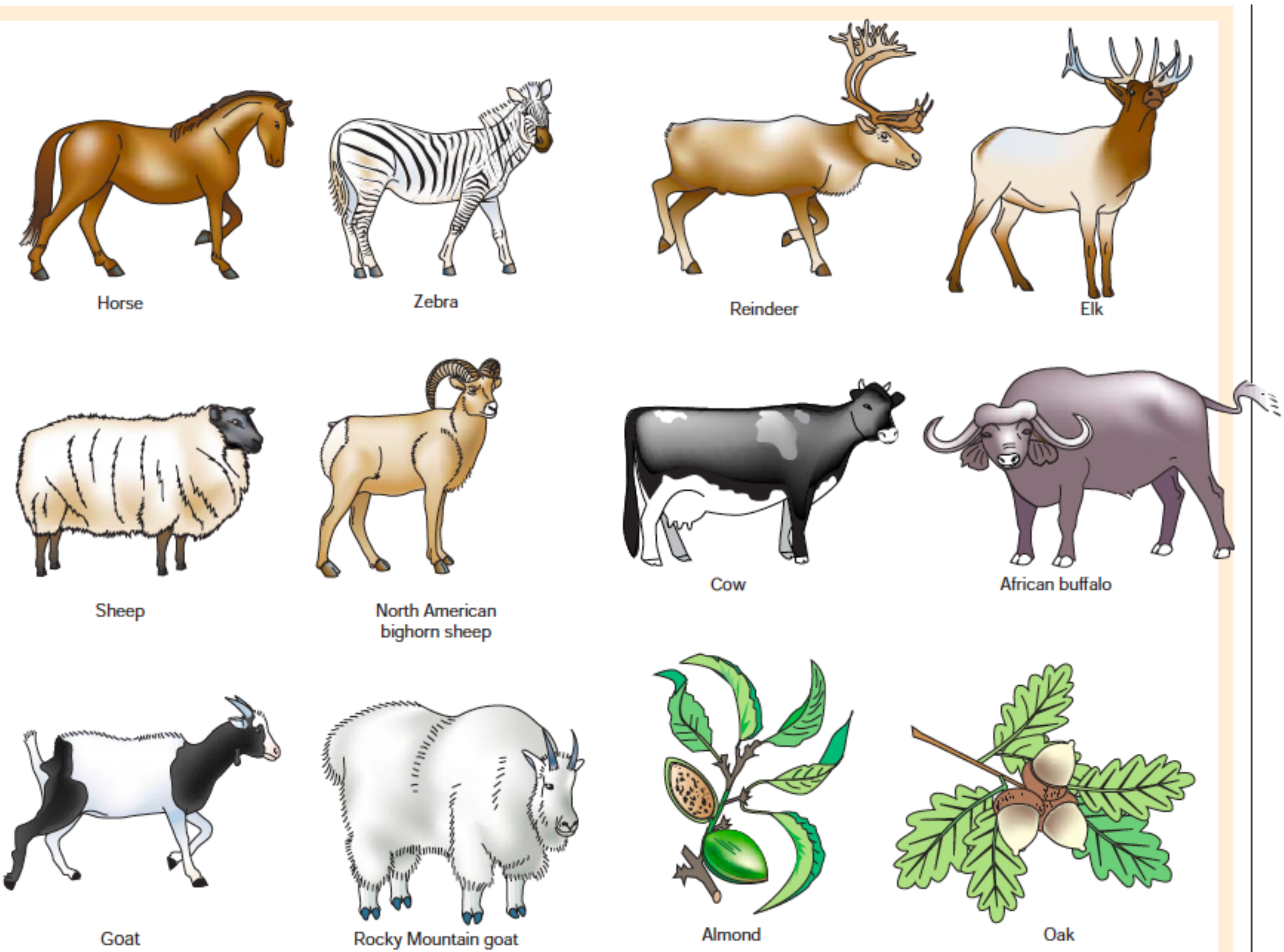

Figure 1 Comparisons of domesticated wild species (left of each pair) and their never-domesticated close relatives (right) reveal the subtle factors that can derail domestication.

game, plus plant foods requiring much preparation, such as grinding, leaching and soaking[14,16]. Eventually, people transported some wild plants (such as wild cereals) from their natural habitats to more productive habitats and began intentional cultivation[17].

The emerging agricultural lifestyle had to compete with the established hunter–gatherer lifestyle. Once domestication began to arise, the changes of plants and animals that followed automatically under domestication, and the competitive advantages that domestication conveyed upon the first farmers (despite their small stature and poor health), made the transition from the hunter–gatherer lifestyle to food production autocatalytic — but the speed of that transition varied considerably among regions[18,19]. Thus, the real question about the origins of agriculture, which I consider below, is: why did food production eventually outcompete the hunter–gatherer lifestyle over almost the whole world, at the particular times and places that it did, but not at earlier times and other places?

Changes of wild species under domestication

These changes are particularly well understood for southwest Asia's Fertile Crescent, the site of domestication that was earliest in the world and that yielded what are still the world's most valuable domestic plant and animal species. For most species domesticated there, the wild ancestor and its wild geographic range have been identified, its relation to the domesticate proven by genetic and chromosomal studies, its changes under domestication delineated (often at the gene level), those changes traced in successive layers of the archaeological record, and the approximate time and place of its domestication identified[9].

For example, wild wheats and barley bear their seeds on top of a stalk that spontaneously shatters, dropping the seeds to the ground where they can germinate (but where they also become difficult for humans to gather). An occasional single-gene mutation that prevents shattering is lethal in the wild (because the seeds fail to drop), but conveniently concentrates the seeds for human gatherers. Once people started harvesting those wild cereal seeds, bringing them back to camp, accidentally spilling some, and eventually planting others, seeds with a non-shattering mutation became unconsciously selected for rather than against[9,17].

Individual wild animals also vary in traits affecting their desirability to humans. Chickens were selected to be larger, wild cattle (aurochs) to be smaller, and sheep to lose their bristly outer hairs (the kemp) and not to shed their soft inner hairs (the wool). Most domestic animals, including even recently domesticated trout[20], have smaller brains and less acute sense organs than do their wild ancestors. Good brains and keen eyes are essential to survival in the wild, but represent a quantitatively important waste of energy in the barnyard, as far as humans are concerned[3,21].

Especially instructive are cases in which the same ancestral species became selected under domestication for alternative purposes, resulting in very different-appearing breeds or crops. For instance, dogs were variously selected to kill wolves, dig out rats, race, be eaten, or be cuddled in our laps. What naive zoologist glancing at wolfhounds, terriers, greyhounds, Mexican hairless dogs and chihuahuas would even guess them to belong to the same species? Similarly, cabbage (*Brassica oleracea*) was variously selected for its leaves (cabbage and kale), stems (kohlrabi), flower shoots (broccoli and cauliflower) and buds (brussels sprouts).

Why so few wild species were domesticated

The wild animal species that most plausibly could have yielded valuable domesticates were large terrestrial mammalian herbivores and omnivores, of which the world holds 148 species weighing 45 kg or more (Table 9.2 of ref. 1). Yet only 14 of those 148 species were actually domesticated (Table 9.1 of ref. 1), prompting us to ask what prevented domestication of the other 134 species? Similarly, worldwide there are about 200,000 wild species of higher plants, of which only about 100 yielded valuable domesticates. Especially surprising are the many cases in which only one of a closely related group of species became domesticated. For example, horses and donkeys were domesticated, but none of the four zebra species congeneric and able to interbreed with them[3,22].

The key question concerning this selectivity of domestication is as follows: in the cases of all those species never domesticated, did the difficulty lie with the species itself, or with the people indigenous to the area to which the species was native? For instance, is the abundance of large wild mammals the reason why no mammal species was ever domesticated in subequatorial Africa, making domestication superfluous for Africans? If that explanation were correct, then African people should also have ignored Eurasian domestic mammals when those were finally introduced to Africa, and European animal breeders on arriving in Africa should have succeeded in domesticating some African wild mammals, but both of those predictions are refuted by the actual course of history.

Six independent lines of evidence[1] converge to prove that, in most cases, the obstacle lay with the species itself, not with the local people: the rapid acceptance of introduced Eurasian domesticates by non-Eurasian peoples; the rapid ancient domestication of the most valuable wild species; the repeated independent domestications of many of them; the failure of even modern European plant and animal breeders to add significantly to our short list of valuable domesticates; ancient discoveries of the value of thousands of species that were regularly harvested in the wild but that never became domesticated; and the identification of the particular reasons preventing the domestication of many of those species.

Comparisons of domesticated wild species with never-domesticated close relatives illustrate the subtle factors that can derail domestication[1] (Fig. 1). For example, it is initially surprising that oak trees, the most important wild food plant in many parts of Eurasia and North America, were never domesticated. Like wild almonds, acorns of most individual wild oaks contain bitter poisons, with occasional non-poisonous mutant trees preferred by human foragers. However, the non-poisonous condition is controlled by a single dominant gene in almonds but polygenically in oaks, so that offspring of the occasional non-poisonous individuals are often non-poisonous in almonds but rarely so in oaks, preventing selection of edible oak varieties to this day. A second example is provided by the European horse breeders who settled in South Africa in the 1600s and — like African herders for previous millennia — tried to domesticate zebras. They gave up after several centuries for two reasons. First, zebras are incurably vicious, have the bad habit of biting a handler and not letting go until the handler is dead, and thereby injure more zoo-keepers each year than do tigers. Second, zebras have better peripheral vision than horses, making them impossible even for professional rodeo cowboys to lasso (they see the rope coming and flick away their head).

Among wild mammal species that were never domesticated, the six main obstacles proved to be a diet not easily supplied by humans (hence no domestic anteaters), slow growth rate and long birth spacing (for example, elephants and gorillas), nasty disposition (grizzly bears and rhinoceroses), reluctance to breed in captivity (pandas and cheetahs), lack of follow-the-leader dominance hierarchies (bighorn sheep and antelope), and tendency to panic in enclosures or when faced with predators (gazelles and deer, except reindeer). Many species passed five of these six tests but were still not domesticated, because they failed a sixth test. Conclusions about non-domesticability from the fact of non-domestication are not circular, because these six obstacles can be assessed independently.

Why there were so few homelands of agriculture

Food production bestowed on farmers enormous demographic, technological, political and military advantages over neighbouring hunter–gatherers. The history of the past 13,000 years consists of tales of hunter–gatherer societies becoming driven out, infected, conquered or exterminated by farming societies in every area of the world suitable for farming. One might therefore have naively anticipated that, in any part of the world, one or more of the local hunter–gatherer societies would have stumbled upon domestication, become farmers, and thereby outcompeted the other local hunter–gatherer societies. In fact, food production arose independently in at most nine areas of the world (Fertile Crescent, China, Mesoamerica, Andes/Amazonia, eastern United States, Sahel, tropical West Africa, Ethiopia and New Guinea).

The puzzle increases when one scrutinizes that list of homelands. One might again naively have expected the areas most productive for farming today to correspond, at least roughly, to the areas most productive in the past. In reality, the list of homelands and the list of breadbaskets of the modern world are almost mutually exclusive (Fig. 2). The latter list includes California, North America's Great Plains, Europe, the pampas of Argentina, the cape of southern Africa, the Indian subcontinent, Java and Australia's wheat belt. Because these areas are evidently so well suited to farming or herding today, why were they not so in the past?

The explanation is that the homelands of agriculture were instead merely those regions to which the most numerous and most valuable domesticable wild plant and animal species were native. Only in those areas were incipient early farmers able to outcompete local hunter–gatherers. Once those locally available wild species had been domesticated and had spread outside the homelands, societies of homelands had no further advantage other than that of a head start, and they were eventually overtaken by societies of more fertile or climatically more favoured areas outside the homelands.

For instance, the Fertile Crescent of southwest Asia was home to wild wheats, barley, peas, sheep, goats, cows and pigs — a list that includes what are still the most valuable crops and livestock of the modern world. Hence hunter–gatherers of the Fertile Crescent domesticated those species and became the world's first farmers and herders, beginning around 8500 BC[1,9,23]. That head start in food production led to them and their close neighbours also developing the world's first metal tools, writing, empires and professional armies. Those tools of conquest, and Fertile Crescent human genes, gradually spread west into Europe and North Africa and east into the western Indian subcontinent and central Asia. However, once those crops, livestock and human inventions had spread, Fertile Crescent societies possessed no other advantages. As all of those elements slowly spread northwest across Europe, farming and power also shifted northwest from the Fertile Crescent to areas where farming had never arisen independently — first to Greece, then to Italy, and finally to northwest Europe. Human societies of the Fertile Crescent inadvertently committed slow ecological suicide in a zone of low rainfall prone to deforestation, soil erosion and salinization.

The spread of food production

From the homelands of domestication, food production spread around the world in either of two ways. The much less common way was for hunter–gatherers outside the homelands to acquire crops or livestock from the homelands, enabling them to settle down as farmers or herders, as attested by archaeological evidence for substantial

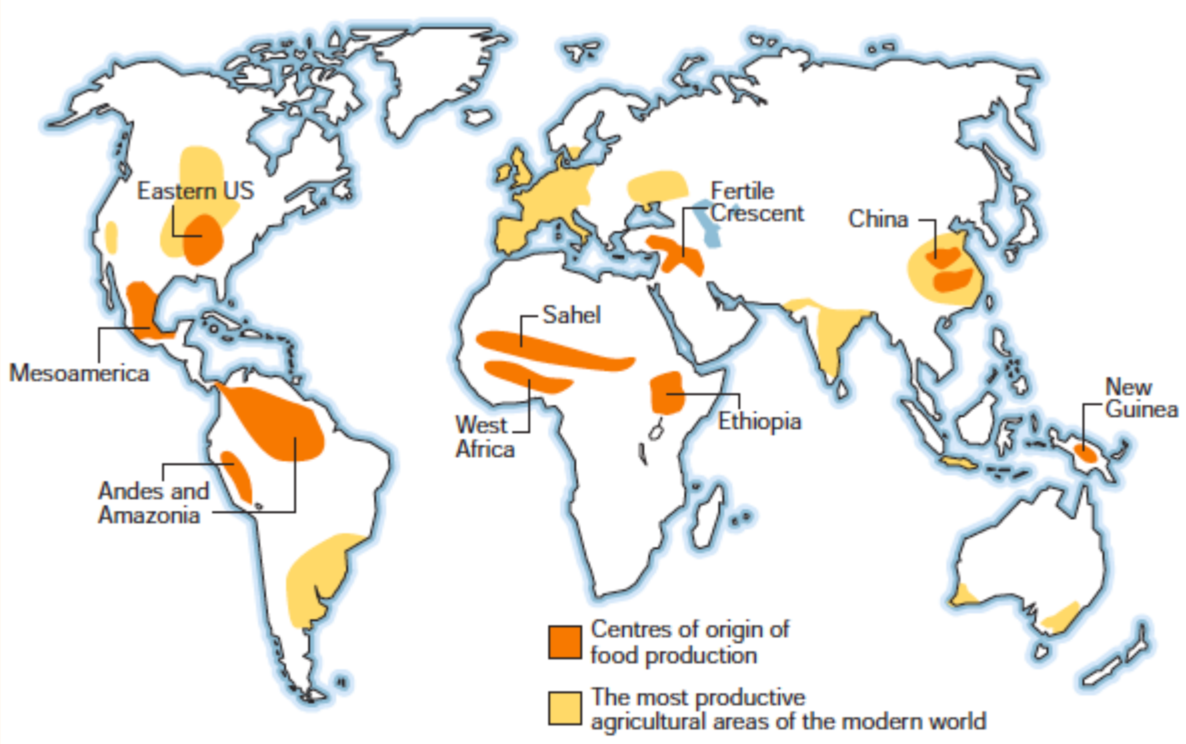

Figure 2 Ancient and modern centres of agriculture. Ancient centres of origin of plant and animal domestication — the nine homelands of food production — are indicated by the orange-shaded areas on the map (based on Fig. 5.1 of ref. 1). The most agriculturally productive areas of the modern world, as judged by cereals and major staples, are indicated by the yellow-shaded areas. Note that there is almost no overlap between the areas highlighted, except that China appears on both distributions, and that the most productive areas of the central United States today approach areas of the eastern United States where domestication originated. The reason why the two distributions are so different is that agriculture arose in areas to which the wild ancestors of the most valuable domesticable crops and animals were native, but other areas proved much more productive when those valuable domesticates reached them.

continuity of material culture, and by genetic, linguistic and skeletal evidence of continuity of human populations. The clearest such example of local adoption of food production is in southern Africa, where around 2,000 years ago some Khoisan hunter–gatherers acquired Eurasian livestock (cattle, sheep and goats) arriving from the north and became herders (so-called Hottentots). Much more often, however, local hunter–gatherers had no opportunity to acquire crops and livestock before they were overrun or replaced by farmers expanding out of the homelands, exploiting their demographic, technological, political and military advantages over the hunter–gatherers.

Expansions of crops, livestock, and even people and technologies tended to occur more rapidly along east–west axes than along north–south axes[1] (Fig. 3). The reason is obvious: locations at the same latitude share identical day-lengths and seasonalities, often share similar climates, habitats and diseases, and hence require less evolutionary change or adaptation of domesticates, technologies and cultures than do locations at different latitudes. Examples include the rapid westwards and eastwards dispersal of wheat, horses, wheels and writing of western Asian origin, and the westwards dispersal of chickens, citrus and peaches of Chinese origin, along the east–west axis of Eurasia. This can be contrasted with the slow spread of Eurasian livestock and non-spread of Eurasian crops southwards along Africa's north–south axis[24], the slow spread of Mexican corn and the non-spread of Mexican writing and wheels and Andean llamas and potatoes along the Americas' north–south axis, and the slow spread of food production southwards along the north–south axis of the Indian subcontinent.

This is not to deny the existence of ecological barriers at the same latitude within Asia and North America, but the general pattern remains. Eurasia's east–west axis, and the resulting rapid enrichment of societies in each part of Eurasia by crops and technologies from other parts of Eurasia, became one of the main ultimate reasons why Eurasian peoples conquered Native American peoples, rather than visa versa. Eurasia's east–west axis also explains why there is much less evidence for multiple independent domestications of the same plant species (see below), and much more evidence for agriculturally driven language expansions, in Eurasia than in the Americas.

Consequences of domestication

Consequences for human societies

Beginning around 8500 BC, the transition from the hunter–gatherer lifestyle to food production enabled people to settle down next to their permanent gardens, orchards and pastures, instead of migrating to follow seasonal shifts in wild food supplies. (Some hunter–gatherer societies in especially productive environments were also sedentary, but most were not). Food production was accompanied by a human population explosion that has continued unabated to this day, resulting from two separate factors. First, the sedentary lifestyle permitted shorter birth intervals. Nomadic hunter–gatherers had previously spaced out birth intervals at four years or more, because a mother shifting camp can carry only one infant or slow toddler. Second, plant and animal species that are edible to humans can be cultivated in much higher density in our gardens, orchards and pastures than in wild habitats.

Food production also led to an explosion of technology, because sedentary living permitted the accumulation of heavy technology (such as forges and printing presses) that nomadic hunter–gatherers could not carry, and because the storable food surpluses resulting from agriculture could be used to feed full-time craftspeople and inventors. By also feeding full-time kings, bureaucrats, nobles and soldiers, those food surpluses led to social stratification, political centralization and standing armies. All of these overwhelming advantages are what enabled farmers eventually to displace hunter–gatherers[1].

Evolution of epidemic infectious diseases

The main killers of humans since the advent of agriculture have been acute, highly infectious, epidemic diseases that are confined to humans and that either kill the victim quickly or, if the victim recovers, immunize him/her for life[1,25–28]. Such diseases could not have existed before the origins of agriculture, because they can sustain themselves only in large dense populations that did not exist before agriculture, hence they are often termed 'crowd diseases'. The mystery of the origins of many of these diseases has been solved by molecular biological studies of recent decades, demonstrating that they evolved from similar epidemic diseases of our herd domestic animals with which we began to come into close contact 10,000 years ago. Thus, the evolution of these diseases depended on two separate roles of domestication: in creating much denser human populations, and in permitting much more frequent transmission of animal diseases from our domesticates than from hunted wild animals. For instance, measles and tuberculosis arose from diseases of cattle, influenza from a disease of pigs and ducks[1]. An outstanding mystery remains the origins of smallpox: did it reach us from camels or from cattle?

Crowd diseases paradoxically became agents of conquest, because exposed individuals acquired immune resistance from childhood exposure, and exposed populations gradually evolved genetic resistance, but unexposed populations had neither type of resistance. In practice, because 13 of our 14 large domestic mammals were Eurasian species, evolution of crowd diseases was concentrated in Eurasia, and the diseases became the most important agents by which Eurasian colonists expanding overseas killed indigenous peoples of the Americas, Australia, Pacific islands and southern Africa.

The agricultural expansions
Because some peoples acquired domesticates before other peoples could, and because domesticates conferred eventual advantages such as guns, germs and steel on the possessors, the history of the past 10,000 years has consisted of farmers replacing hunter–gatherers or less advanced farmers. These agricultural expansions, originating mainly from the nine homelands of agriculture, remade genetic and linguistic maps of the world (Table 18.2 of ref. 1). Among the most discussed (and often highly controversial) possible examples are the expansions of Bantu-speaking farmers out of tropical West Africa over subequatorial Africa[29], Austronesian-speaking farmers out of Taiwan over Island Southeast Asia[30], Fertile Crescent farmers over Europe[31,32], and Korean farmers over Japan[33].

Human genetic evolution
Domestication has been by far the most important cause of changes in human gene frequencies in the past 10,000 years. Among the mechanisms responsible are: the spread of human genes from the agricultural homelands; the evolution of genetic resistance factors (including the ABO blood groups) to our new crowd infectious diseases[34,35]; the evolution of adult-persistent lactase in milk-consuming populations of northern Europe and several parts of Africa; the evolution of allozymes of alcohol metabolism permitting consumption of large quantities of nutritionally important beer in western Eurasia; and the evolution of adaptations to a diet higher in simple carbohydrates, saturated fats and (in modern times) calories and salt, and lower in fibre, complex carbohydrates, calcium and unsaturated fats, than the hunter–gatherer diet[36].

Unsolved questions
Among the host of unsolved questions, I focus here on six: what triggered the emergence of agriculture around 8500 BC and why did it not evolve earlier? Do crop and livestock species stem from a single domestication event or from multiple independent domestications? Can areas of food production be segregated into primary and secondary homelands, the latter describing areas where the arrival of primary homeland crops triggered local domestication? How did food production spread? Why were large domestic mammals predominantly Eurasian? And how can we gain a better understanding of the history of domestication of particular species?

Why then but not earlier?
The human lineage diverged from that of chimpanzees around 6,000,000 years ago. For the next 99.8% of our separate history, there was no agriculture, until it emerged independently in up to nine areas on four continents in the short span of 6,000 years between 8500 and 2500 BC. All of those nearly-simultaneous independent origins seem to be too much of a coincidence. What triggered agriculture repeatedly then, and why had it never arisen during the previous 6,000,000 years?

Posing the question in this way both understates and overstates the puzzle. It understates the puzzle, because there are not only up to nine independent trajectories of intensification that did culminate in agriculture, but also many other ones that didn't quite (or that hadn't yet at the time that European conquest aborted them). Areas of the world where hunter–gatherers in the Holocene developed increased population densities, complex material culture, in some cases pottery, and (some anthropologists argue) sedentary living and ranked societies with chiefs included Mesolithic Europe, Japan and maritime Far East Asia, the North American high Arctic, the Pacific coast of northwest North America, interior California's oak woodlands, the California Channel Islands, the Calusa of Florida, the coast of Ecuador, and the Murray–Darling Basin of southeast Australia (for examples, see refs 37–39). But a similar intensification of hunter–gatherer societies also preceded the emergence of food production in its nine homelands; I suspect that the sole difference between the areas where people remained hunter–gatherers and the areas where food production evolved was that plant and animal species harvested in the latter but not the former areas included ones that automatically evolved domesticates, as already discussed. Thus, there were not just 5–9, but several dozen, independent trajectories of intensification in the Holocene.

On the other hand, my formulation of the question also overstates the puzzle. Only behaviourally modern *Homo sapiens* was biologically and mentally capable of the technological advances and foraging efficiency that resulted in intensified hunting and gathering, and (sometimes) in food production[40]. But behaviourally modern *Homo sapiens* did not emerge until around 55,000–80,000 years ago (the exact date is debated), so we should say that the independent simultaneous emergences were not concentrated in the last 0.2% of hominid history, but 'only' in the last 15% of modern human history. Still, even that seems too concentrated a bout of simultaneous emergences to be coincidental. Was it just that the origins of behaviourally modern *Homo sapiens* set clocks ticking by chance at the same rate all over the globe? That strains credulity, especially as intensified hunter–gatherer economies failed to arise in more areas than the areas in which they did arise.

A possible explanation seems to me to derive from four developments in the Late Pleistocene that may indeed have driven the clock's ticking. First, improvements in human hunting skills and consequent depletion or extermination of large mammalian prey would have made the hunter–gatherer lifestyle less rewarding and less able to compete with food production. Second was the development of human technology to collect, process and store wild foods (such as wild cereals), without which subsequently exploiting the same food species as domesticates would have been impossible (that is, what is the point of sowing wheat if you have not yet determined how to reap, roast and store it?). The third development was the on-going competition between human societies, such that those societies with more effective technology at any moment prevailed over other societies. Fourth, the gradual rise in human population numbers through the Pleistocene required intensified food procurement to feed those larger populations.

Against that background of gradual change, a trigger that may have caused intensification and food production to emerge only after the end of the Pleistocene would have been the end-of-Pleistocene climate changes in temperature, rainfall and unpredictability. These changes could have triggered the broad-spectrum reduction in diet[14–17], and made agriculture possible in areas where it would have been impossible during the Ice Ages (for example, expanding Fertile Crescent woodland habitats with understories of wild cereals[41]). Once food production had thus begun, the autocatalytic nature of the many changes accompanying domestication (for example, more food stimulating population growth that required still more food) made the transition rapid. By this interpretation, the independent emergences of food production are no longer remarkably simultaneous — they could not have happened before the end of the Pleistocene (11000 BC), and after the end of the Pleistocene they occurred at very different times, ranging from about 8500 BC (in the Fertile Crescent) to about 2500 BC (eastern North America). Most of the links in this speculative hypothesis are in obvious need of testing.

Multiple versus single domestications
A long-standing question concerns whether each crop and livestock species stems from a single domestication event within a restricted

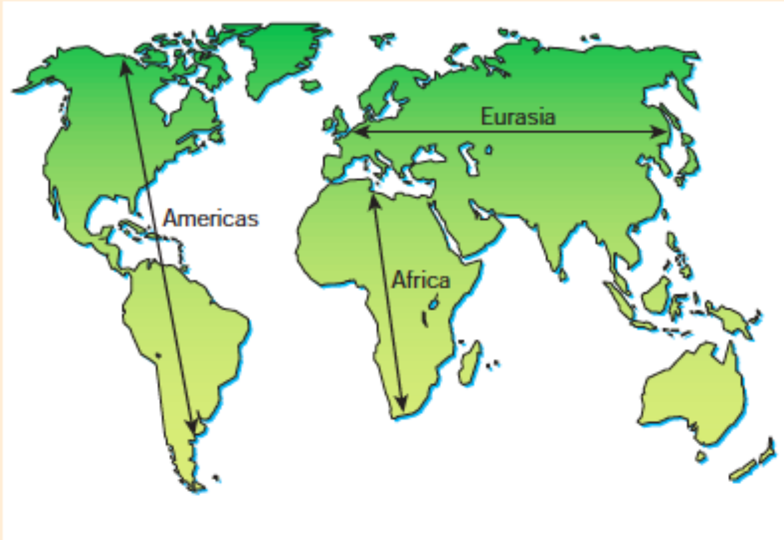

Figure 3 The continental major axis is oriented east–west for Eurasia but north–south for the Americas and Africa. The spread of food production tended to occur more rapidly along east–west axes than along north–south axes, mainly because locations at the same latitudes required less evolutionary change or adaptation of domesticates than did locations at different latitudes. Modified from Fig. 10.1 of ref. 1.

geographic area, or from multiple independent domestications at different sites. An accumulation of recent evidence suggests to me the following generalization: that the former interpretation applies to most major Eurasian crops, the latter interpretation to many New World crops and the major Eurasian livestock species.

Among New World crops, many are represented by distinct but related species in South America, Mesoamerica and the eastern United States, leaving no doubt that related species were domesticated independently in these areas (for example, beans, chenopods, chilli peppers, cotton, squashes, tobaccos and possibly amaranths). Multiple independent domestications are attested within the same species for the chilli pepper species *Capsicum annuum*, common bean *Phaseolus vulgaris*, lima bean *Phaseolus lunatus* and squash species *Cucurbita pepo*[4,7,8,42]. Conversely, the eight crops that founded Fertile Crescent agriculture, with the possible exception of barley, each seem to derive from only a single domestication event[5,9,43–45].

Evidence for separate independent domestications in western and more eastern parts of Eurasia are now available for all of the 'big five' domesticated mammals (cow, sheep, goat, pig and horse), plus one of the 'minor nine' (water buffalo)[46–54]. For example, cows were domesticated independently in the Fertile Crescent (yielding modern humpless cows), in the Indian subcontinent (yielding modern humped Zebu cows) and in North Africa[46,50,53].

I suggest the following hypothesis to explain predominantly single domestications of Fertile Crescent founder crops, but multiple domestications of Eurasian livestock and many New World crops. Except for barley and flax, the wild ancestors of the Fertile Crescent founder crops had restricted geographic ranges confined to the area between modern Turkey and western Iran, while chickpea was even more narrowly restricted, to southeastern Turkey. Those small geographic ranges, plus the rapid spread of domesticates along Eurasia's east–west axis, meant that, once a wild plant had been domesticated, it spread so rapidly that further independent domestications of the same or related species were pre-empted. The large Eurasian mammals, however, had such wide geographic ranges (in the case of pigs extending for 13,000 km from Spain to China) that there was ample time for independent domestications at locations west and east of each other. In the New World, even though all the homelands of agriculture lay within only 4000 km of each other, the slowness of crop diffusion along the New World's north–south axis meant that repeated independent domestications were frequent. So slow was that diffusion that the New World's main animal domesticates — the llama and guinea pig of the Andes, and the turkey of Mexico — had not even spread the mere 2,000 km north to Mexico and south to the Andes, respectively, by the time that Europeans arrived in AD 1492.

Primary versus secondary homelands

In several parts of the world, food production arose only upon the arrival of domesticates from the primary homelands, whereupon people proceeded to domesticate some local wild plants or animals that had not been domesticated previously[9]. Clear examples of such 'secondary' homelands, in which local domestication was triggered by the arrival of Fertile Crescent crops, were Europe (local domestication of poppies and possibly oats) and Egypt (chufa and sycamore fig).

The recognition of those secondary homelands requires us to reconsider the supposed primary homelands. On the one hand, some of the primary homelands may better be viewed as consisting of multiple homelands in which distinct systems of food production arose nearby but independently of each other. This is especially true for the homeland of Andes/Amazonia, which actually comprised primary highland sites in the Andes as well as primary lowland sites scattered from Panama through the Amazon Basin to the Pacific coast of Ecuador and Peru[55,56]. Similarly, the Mesoamerican and Fertile Crescent homelands may have consisted of a mixture of highland and lowland sites, while China probably included northern and southern sites in the Yellow River and Yangtze River basins, respectively, as well as coastal lowland and interior upland sites.

On the other hand, some of the nine candidates for primary homelands may actually be secondary homelands in which domestication was triggered by the arrival of domesticates or of farmers from elsewhere. Independent origins of food production seem indisputable for five of the candidates (the Fertile Crescent, China, Mesoamerica, South America and eastern United States), because they were the earliest sites of domestication in their respective parts of the world. But questions have been raised, at least in conversation, regarding the independence of the other four candidates. Especially uncertain is the status of Ethiopia, where it is unknown whether several undoubted local domesticates (teff, coffee, finger millet, chat, noog and ensete) were cultivated before or only after the arrival of Fertile Crescent domesticates, and the New Guinea highlands, where remains of irrigation and drainage systems attest to early agriculture but where the first crops grown remain unidentified and the earliest dates of food production remain disputed. The independence of even the eastern United States has been challenged recently[42,57], but the evidence seems compelling that Mexican crops arrived there only by way of southwestern United States and only long after local eastern origins of domestication[8,58]. Conversely, in southern India the exact dates of arrival of Fertile Crescent domesticates and of earliest cultivation of local domesticates remain uncertain.

Mechanism of the spread of food production

As already noted, the spread of agriculture from its homelands involved in a few cases the acquisition of domesticates by hunter–gatherers outside the homelands, and in more cases the spread of farmers themselves from the homelands. The contributions of these two processes await resolution in many other cases. For example, contrary to what I wrote five years ago[1], the spread of farming in coastal west Mediterranean Europe (in the form of the Cardial and impressed ware cultures) now seems to have involved the rapid transport by sea of a complete package of Neolithic domesticates around 5400 BC by colonizing pioneer farmers[59]. The Yayoi horizon, which marks the arrival of intensive rice agriculture in Japan, and which Japanese scholars until recently preferred to view as an adoption of mainland practices by the indigenous pre-existing Japanese population, now seems increasingly likely on genetic evidence to represent the arrival, population increase and spread of Korean farmers[33].

Why large domestic mammals were mainly Eurasian

Part of the reason why large domestic mammals were mainly Eurasian is simply that Eurasia, being the largest continent and having escaped the Late-Pleistocene extinctions that eliminated most large mammal species of the Americas and Australia[60], has the largest number of large wild mammal species. But there is a second part to the answer — a much higher percentage of large mammal species proved domesticable in Eurasia (18%) than in any other continent (Table 9.2 of ref. 1). Especially striking is the contrast of Eurasia with sub-Saharan Africa, where none of the 51 large mammal species was domesticable.

This difference constitutes a problem not in human behaviour, but in animal behaviour and sociobiology — something about African environments selected for one or more of the six mammalian traits that made domestication difficult. We already have some clues, as many of Africa's large mammals are species of antelopes and other open-country mammals whose herds lack the follow-the-leader dominance hierarchies characterizing Eurasian cattle, sheep, goats and horses[3,61]. To resolve this problem, I suggest attempting to assign one or more of the six traits derailing domestication to each of the non-domesticated large mammal species of Eurasia and Africa, then evaluating the environmental factors behind the evolution of that trait.

History of domestication of particular species

The history of domestication is much better understood for domesticates of western Eurasia than of other parts of world. Taking Zohary & Hopf's[9] account of western Eurasian plant domestication as a gold standard, it will be a challenge to workers on other biotas to match that standard. Even for western Eurasia, important unanswered questions abound. To mention only one out of dozens, calculation of molecular divergence times between dogs and wolves suggests that domestication of wolves began around 100,000 years ago[62,63], yet the marked morphological differences between wolves and dogs (which should be easily detectable in fossilized skeletons) do not appear until about 11,000 years ago. How can the molecular data and the morphological data be reconciled?

The Future of domestication

Further domestications of plants and animals

We humans today depend for our survival on that tiny fraction of wild species that has been domesticated. Might the rise of molecular biology, genetics and understanding of animal behaviour help feed our growing numbers by increasing that tiny fraction? Modern science has indeed made it technically possible to 'domesticate' species undomesticable in the past, in the sense that we achieve far more draconian control over the captive breeding of endangered California condors (computer-matched for mating to maximize genetic diversity) than the low-tech control that ancient animal breeders exerted over their livestock. But although this 'domestication' is of great interest to conservation biologists, it holds no promise of a condor industry to displace chicken from the supermarkets. What wild species might now be domesticated with profit?

It is instructive to reflect on the meagre additions to our repertoire of domestic species in recent millennia, despite monumental efforts. Of the world's 14 valuable big domestic mammals, the sole addition within the last millennium has been the reindeer, one of the least valuable of the 14. (In contrast, the five most valuable — the sheep, goat, cow, pig and horse — had all been domesticated repeatedly by 4000 BC.) Long-ongoing efforts by modern livestock breeders to domesticate other large wild mammals have resulted either in virtual failure (for example, eland, elk, moose, musk ox and zebra), or else in ranched animals (deer and American bison) that still cannot be herded and that remain of trivial economic value compared to the five most valuable mammals. Instead, all of the mammalian species that have recently become well established as domesticates (for example, arctic fox, chinchilla, hamster, laboratory rat and rabbit) are small mammals dwarfed in usefulness as well as in size by cows and sheep. Similarly, whereas several wild plants were first domesticated only in modern times (for example, blueberries, macadamia nuts, pecans and strawberries), their value is insignificant compared to that of ancient domesticates such as wheat and rice.

Our best hopes for valuable new domesticates lie in recognizing the specific difficulties that previously derailed domestication of particular valuable wild species, and using modern science to overcome those difficulties. For instance, now that we understand the polygenic control of non-bitterness in acorns, perhaps we could use that knowledge to select for oaks with non-bitter acorns, just as ancient farmers selected for non-bitterness controlled by a single gene in almonds. I am concerned, however, that such attempts may in the long run do us more harm than good. Humanity's greatest risk today is of our growing numbers and aspirations ultimately destroying our society by destroying our environment. Providing undernourished people with more food would be a laudable goal if it were inexorably linked to reducing our numbers, but in the past more food has always resulted in more people. Only when crop and animal breeders take the lead in reducing our numbers and our impacts will they end up by doing us net good.

Further domestication of humans

Some genotypes that used to serve us well as hunter–gatherers now serve us poorly as first-world citizens who forage only in supermarkets — especially metabolically thrifty genotypes that now predispose to type II diabetes, salt-conserving genotypes that predispose to hypertension, and other genotypes predisposing to other cardiovascular diseases and lipid disorders. As formerly spartan populations become westernized ('coca-colonized')[64], they fall victim to these diseases of the western lifestyle, extreme examples being the 70% incidence of type II diabetes in those Nauru Islanders and Pima Indians lucky enough to survive to the age of 60 (ref. 65). Because diabetes now afflicts south Asians and Pacific Islanders already in their twenties with high morbidity and mortality, there has been detectable natural selection against the predisposing genotypes even within just recent decades. The lower frequency of type II diabetes in Europeans than in non-Europeans matched for diet and lifestyle suggests that natural selection had already reduced European frequencies of those genotypes in previous centuries, as the western lifestyle was developing in Europe. In effect, the unconscious domestication of humans by agriculture that began over 10,000 years ago is still underway.

Even more such gene-frequency changes, also known as illness and deaths, are expected in the near future, as westernization accelerates in the world's two most populous countries, China and India[66,67]. For example, the incidence of type II diabetes in mainland China, until recently less than 1%, has already tripled in some areas. What lies ahead for China can be projected by considering overseas Chinese populations in Hong Kong, Taiwan, Singapore and Mauritius, where westernization is further advanced and the incidence of type II diabetes is up to 17%. Similarly, the incidence in overseas Indian populations such as that of Fiji gives a foretaste of diabetes' future in India itself.

The resulting projections are that the number of cases of diabetes is expected to increase worldwide by 46% from the year 2000 to 2010, to reach around 220 million in 2010 and around 300 million in 2025. The steepest increase will be in east Asia (including China and India), the projected home of 60% of the world's diabetics in 2010. Similar diet-related disease epidemics are underway in less numerous peoples (from Africans to Aboriginal Australians), involving not just diabetes but also hypertension and other conditions. Thus, these epidemics pose the same dilemma as do efforts to domesticate more wild plant and animal species: how can we ensure that agriculture spreads only happiness, and not suffering as well? □

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REVIEWS

Origins of major human infectious diseases

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Many of the major human infectious diseases, including some now confined to humans and absent from animals, are 'new' ones that arose only after the origins of agriculture. Where did they come from? Why are they overwhelmingly of Old World origins? Here we show that answers to these questions are different for tropical and temperate diseases; for instance, in the relative importance of domestic animals and wild primates as sources. We identify five intermediate stages through which a pathogen exclusively infecting animals may become transformed into a pathogen exclusively infecting humans. We propose an initiative to resolve disputed origins of major diseases, and a global early warning system to monitor pathogens infecting individuals exposed to wild animals.

Human hunter/gatherer populations currently suffer, and presumably have suffered for millions of years, from infectious diseases similar or identical to diseases of other wild primate populations. However, the most important infectious diseases of modern food-producing human populations also include diseases that could have emerged only within the past 11,000 years, following the rise of agriculture[1,2]. We infer this because, as discussed below, these diseases can only be sustained in large dense human populations that did not exist anywhere in the world before agriculture. What were the sources of our major infectious diseases, including these 'new' ones? Why do so many animal pathogens, including virulent viruses like Ebola and Marburg, periodically infect human hosts but then fail to establish themselves in human populations?

A tentative earlier formulation[1] noted that major infectious diseases of temperate zones seem to have arisen overwhelmingly in the Old World (Africa, Asia and Europe), often from diseases of Old World domestic animals. Hence one goal of this article is to reappraise that conclusion in the light of studies of the past decade. Another goal is to extend the analysis to origins of tropical diseases[3]. We shall show that they also arose mainly in the Old World, but for different reasons, and mostly not from diseases of domestic animals.

These results provide a framework for addressing unanswered questions about the evolution of human infectious diseases—questions not only of practical importance to physicians, and to all the rest of us as potential victims, but also of intellectual interest to historians and evolutionary biologists. Historians increasingly recognize that infectious diseases have had major effects on the course of history; for example, on the European conquest of Native Americans and Pacific Islanders, the inability of Europeans to conquer the Old World tropics for many centuries, the failure of Napoleon's invasion of Russia, and the failure of the French attempt to complete construction of a Panama Canal[4–6]. Evolutionary biologists realize that infectious diseases, as a leading cause of human morbidity and mortality, have exerted important selective forces on our genomes[2,7].

We begin by defining five stages in the evolutionary transformation of an animal pathogen into a specialized pathogen of humans, and by considering why so many pathogens fail to make the transition from one stage to the next. We then assemble a database of 15 temperate and 10 tropical diseases of high evolutionary and/or historical impact, and we compare their characteristics and origins. Our concluding section lays out some unresolved questions and suggests two expanded research priorities. We restrict our discussion to unicellular microbial pathogens. We exclude macroparasites (in the sense of ref. 7), as well as normally benign commensals that cause serious illness only in weakened hosts. The extensive Supplementary Information provides details and references on our 25 diseases, robustness tests of our conclusions, factors affecting transitions between disease stages, and modern practices altering the risk of emergence of new diseases.

Evolutionary stages

Box 1 delineates five intergrading stages (Fig. 1) through which a pathogen exclusively infecting animals (Stage 1) may become transformed into a pathogen exclusively infecting humans (Stage 5). Supplementary Table S1 assigns each of the 25 major diseases discussed (Supplementary Note S1) to one of these five stages.

A large literature discusses the conditions required for a Stage 5 epidemic to persist[2,7]. Briefly, if the disease infects only humans and lacks an animal or environmental reservoir, each infected human introduced into a large population of susceptible individuals must on average give rise during his/her contagious lifespan to an infection in at least one other individual. Persistence depends on factors such as the duration of a host's infectivity; the rate of infection of new hosts; rate of development of host protective immunity; and host population density, size and structure permitting the pathogen's regional persistence despite temporary local extinctions.

Less well understood are two of the critical transitions between stages, discussed in Box 2. One is the transition from Stage 1 to Stage 2, when a pathogen initially confined to animals first infects humans. The other is the transition from Stage 2 to Stages 3 and 4 (see also Supplementary Note S2), when a pathogen of animal origin that is nevertheless transmissible to humans evolves the ability to sustain many cycles of human-to-human transmission, rather than just a few cycles before the outbreak dies out (as seen in modern Ebola outbreaks).

Database and conclusions

Database. Supplementary Table S1 lists 10 characteristics for each of 25 important 'temperate' (15) and 'tropical' (10) diseases (see Supplementary Note S3 for details of this distinction). Our aim was to select well-defined diseases causing the highest mortality and/or morbidity and hence of the highest historical and evolutionary significance (see Supplementary Note S1 for details of our selection criteria). Of the 25 diseases, we selected 17 because they are the ones assessed by ref. 8 as imposing the heaviest world burdens today

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Box 1 | Five stages leading to endemic human diseases

We delineate five stages in the transformation of an animal pathogen into a specialized pathogen of humans (Fig. 1). There is no inevitable progression of microbes from Stage 1 to Stage 5: at each stage many microbes remain stuck, and the agents of nearly half of the 25 important diseases we selected for analysis (Supplementary Table S1) have not reached Stage 5.

- **Stage 1.** A microbe that is present in animals but that has not been detected in humans under natural conditions (that is, excluding modern technologies that can inadvertently transfer microbes, such as blood transfusion, organ transplants, or hypodermic needles). Examples: most malarial plasmodia, which tend to be specific to one host species or to a closely related group of host species.
- **Stage 2.** A pathogen of animals that, under natural conditions, has been transmitted from animals to humans ('primary infection') but has not been transmitted between humans ('secondary infection'). Examples: anthrax and tularemia bacilli, and Nipah, rabies and West Nile viruses.
- **Stage 3.** Animal pathogens that can undergo only a few cycles of secondary transmission between humans, so that occasional human outbreaks triggered by a primary infection soon die out. Examples: Ebola, Marburg and monkeypox viruses.
- **Stage 4.** A disease that exists in animals, and that has a natural (sylvatic) cycle of infecting humans by primary transmission from the animal host, but that also undergoes long sequences of secondary transmission between humans without the involvement of animal hosts. We arbitrarily divide Stage 4 into three substages distinguished by the relative importance of primary and secondary transmission:
  Stage 4a. Sylvatic cycle much more important than direct human-to-human spread. Examples: Chagas' disease and (more frequent secondary transmission approaching Stage 4b) yellow fever.
  Stage 4b. Both sylvatic and direct transmission are important. Example: dengue fever in forested areas of West Africa and Southeast Asia.
  Stage 4c. The greatest spread is between humans. Examples: influenza A, cholera, typhus and West African sleeping sickness.
- **Stage 5.** A pathogen exclusive to humans. Examples: the agents causing *falciparum* malaria, measles, mumps, rubella, smallpox and syphilis. In principle, these pathogens could have become confined to humans in either of two ways: an ancestral pathogen already present in the common ancestor of chimpanzees and humans could have co-speciated long ago, when the chimpanzee and human lineages diverged around five million years ago; or else an animal pathogen could have colonized humans more recently and evolved into a specialized human pathogen. Co-speciation accounts well for the distribution of simian foamy viruses of non-human primates, which are lacking and presumably lost in humans: each virus is restricted to one primate species, but related viruses occur in related primate species[19]. While both interpretations are still debated for *falciparum* malaria, the latter interpretation of recent origins is widely preferred for most other human Stage 5 diseases of Supplementary Table S1.

(they have the highest disability-adjusted life years (DALY) scores). Of the 17 diseases, 8 are temperate (hepatitis B, influenza A, measles, pertussis, rotavirus A, syphilis, tetanus and tuberculosis), and 9 are tropical (acquired immune deficiency syndrome (AIDS), Chagas' disease, cholera, dengue haemorrhagic fever, East and West African sleeping sicknesses, *falciparum* and *vivax* malarias, and visceral leishmaniasis). We selected eight others (temperate diphtheria, mumps, plague, rubella, smallpox, typhoid and typhus, plus tropical yellow fever) because they imposed heavy burdens in the past, although modern medicine and public health have either eradicated them (smallpox) or reduced their burden. Except for AIDS, dengue fever, and cholera, which have spread and attained global impact in modern times, most of these 25 diseases have been important for more than two centuries.

Are our conclusions robust to variations in these selection criteria? For about a dozen diseases with the highest modern or historical burdens (for example, AIDS, malaria, plague, smallpox), there can be little doubt that they must be included, but one could debate some of the next choices. Hence we drew up three alternative sets of diseases sharing a first list of 16 indisputable major diseases but differing in the next choices, and we performed all 10 analyses described below on all three sets. It turned out that, with one minor exception, the three sets yielded qualitatively the same conclusions for all 10 analyses, although differing in their levels of statistical significance (see Supplementary Note S4). Thus, our conclusions do seem to be robust.

Temperate/tropical differences. Comparisons of these temperate and tropical diseases yield the following conclusions:

- A higher proportion of the diseases is transmitted by insect vectors in the tropics (8/10) than in the temperate zones (2/15) ($P < 0.005$, χ^2-test, degrees of freedom, d.f. = 1). This difference may be partly related to the seasonal cessations or declines of temperate insect activity.
- A higher proportion ($P = 0.009$) of the diseases conveys long-lasting immunity (11/15) in the temperate zones than in the tropics (2/10).
- Animal reservoirs are more frequent ($P < 0.005$) in the tropics (8/10) than in the temperate zones (3/15). The difference is in the reverse direction ($P = 0.1$, NS, not significant) for environmental reservoirs (1/10 versus 6/15), but those environmental reservoirs that do exist are generally not of major significance except for soil bearing tetanus spores.
- Most of the temperate diseases (12/15) are acute rather than slow, chronic, or latent: the patient either dies or recovers within one to several weeks. Fewer ($P = 0.01$) of the tropical diseases are acute: 3/10 last for one or two weeks, 3/10 last for weeks to months or years, and 4/10 last for many months to decades.
- A somewhat higher proportion of the diseases ($P = 0.08$, NS) belongs to Stage 5 (strictly confined to humans) in the temperate zones (10/15 or 11/15) than in the tropics (3/10). The paucity of Stage 2 and Stage 3 diseases (a total of only 5 such diseases) on our list of 25 major human diseases is noteworthy, because some Stage 2 and Stage 3 pathogens (such as anthrax and Ebola) are notoriously virulent, and because theoretical reasons are often advanced (but also denied) as to why Stage 5 microbes with long histories of adaptation to humans should tend to evolve low morbidity and mortality and not cause major diseases. We discuss explanations for this outcome in Supplementary Note S5.

Most (10/15) of the temperate diseases, but none of the tropical diseases ($P < 0.005$), are so-called 'crowd epidemic diseases' (asterisked in Supplementary Table S1), defined as ones occurring locally as a brief epidemic and capable of persisting regionally only in large human populations. This difference is an immediate consequence of the differences enumerated in the preceding five paragraphs. If a disease is acute, efficiently transmitted, and quickly leaves its victim either dead or else recovering and immune to re-infection, the epidemic soon exhausts the local pool of susceptible potential victims. If in addition the disease is confined to humans and lacks significant animal and environmental reservoirs, depletion of the local pool of potential victims in a small, sparse human population results in local termination of the epidemic. If, however, the human population is large and dense, the disease can persist by spreading to infect people in adjacent areas, and then returning to the original area in a later year, when births and growth have regenerated a new crop of previously unexposed non-immune potential victims. Empirical epidemiological studies of disease persistence or disappearance in isolated human populations of various sizes have yielded estimates of the population required to sustain a crowd disease: at least several hundred thousand people in the cases of measles, rubella and pertussis[2,7]. But human populations of that size did not exist anywhere in the

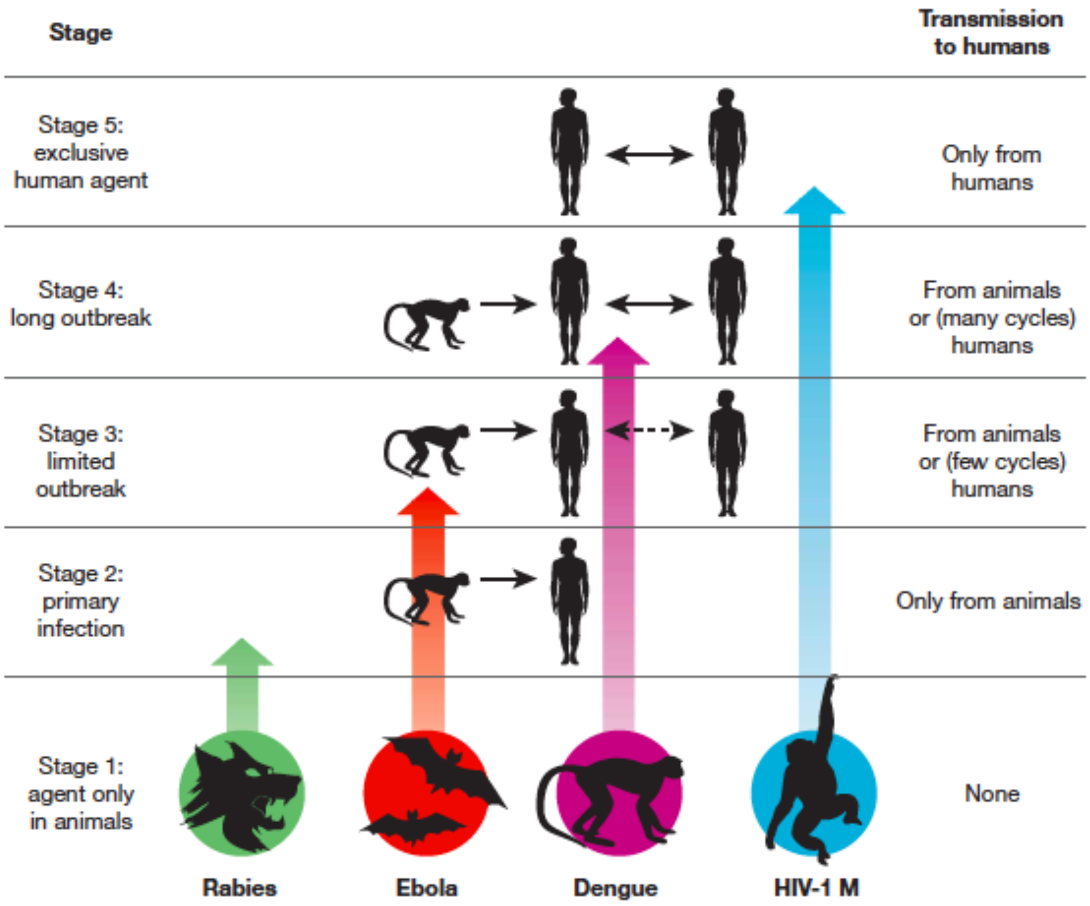

Figure 1 | Illustration of the five stages through which pathogens of animals evolve to cause diseases confined to humans. (See Box 1 for details.) The four agents depicted have reached different stages in the process, ranging from rabies (still acquired only from animals) to HIV-1 (now acquired only from humans).

world until the steep rise in human numbers that began around 11,000 years ago with the development of agriculture[1,9]. Hence the crowd epidemic diseases of the temperate zones must have evolved since then.

Of course, this does not mean that human hunter/gatherer communities lacked infectious diseases. Instead, like the sparse populations of our primate relatives, they suffered from infectious diseases with characteristics permitting them to persist in small populations, unlike crowd epidemic diseases. Those characteristics include: occurrence in animal reservoirs as well as in humans (such as yellow fever); incomplete and/or non-lasting immunity, enabling recovered patients to remain in the pool of potential victims (such as malaria); and a slow or chronic course, enabling individual patients to continue to infect new victims over years, rather than for just a week or two (such as Chagas' disease).

Pathogen origins. (See details for each disease in Supplementary Note S10). Current information suggests that 8 of the 15 temperate diseases probably or possibly reached humans from domestic animals (diphtheria, influenza A, measles, mumps, pertussis, rotavirus, smallpox, tuberculosis); three more probably reached us from apes (hepatitis B) or rodents (plague, typhus); and the other four (rubella, syphilis, tetanus, typhoid) came from still-unknown sources (see Supplementary Note S6). Thus, the rise of agriculture starting 11,000 years ago played multiple roles in the evolution of animal pathogens into human pathogens[1,4,10]. Those roles included both generation of the large human populations necessary for the evolution and persistence of human crowd diseases, and generation of large populations of domestic animals, with which farmers came into much closer and more frequent contact than hunter/gatherers had with wild animals. Moreover, as illustrated by influenza A, these domestic animal herds served as efficient conduits for pathogen transfers from wild animals to humans, and in the process may have evolved specialized crowd diseases of their own.

It is interesting that fewer tropical than temperate pathogens originated from domestic animals: not more than three of the ten tropical diseases of Supplementary Table S1, and possibly none (see Supplementary Note S7). Why do temperate and tropical human diseases differ so markedly in their animal origins? Many (4/10) tropical diseases (AIDS, dengue fever, *vivax* malaria, yellow fever) but only 1/15 temperate diseases (hepatitis B) have wild non-human primate origins ($P = 0.04$). This is because although non-human primates are the animals most closely related to humans and hence pose the weakest species barriers to pathogen transfer, the vast majority of primate species is tropical rather than temperate. Conversely, few tropical but many temperate diseases arose from domestic animals, and this is because domestic animals live mainly in the temperate zones, and their concentration there was formerly even more lop-sided (see Supplementary Note S8).

A final noteworthy point about animal-derived human pathogens is that virtually all arose from pathogens of other warm-blooded vertebrates, primarily mammals plus in two cases (influenza A and ultimately *falciparum* malaria) birds. This comes as no surprise, considering the species barrier to pathogen transfer posed by phylogenetic distance (Box 2). An expression of this barrier is that primates constitute only 0.5% of all vertebrate species but have contributed about 20% of our major human diseases. Expressed in another way, the number of major human diseases contributed, divided by the number of animal species in the taxonomic group contributing those diseases, is approximately 0.2 for apes, 0.017 for non-human primates other than apes, 0.003 for mammals other than primates, 0.00006 for vertebrates other than mammals, and either 0 or else 0.000003 (if cholera really came from aquatic invertebrates) for animals other than vertebrates (see Supplementary Note S9).

Geographic origins. To an overwhelming degree, the 25 major human pathogens analysed here originated in the Old World. That proved to be of great historical importance, because it facilitated the European conquest of the New World (the Americas). Far more Native Americans resisting European colonists died of newly introduced Old World diseases than of sword and bullet wounds. Those invisible agents of New World conquest were Old World microbes to which Europeans had both some acquired immunity based on individual exposure and some genetic resistance based on population

Box 2 | Transitions between stages

Transition from Stage 1 to Stage 2. Most animal pathogens are not transmitted to humans, that is, they do not even pass from Stage 1 to Stage 2. This problem of cross-species infection has been discussed previously[20–23]. Briefly, the probability-per-unit-time (p) of infection of an individual of a new (that is, new recipient) host species increases with the abundance of the existing (that is, existing donor) host, with the fraction of the existing host population infected, with the frequency of 'encounters' (opportunities for transmission, including indirect 'encounters' via vectors) between an individual of the existing host and of the new host, and with the probability of transmission per encounter. p decreases with increasing phylogenetic distance between the existing host and new host. p also varies among microbes (for example, trypanosomes and flaviviruses infect a wide taxonomic range of hosts, while plasmodia and simian foamy viruses infect only a narrow range), and this variation is related to a microbe's characteristics, such as its ability to generate genetic variability, or its ability to overcome host molecular barriers of potential new hosts (such as humoral and cellular defenses or lack of cell membrane receptors essential for microbe entry into host cells).

These considerations illuminate different reasons why a given animal host species may or may not become a source of many infections in humans. For instance, despite chimpanzees' very low abundance and infrequent encounters with humans, they have donated to us numerous zoonoses (diseases that still mainly afflict animals) and one or two established human diseases (AIDS and possibly hepatitis B) because of their close phylogenetic relationship to humans. Despite their large phylogenetic distance from humans, many of our zoonoses and probably two of our established diseases (plague and typhus) have been acquired from rodents, because of their high abundance and frequent encounters with humans in dwellings. Similarly, about half of our established temperate diseases have been acquired from domestic livestock, because of high local abundance and very frequent contact. Conversely, elephants and bats are not known to have donated directly to us any established diseases and rarely donate zoonoses, because they are heavily penalized on two or three counts: large phylogenetic distance, infrequent encounters with humans, and (in the case of elephants) low abundance. One might object that Nipah, severe acute respiratory syndrome (SARS) and rabies viruses do infect humans from bats, but these apparent exceptions actually support our conclusion. While bats may indeed be the primary reservoir for Nipah and SARS, human infections by these viruses are acquired mainly from intermediate animal hosts that frequently encounter humans (respectively, domestic pigs, and wild animals sold for food). The rare cases of rabies transmission directly to humans from bats arise because rabies changes a bat's behaviour so that it does encounter and bite humans, which a healthy bat (other than a vampire bat) would never do.

Transition from Stage 2 to Stage 3 or 4. Although some Stage 2 and 3 pathogens, such as the anthrax and Marburg agents, are virulent and feared, they claim few victims at present. Yet if they made the transition to Stage 4 or 5, their global impact would be devastating. Why do animal pathogens that have survived the initial jump across species lines into a human host (Stages 1 to 2) usually reach a dead end there, and not evolve past Stages 3 and 4 into major diseases confined to humans (Stage 5)? Barriers between Stages 2 and 3 (consider the rabies virus) include differences between human and animal behaviour affecting transmission (for example, animals often bite humans but humans rarely bite other humans); a pathogen's need to evolve adaptations to the new human host and possibly also to a new vector; and obstacles to a pathogen's spread between human tissues (for example, BSE is restricted to the central nervous system and lymphoid tissue). Barriers between Stages 3 and 4 (consider Ebola virus) include those related to human population size and to transmission efficiency between humans. The emergence of novel pathogens is now being facilitated by modern developments exposing more potential human victims and/or making transmission between humans more efficient than before[24–27]. These developments include blood transfusion (hepatitis C), the commercial bushmeat trade (retroviruses), industrial food production (bovine spongiform encephalitis, BSE), international travel (cholera), intravenous drug use (HIV), vaccine production (simian virus 40, SV40), and susceptible pools of elderly, antibiotic-treated, immunosuppressed patients (see Supplementary Note S2 for details).

exposure over time, but to which previously unexposed Native American populations had no immunity or resistance[1,4–6]. In contrast, no comparably devastating diseases awaited Europeans in the New World, which proved to be a relatively healthy environment for Europeans until yellow fever and malaria of Old World origins arrived[11].

Why was pathogen exchange between Old and New Worlds so unequal? Of the 25 major human diseases analysed, Chagas' disease is the only one that clearly originated in the New World. For two others, syphilis and tuberculosis, the debate is unresolved: it remains uncertain in which hemisphere syphilis originated, and whether tuberculosis originated independently in both hemispheres or was brought to the Americas by Europeans. Nothing is known about the geographic origins of rotavirus, rubella, tetanus and typhus. For all of the other 18 major pathogens, Old World origins are certain or probable.

Our preceding discussion of the animal origins of human pathogens may help explain this asymmetry. More temperate diseases arose in the Old World than New World because far more animals that could furnish ancestral pathogens were domesticated in the Old World. Of the world's 14 major species of domestic mammalian livestock, 13, including the five most abundant species with which we come into closest contact (cow, sheep, goat, pig and horse), originated in the Old World[1]. The sole livestock species domesticated in the New World was the llama, but it is not known to have infected us with any pathogens[1,2]—perhaps because its traditional geographic range was confined to the Andes, it was not milked or ridden or hitched to ploughs, and it was not cuddled or kept indoors (as are some calves, lambs and piglets). Among the reasons why far more tropical diseases (nine versus one) arose in the Old World than the New World are that the genetic distance between humans and New World monkeys is almost double that between humans and Old World monkeys, and is many times that between humans and Old World apes; and that much more evolutionary time was available for transfers from animals to humans in the Old World (about 5 million years) than in the New World (about 14,000 years).

Outlook and future research directions

Many research directions on infectious disease origins merit more effort. We conclude by calling attention to two such directions: clarifying the origins of existing major diseases, and surveillance for early detection of new potentially major diseases.

Origins of established diseases. This review illustrates big gaps in our understanding of the origins of even the established major infectious diseases. Almost all the studies that we have reviewed were based on specimens collected opportunistically from domestic animals and a few easily sampled wild animal species, rather than on systematic surveys for particular classes of agents over the spectrum of domestic and wild animals. A case in point is our ignorance even about smallpox virus, the virus that has had perhaps the greatest impact on human history in the past 4,000 years. Despite some knowledge of poxviruses infecting our domestic mammals, we know little about poxvirus diversity among African rodents, from which those poxviruses of domestic mammals are thought to have evolved. We do not even know whether 'camelpox', the closest known relative of smallpox virus, is truly confined to camels as its name implies or is instead a rodent virus with a broad host range. There could be still-unknown poxviruses more similar to smallpox virus in yet unstudied animal reservoirs, and those unknown poxviruses could be important not only as disease threats but also as reagents for drug and vaccine development.

Equally basic questions arise for other major pathogens. While *falciparum* malaria, an infection imposing one of the heaviest global burdens today, seems to have originated from a bird parasite whose descendants include both the *Plasmodium falciparum* infecting humans and the *P. reichenowii* infecting chimpanzees, malaria researchers still debate whether the bird parasite was introduced to both humans and chimpanzees[12] a few thousand years ago in association with human agriculture, or instead more than five million years ago before the split of humans and chimpanzees from each other[13]. Although resolving this debate will not help us eradicate malaria, it is fascinating in its own right and could contribute to our broader understanding of disease emergence. In the case of rubella, a human crowd disease that must have emerged only in the past 11,000 years and for which some close relative may thus still exist among animals, no even remotely related virus is known; one or more may be lurking undiscovered somewhere. Does the recent identification of porcine rubulavirus and the Mapuera virus in bats as the closest known relatives of mumps virus mean that pigs infected humans, or that human mumps infected pigs, or that bats independently infected both humans and pigs? Is human tuberculosis descended from a ruminant mycobacterium that recently infected humans from domestic animals (a formerly prevalent view), or from an ancient human mycobacterium that has come to infect domestic and wild ruminants (a currently popular view)?

To fill these and other yawning gaps in our understanding of disease origins, we propose an 'origins initiative' aimed at identifying the origins of a dozen of the most important human infectious diseases: for example, AIDS, cholera, dengue fever, *falciparum* malaria, hepatitis B, influenza A, measles, plague, rotavirus, smallpox, tuberculosis and typhoid. Although more is already known about the origins of some of these agents (AIDS, influenza A and measles) than about others (rotavirus, smallpox and tuberculosis), more comprehensive screening is still likely to yield significant new information about even the most studied agents, as illustrated by the recent demonstration that gorillas rather than chimpanzees were probably the donor species for the O-group of human immunodeficiency virus (HIV)-1[14]. The proposed effort would involve systematic sampling and phylogeographic analysis of related pathogens in diverse animal species: not just pigs and other species chosen for their ready availability, but a wider range of wild and domestic species whose direct contact (for example, as bushmeat) or indirect contact (for example, vector-mediated) with humans could plausibly have led to human infections. In addition to the historical and evolutionary significance of knowledge gained through such an origins initiative, it could yield other benefits such as: identifying the closest relatives of human pathogens; a better understanding of how diseases have emerged; new laboratory models for studying public health threats; and perhaps clues that could aid in predictions of future disease threats.

A global early warning system. Most major human infectious diseases have animal origins, and we continue to be bombarded by novel animal pathogens. Yet there is no ongoing systematic global effort to monitor for pathogens emerging from animals to humans. Such an effort could help us to describe the diversity of microbial agents to which our species is exposed; to characterize animal pathogens that might threaten us in the future; and perhaps to detect and control a local human emergence before it has a chance to spread globally.

In our view, monitoring should focus on people with high levels of exposure to wild animals, such as hunters, butchers of wild game, wildlife veterinarians, workers in the wildlife trade, and zoo workers. Such people regularly become infected with animal viruses, and their infections can be monitored over time and traced to other people in contact with them. One of us (N.D.W.) has been working in Cameroon to monitor microbes in people who hunt wild game, in other people in their community, and in their animal prey[15]. The study is now expanding to other continents and to monitor domestic animals (such as dogs) that live in close proximity to humans but are exposed to wild animals through hunting and scavenging. Monitoring of people, animals, and animal die-offs[16] will serve as an early warning system for disease emergence, while also providing a unique archive of pathogens infecting humans and the animals to which we are exposed. Specimens from such highly exposed human populations could be screened specifically for agents known to be present in the animals they hunt (for example, retroviruses among hunters of non-human primates), as well as generically using broad screening tools such as viral microarrays[17] and random amplification polymerase chain reaction (PCR)[18]. Such monitoring efforts also provide potentially invaluable repositories, which would be available for study after future outbreaks in order to reconstruct an outbreak's origin, and as a source of relevant reagents.

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PERSPECTIVE

Radically Rethinking Agriculture for the 21st Century

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Population growth, arable land and fresh water limits, and climate change have profound implications for the ability of agriculture to meet this century's demands for food, feed, fiber, and fuel while reducing the environmental impact of their production. Success depends on the acceptance and use of contemporary molecular techniques, as well as the increasing development of farming systems that use saline water and integrate nutrient flows.

Population experts anticipate the addition of another roughly 3 billion people to the planet's population by the mid-21st century. However, the amount of arable land has not changed appreciably in more than half a century. It is unlikely to increase much in the future because we are losing it to urbanization, salinization, and desertification as fast as or faster than we are adding it (*1*). Water scarcity is already a critical concern in parts of the world (*2*).

Climate change also has important implications for agriculture. The European heat wave of 2003 killed some 30,000 to 50,000 people (*3*). The average temperature that summer was only about 3.5°C above the average for the last century. The 20 to 36% decrease in the yields of grains and fruits that summer drew little attention. But if the climate scientists are right, summers will be that hot on average by mid-century, and by 2090 much of the world will be experiencing summers hotter than the hottest summer now on record.

The yields of our most important food, feed, and fiber crops decline precipitously at temperatures much above 30°C (*4*). Among other reasons, this is because photosynthesis has a temperature optimum in the range of 20° to 25°C for our major temperate crops, and plants develop faster as temperature increases, leaving less time to accumulate the carbohydrates, fats, and proteins that constitute the bulk of fruits and grains (*5*). Widespread adoption of more effective and sustainable agronomic practices can help buffer crops against warmer and drier environments (*6*), but it will be increasingly difficult to maintain, much less increase, yields of our current major crops as temperatures rise and drylands expand (*7*).

Climate change will further affect agriculture as the sea level rises, submerging low-lying cropland, and as glaciers melt, causing river systems to experience shorter and more intense seasonal flows, as well as more flooding (*7*).

Recent reports on food security emphasize the gains that can be made by bringing existing agronomic and food science technology and know-how to people who do not yet have it (*8*, *9*), as well as by exploring the genetic variability in our existing food crops and developing more ecologically sound farming practices (*10*). This requires building local educational, technical, and research capacity, food processing capability, storage capacity, and other aspects of agribusiness, as well as rural transportation and water and communications infrastructure. It also necessitates addressing the many trade, subsidy, intellectual property, and regulatory issues that interfere with trade and inhibit the use of technology.

What people are talking about today, both in the private and public research sectors, is the use and improvement of conventional and molecular breeding, as well as molecular genetic modification (GM), to adapt our existing food crops to increasing temperatures, decreased water availability in some places and flooding in others, rising salinity (*8*, *9*), and changing pathogen and insect threats (*11*). Another important goal of such research is increasing crops' nitrogen uptake and use efficiency, because nitrogenous compounds in fertilizers are major contributors to waterway eutrophication and greenhouse gas emissions.

There is a critical need to get beyond popular biases against the use of agricultural biotechnology and develop forward-looking regulatory frameworks based on scientific evidence. In 2008, the most recent year for which statistics are available, GM crops were grown on almost 300 million acres in 25 countries, of which 15 were developing countries (*12*). The world has consumed GM crops for 13 years without incident. The first few GM crops that have been grown very widely, including insect-resistant and herbicide-tolerant corn, cotton, canola, and soybeans, have increased agricultural productivity and farmers' incomes. They have also had environmental and health benefits, such as decreased use of pesticides and herbicides and increased use of no-till farming (*13*).

Despite the excellent safety and efficacy record of GM crops, regulatory policies remain almost as restrictive as they were when GM crops were first introduced. In the United States, case-by-case review by at least two and sometimes three regulatory agencies (USDA, EPA, and FDA) is still commonly the rule rather than the exception. Perhaps the most detrimental effect of this complex, costly, and time-intensive regulatory apparatus is the virtual exclusion of public-sector researchers from the use of molecular methods to improve crops for farmers. As a result, there are still only a few GM crops, primarily those for which there is a large seed market (*12*), and the benefits of biotechnology have not been realized for the vast majority of food crops.

What is needed is a serious reevaluation of the existing regulatory framework in the light of accumulated evidence and experience. An authoritative assessment of existing data on GM crop safety is timely and should encompass protein safety, gene stability, acute toxicity, composition, nutritional value, allergenicity, gene flow, and effects on nontarget organisms. This would establish a foundation for reducing the complexity of the regulatory process without affecting the integrity of the safety assessment. Such an evolution of the regulatory process in the United States would be a welcome precedent globally.

It is also critically important to develop a public facility within the USDA with the mission of conducting the requisite safety testing of GM crops developed in the public sector. This would make it possible for university and other public-sector researchers to use contemporary molecular knowledge and techniques to improve local crops for farmers.

However, it is not at all a foregone conclusion that our current crops can be pushed to perform as well as they do now at much higher temperatures and with much less water and other agricultural inputs. It will take new approaches, new methods,

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Fig. 1. Saline farming. Upper and lower right, brackish-water agriculture and tomato farming, Negev desert, Israel; center, saline farming of the halophyte salicornia, Eritrea.

new technology—indeed, perhaps even new crops and new agricultural systems.

Aquaculture is part of the answer. A kilogram of fish can be produced in as little as 50 liters of water (*14*), although the total water requirements depend on the feed source. Feed is now commonly derived from wild-caught fish, increasing pressure on marine fisheries. As well, much of the growing aquaculture industry is a source of nutrient pollution of coastal waters, but self-contained and isolated systems are increasingly used to buffer aquaculture from pathogens and minimize its impact on the environment (*15*).

Another part of the answer is in the scale-up of dryland and saline agriculture (Fig. 1) (*16*). Among the research leaders are several centers of the Consultative Group on International Agricultural Research, the International Center for Biosaline Agriculture, and the Jacob Blaustein Institutes for Desert Research of the Ben-Gurion University of the Negev.

Systems that integrate agriculture and aquaculture are rapidly developing in scope and sophistication. A 2001 United Nations Food and Agriculture Organization report (*17*) describes the development of such systems in many Asian countries. Today, such systems increasingly integrate organisms from multiple trophic levels (*18*). An approach particularly well suited for coastal deserts includes inland seawater ponds that support aquaculture, the nutrient efflux from which fertilizes the growth of halophytes, seaweed, salt-tolerant grasses, and mangroves useful for animal feed, human food, and biofuels, and as carbon sinks (*19*). Such integrated systems can eliminate today's flow of agricultural nutrients from land to sea. If done on a sufficient scale, inland seawater systems could also compensate for rising sea levels.

The heart of new agricultural paradigms for a hotter and more populous world must be systems that close the loop of nutrient flows from microorganisms and plants to animals and back, powered and irrigated as much as possible by sunlight and seawater. This has the potential to decrease the land, energy, and freshwater demands of agriculture, while at the same time ameliorating the pollution currently associated with agricultural chemicals and animal waste. The design and large-scale implementation of farms based on nontraditional species in arid places will undoubtedly pose new research, engineering, monitoring, and regulatory challenges, with respect to food safety and ecological impacts as well as control of pests and pathogens. But if we are to resume progress toward eliminating hunger, we must scale up and further build on the innovative approaches already under development, and we must do so immediately.

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THE CHALLENGE OF CHANGE

Fixing the communications failure

People's grasp of scientific debates can improve if communicators build on the fact that cultural values influence what and whom we believe, says **Dan Kahan**.

In a famous 1950s psychology experiment, researchers showed students from two Ivy League colleges a film of an American football game between their schools in which officials made a series of controversial decisions against one side. Asked to make their own assessments, students who attended the offending team's college reported seeing half as many illegal plays as did students from the opposing institution. Group ties, the researchers concluded, had unconsciously motivated students from both colleges to view the tape in a manner that favoured their own school[1].

Since then, a growing body of work has suggested that ordinary citizens react to scientific evidence on societal risks in much the same way. People endorse whichever position reinforces their connection to others with whom they share important commitments. As a result, public debate about science is strikingly polarized. The same groups who disagree on 'cultural issues' — abortion, same-sex marriage and school prayer — also disagree on whether climate change is real and on whether underground disposal of nuclear waste is safe.

The ability of democratic societies to protect the welfare of their citizens depends on finding a way to counteract this culture war over empirical data. Unfortunately, prevailing theories of science communication do not help much. Many experts attribute political controversy over risk issues to the complexity of the underlying science, or the imperfect dissemination of information. If that were the problem, we would expect beliefs about issues such as environmental risk, public health and crime control to be distributed randomly or according to levels of education, not by moral outlook. Various cognitive biases — excessive attention to vivid dangers, for example, or self-reinforcing patterns of social interaction — distort people's perception of risk, but they, too, do not explain why people who subscribe to competing moral outlooks react differently to scientific data.

A process that does account for this distinctive form of polarization is 'cultural cognition'. Cultural cognition refers to the influence of group values — ones relating to equality and authority, individualism and community — on risk perceptions and related beliefs[2,3]. In ongoing research, Donald Braman at George Washington University Law School in Washington DC, Geoffrey Cohen at Stanford University in Palo Alto, California, John Gastil at the University of Washington in Seattle, Paul Slovic at the University of Oregon in Eugene and I study the mental processes behind cultural cognition.

For example, people find it disconcerting to believe that behaviour that they find noble is nevertheless detrimental to society, and behaviour that they find base is beneficial to it. Because accepting such a claim could drive a wedge between them and their peers, they have a strong emotional predisposition to reject it.

Picking sides

Our research suggests that this form of 'protective cognition' is a major cause of political conflict over the credibility of scientific data on climate change and other environmental risks. People with individualistic values, who prize personal initiative, and those with hierarchical values, who respect authority, tend to dismiss evidence of environmental risks, because the widespread acceptance of such evidence would lead to restrictions on commerce and industry, activities they admire. By contrast, people who subscribe to more egalitarian and communitarian values are suspicious of commerce and industry, which they see as sources of unjust disparity. They are thus more inclined to believe that such activities pose unacceptable risks and should be restricted. Such differences, we have found, explain disagreements in environmental-risk perceptions more completely than differences in gender, race, income, education level, political ideology, personality type or any other individual characteristic[4].

Citizens experience scientific debates as contests between warring cultural factions.

P. DEJONG/AP

Cultural cognition also causes people to interpret new evidence in a biased way that reinforces their predispositions. As a result, groups with opposing values often become more polarized, not less, when exposed to scientifically sound information.

In one study, we examined how this process can influence people's perceptions of the risks of nanotechnology. We found that relative to counterparts in a control group, people who were supplied with neutral, balanced information immediately splintered into highly polarized factions consistent with their cultural predispositions towards more familiar environmental risks, such as nuclear power and genetically modified foods[5].

Of course, because most people aren't in a position to evaluate technical data for themselves, they tend to follow the lead of credible experts. But cultural cognition operates here too: the experts whom laypersons see as credible, we have found, are ones whom they perceive to share their values. This was the conclusion of a study we carried out of Americans' attitudes towards human-papillomavirus (HPV) vaccination for schoolgirls. This common, sexually transmitted virus is the leading cause of cervical cancer. The US government's Centers for Disease Control and Prevention (CDC) recommended in 2006 that the vaccine be routinely administered to girls aged 11 or 12 — before they are likely to become exposed to the virus. That proposal has languished amid intense political controversy, with critics claiming that the vaccine causes harmful side effects and will increase unsafe sex among teens.

To test how expert opinion affects this debate, we constructed arguments for and against mandatory vaccination and matched them with fictional male experts, whose appearance (besuited and grey-haired, for example, or denim-shirted and bearded) and publication titles were designed to make them look as if they had distinct cultural perspectives. When the expert who was perceived as hierarchical and individualistic criticized the CDC recommendation, people who shared those values and who were already predisposed to see the vaccine

J. AMIS/AP

Political controversy stalled a plan to vaccinate US girls against a virus that causes cervical cancer.

as risky became even more intensely opposed to it. Likewise, when the expert perceived as egalitarian and communitarian defended the vaccine as safe, people with egalitarian values became even more supportive of it. Yet when we inverted the expert-argument pairings, attributing support for mandatory vaccination to the hierarchical expert and opposition to the egalitarian one, people shifted their positions and polarization disappeared[6].

Rooting for the same team

Taken together, these dynamics help to explain the peculiar cultural polarization on scientific issues in the United States and beyond. Like fans at a sporting contest, people deal with evidence selectively to promote their emotional interest in their group. On issues ranging from climate change to gun control, from synthetic biology to counter-terrorism, they take their cue about what they should feel, and hence believe, from the cheers and boos of the home crowd.

But unlike sports fans watching a game, citizens who hold opposing cultural outlooks are in fact rooting for the same outcome: the health, safety and economic well-being of their society. Are there remedies for the tendency of cultural cognition to interfere with their ability to reach agreement on what science tells them about how to attain that goal?

Research on how to control cultural cognition is less advanced than research on the mechanisms behind it. Nevertheless, two techniques of science communication may help.

One method, examined in depth by Geoffrey Cohen, is to present information in a manner that affirms rather than threatens people's values[7]. As my colleagues and I have shown, people tend to resist scientific evidence that could lead to restrictions on activities valued by their group. If, on the other hand, they are presented with information in a way that upholds their commitments, they react more open-mindedly[8].

For instance, people with individualistic values resist scientific evidence that climate change is a serious threat because they have come to assume that industry-constraining carbon-emission limits are the main solution. They would probably look at the evidence more favourably, however, if made aware that the possible responses to climate change include nuclear power and geoengineering, enterprises that to them symbolize human resourcefulness. Similarly, people with an egalitarian outlooks are less likely to reflexively dismiss evidence of the safety of nanotechnology if they are made aware of the part that nanotechnology might play in environmental protection, and not just its usefulness in the manufacture of consumer goods.

"People endorse whichever position reinforces their connection to others with whom they share important commitments."

The second technique for mitigating public conflict over scientific evidence is to make sure that sound information is vouched for by a diverse set of experts. In our HPV-vaccine experiment, polarization was also substantially reduced when people encountered advocates with diverse values on both sides of the issue. People feel that it is safe to consider evidence with an open mind when they know that a knowledgeable member of their cultural community accepts it. Thus, giving a platform to a spokesperson likely to be recognized as a typical traditional parent with a hierarchical world view might help to dispel any association between mandatory HPV vaccination and the condoning of permissive sexual practices.

It would not be a gross simplification to say that science needs better marketing. Unlike commercial advertising, however, the goal of these techniques is not to induce public acceptance of any particular conclusion, but rather to create an environment for the public's open-minded, unbiased consideration of the best available scientific information.

As straightforward as these recommendations might seem, however, science communicators routinely flout them. The prevailing approach is still simply to flood the public with as much sound data as possible on the assumption that the truth is bound, eventually, to drown out its competitors. If, however, the truth carries implications that threaten people's cultural values, then holding their heads underwater is likely to harden their resistance and increase their willingness to support alternative arguments, no matter how lacking in evidence. This reaction is substantially reinforced when, as often happens, the message is put across by public communicators who are unmistakably associated with particular cultural outlooks or styles — the more so if such advocates indulge in partisan rhetoric, ridiculing opponents as corrupt or devoid of reason. This approach encourages citizens to experience scientific debates as contests between warring cultural factions — and to pick sides accordingly.

We need to learn more about how to present information in forms that are agreeable to culturally diverse groups, and how to structure debate so that it avoids cultural polarization. If we want democratic policy-making to be backed by the best available science, we need a theory of risk communication that takes full account of the effects of culture on our decision-making. ■

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Science and Opinion

U.S.

A Lonely Quest for Facts on Genetically Modified Crops

By **AMY HARMON** JAN. 4, 2014

Greggor Ilagan initially thought a ban on genetically modified organisms was a good idea.
Jim Wilson/The New York Times

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KONA, Hawaii — From the moment the bill to ban genetically engineered crops on the island of Hawaii was introduced in May 2013, it garnered more vocal support than any the County Council here had ever considered, even the perennially popular bids to decriminalize marijuana.

Public hearings were dominated by recitations of the ills often attributed to genetically modified organisms, or G.M.O.s: cancer in rats, a rise in childhood allergies, out-of-control superweeds, genetic contamination, overuse of pesticides, the disappearance of butterflies and bees.

Like some others on the nine-member Council, Greggor Ilagan was not even sure at the outset of the debate exactly what genetically modified organisms were: living things whose DNA has been altered, often with the addition of a gene from a distant species, to produce a desired trait. But he could see why almost all of his colleagues had been persuaded of the virtue of turning the island into what the bill's proponents called a "G.M.O.-free oasis."

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Papaya genetically modified to resist a virus became one part of a controversy.
Jim Wilson/The New York Times

“You just type ‘G.M.O.’ and everything you see is negative,” he told his staff. Opposing the ban also seemed likely to ruin anyone’s re-election prospects.

Yet doubts nagged at the councilman, who was serving his first two-year term. The island’s papaya farmers said that an engineered variety had saved their fruit from a devastating disease. A study reporting that a diet of G.M.O. corn caused tumors in rats, mentioned often by the ban’s supporters, turned out to have been thoroughly debunked.

And University of Hawaii biologists urged the Council to consider the global scientific consensus, which holds that existing genetically engineered crops are no riskier than others, and have provided some tangible benefits.

“Are we going to just ignore them?” Mr. Ilagan wondered.

Urged on by Margaret Wille, the ban’s sponsor, who spoke passionately of the need to “act before it’s too late,” the Council declined to form a task force to look into such questions before its November vote. But Mr. Ilagan, 27, sought answers on his own. In the process, he found himself, like so many public and business leaders worldwide, wrestling with a subject in which popular beliefs often do not reflect scientific evidence.

At stake is how to grow healthful food most efficiently, at a time when a warming world and a growing population make that goal all the more urgent.

Scientists, who have come to rely on liberals in political battles over stem-cell research, climate change and the teaching of evolution, have been dismayed to find themselves at odds with their traditional allies on this issue. Some compare the hostility to G.M.O.s to the rejection of climate-change science, except with liberal opponents instead of conservative ones.

“These are my people, they’re lefties, I’m with them on almost everything,” said Michael Shintaku, a plant pathologist at the University of Hawaii at Hilo, who testified several times against the bill. “It hurts.”

But, supporters of the ban warned, scientists had not always correctly assessed the health and environmental risks of new technology. “Remember DDT?” one proponent demanded.

Ms. Wille’s bill would ban the cultivation of any genetically engineered crop on the island, with the exception of the two already grown there: corn recently planted by an island dairy to feed its cows, and papaya. Field tests to study new G.M.O. crops would also be prohibited. Penalties would be $1,000 per day.

Like three-quarters of the voters on Hawaii Island, known as the Big Island, Mr. Ilagan supported President Obama in the 2012 election. When he took office himself a month later, after six years in the Air National Guard, he planned to focus on squatters, crime prevention and the inauguration of a bus line in his district on the island’s eastern rim.

He had also promised himself that he would take a stance on all topics, never registering a “kanalua” vote — the Hawaiian term for “with reservation.”

But with the G.M.O. bill, he often despaired of assembling the information he needed to definitively decide. Every time he answered one question, it seemed, new ones arose. Popular opinion masqueraded convincingly as science, and the science itself was hard to grasp. People who spoke as experts lacked credentials, and G.M.O. critics discounted those with credentials as being pawns of biotechnology companies.

“It takes so much time to find out what’s true,” he complained.

So many emails arrived in support of the ban that, as a matter of environmental responsibility, the Council clerks suspended the custom of printing them out for each Council member. But Mr. Ilagan had only to consult his inbox to be reminded of the prevailing opinion.

“Do the right thing,” one Chicago woman wrote, “or no one will want to take a toxic tour of your poisoned paradise.”

Distrust on the Left

Margaret Wille, 66, had the island's best interests at heart when she proposed the ban, Mr. Ilagan knew.

She majored in cultural anthropology at Bennington College in Vermont and practiced public advocacy law in Maine before moving a decade ago to the island, where her brothers once owned a health food store.

And her bill, like much anti-G.M.O. action, was inspired by distrust of the seed-producing biotechnology companies, which had backed a state measure to prevent local governments from regulating their activity.

That bill, which passed the State Senate but stalled in the House, appeared largely aimed at other Hawaiian islands, which were used by companies like Monsanto, Syngenta and Dow as a nursery for seeds. On Kauai, for instance, activists had been talking about how to limit the companies' pesticide use.

The companies had no corporate presence here on the Big Island, which lacks the large parcels of land they preferred. Still, Ms. Wille said at a "March Against Monsanto" rally last spring, if the island allowed farmers to grow genetically modified crops, the companies could gain a foothold. "This represents nothing less than a takeover of our island," she told the crowd. "There's a saying, 'If you control the seed, you control the food; if you control the food, you control the people.' "

Ms. Wille, chairwoman of the Council's Agriculture Committee, warned her colleagues that what mattered was not the amount of food produced, but its quality and the sustainability of how it was grown.

"My focus is on protecting our soil and the farms and properties that are not G.M.O.," she said, noting also that there was a marketing opportunity for non-G.M.O. products.

Margaret Wille, the sponsor of the ban on G.M.O.'s, spoke of the need to "act before it's too late."
Jim Wilson/The New York Times

Such sentiments echoed well beyond Hawaii, as Mr. Ilagan's early research confirmed.

College students, eco-conscious shoppers and talk show celebrities like Oprah Winfrey, Dr. Oz and Bill Maher warned against consuming food made with genetically modified ingredients. Mr. Maher's audience, in turn, recently hissed at a commentator who defended genetic modification as merely an extension of traditional breeding.

New applications of the technology, so far used mostly on corn, soybeans, cotton, canola and sugar beets to make them more resistant to weeds and pests, have drawn increased scrutiny. A recent Organic Consumers Association bulletin, for instance, pictures the first genetically modified animal to be submitted for regulatory approval (a faster-growing salmon) jumping from a river to attack a bear, with the caption "No Frankenfish!" In a 2013 New York Times poll, three-quarters of Americans surveyed expressed concern about G.M.O.s in their food, with most of those worried about health risks.

As Ms. Wille's bill was debated here throughout 2013, activists elsewhere collected 354,000 signatures for a petition asserting that G.M.O.s endanger public health. In the Philippines, protesters, citing safety concerns, ripped up a test field of rice genetically engineered to address Vitamin A deficiency among the world's poor. A new children's book turned its heroine into a crusader against genetic modification: "These fruits and vegetables are not natural," she declares.

And bills were proposed in some 20 states to require "G.M.O." labels on foods with ingredients made from genetically engineered crops (about three-quarters of processed foods now have such ingredients, mostly corn syrup, corn oil and soy meal and sugar).

The legislation is backed by the fast-growing organic food industry, which sees such labeling as giving it a competitive advantage. It has also become a rallying cry among activists who want to change the industrial food system. Rachel Maddow declared the narrow failure of ballot initiatives to require G.M.O. labeling in California and Washington a "big loss for liberal politics."

Whole Foods has pledged that by 2018 it will replace some foods containing genetically modified ingredients and label others; signs in Trader Joe's proclaim, "No G.M.O.s Sold Here." General Mills announced last week that it would stop using genetically modified ingredients in its Cheerios.

But the groundswell against genetically modified food has rankled many scientists, who argue that opponents of G.M.O.s have distorted the risks associated with them and underplayed the risks of failing to try to use the technology to improve how food is grown. Wading into a debate that has more typically pitted activists against industry, some have argued that opposition from even small pockets of an American elite influences investment in research and the deployment of genetically modified crops, particularly in the developing world, where hunger raises the stakes.

“Just as many on the political right discount the broad scientific consensus that human activities contribute to global warming, many progressive advocacy groups disregard, reject or ignore the decades of scientific studies demonstrating the safety and wide-reaching benefits” of genetically engineered crops, Pamela Ronald, a professor of plant pathology at the University of California, Davis, wrote on the blog of the nonprofit Biology Fortified.

And other scientists, including two Nobel Prize winners, wrote an opinion article for the journal Science last fall titled “Standing Up for G.M.O.s.”

As he traversed the island and the Internet, Mr. Ilagan agreed with constituents that there was good reason to suspect that companies like Monsanto would place profit above public safety. He, too, wished for more healthful food to be grown more sustainably.

But even a national ban on such crops, it seemed to him, would do little to solve the problems of an industrial food system that existed long before their invention. Nor was it likely to diminish the market power of the “Big Ag” companies, which also dominate sales of seeds that are not genetically modified, and the pesticides used on both. The arguments for rejecting them, he concluded, ultimately relied on the premise that they are unsafe.

Making up his mind about that alone would prove difficult enough.

The Rainbow Papaya

The papaya farmers appeared, pacing restlessly, outside Mr. Ilagan’s office shortly after Ms. Wille introduced the proposal for a G.M.O. ban in May.

There were only around 200 of them on an island with a population of about 185,000, but many lived in his district. They wanted to be sure he understood that genetically modified papayas, the only commercially grown G.M.O. fruit in the United States, account for three-quarters of the 30 million pounds harvested annually here.

“They’re treating us like we’re criminals,” said Ross Sibucao, the head of the growers’ association.

Another Council member favored razing every genetically modified papaya tree on the island.

But under Ms. Wille’s bill, the modified papaya, known as the Rainbow, was grandfathered in, as long as farmers registered with the county and paid a $100 annual fee.

“You’re exempted,” Mr. Ilagan reassured Mr. Sibucao.

Even so, Mr. Sibucao replied, the bill would stigmatize any genetically modified food, making the Rainbow harder to sell.

Many of the island's papaya farmers, descendants of immigrants who came to work on sugar plantations, have links to the Philippines, as does Mr. Ilagan, who immigrated from there as a child. As the plantations faded in the 1980s, some began growing papayas. But after an outbreak of Papaya ringspot virus in the mid-'90s, only the Rainbow, endowed with a gene from the virus itself that effectively gave it immunity, had saved the crop, they told him.

If Mr. Ilagan worried about big biotechnology companies, the farmers told him, the Rainbow should reassure him. Developed primarily by scientists at academic institutions, it was a model for how the technology could benefit small farmers. Its lead developer, the Hawaiian-born Dennis Gonsalves, was, along with others on the team, awarded the 2002 Humboldt Prize for the most significant contribution to United States agriculture in five years.

Japanese as well as American regulators had approved the papaya. And because the virus was spread by insects, which growers had sought to control with pesticide sprays, the Rainbow had reduced the use of chemicals.

The idea of the ban was popular, but not universally so, as pro-G.M.O. T-shirts made clear.
Jim Wilson/The New York Times

Mr. Ilagan took their point. "If we as a body pass this," he said, thinking aloud at the second public hearing in July, "it shows we think all G.M.O.s are wrong."

Superweeds and Rats

Instructed by the chairman not to applaud, the residents who packed the County Council chamber in Kona on July 3 erupted in frequent silent cheers, signaled by a collective waving of hands and wiggling of fingers.

A few, like Richard Ha, an island farmer who hoped that the diseases afflicting his bananas and tomatoes might be solved with a genetic modification, were there to testify against the ban. Ranchers also were opposed; they wanted the option to grow the genetically modified corn and soybeans for cattle feed that are common elsewhere.

But a vast majority were there in support. Some were members of G.M.O. Free Hawaii Island, a mix of food activists and entrepreneurs, who argued that the organisms were bad for human health, the island's ecosystem and eco-conscious business. Others, veterans of the campaign for a partial ban already in place here, reminded the Council of the precedents for Ms. Wille's bill: In 2008, organic Kona coffee farmers successfully lobbied for a ban on any cultivation of genetically modified coffee. The presence of a G.M.O. crop, they argued, would hurt their reputation and their ability to charge a premium.

At the same time, the county had banned the cultivation of genetically engineered taro, a root vegetable cultivated for centuries in Hawaii.

In the three minutes allotted to each speaker at the July hearing, some told personal tales of all manner of illness, including children's allergies, cured after going on a "non-G.M.O." diet. One woman took the microphone "on behalf of Mother Earth and all sentient beings." Nomi Carmona encouraged Council members to visit the website of her group, Babes Against Biotech, where analyses of Monsanto's campaign contributions are intermingled with pictures of bikini-clad women.

Many of the most impassioned speakers came from Mr. Ilagan's district of Puna, known for its anti-establishment spirit. "These chemical companies think they're going to win," one woman said. "Hell, no, they're never going to win here."

Organic farmers worried that their crops would be contaminated also made an impression on the councilman, though he felt that the actress Roseanne Barr, who owns an organic macadamia nut farm here, could have been kinder to the papaya farmers in the room.

"Everybody here is very giving," she had told them. "They will bend over backwards to help you burn those papayas and grow something decent."

More striking to Mr. Ilagan was the warning of Derek Brewer, 29, an Army veteran who served in Iraq and Afghanistan before coming to Hawaii to help found an eco-hostel. "We don't fully understand genetics," Mr. Brewer said, his dark hair tied back in a ponytail. "Once you change something like this, there is no taking it back."

What really stuck with Mr. Ilagan were the descriptions of tumorous rats. Reading testimony submitted before the hearing, he had blanched at grotesque pictures of the animals fed Monsanto's corn, modified with a gene from bacteria to tolerate an herbicide. According to the French researcher who performed the study, they developed more tumors and died earlier than those in the control group.

"Are we all going to get cancer?" Mr. Ilagan wondered.

Sifting Through Claims

The next week, when his legislative assistant alerted him that the rat study encountered near-universal scorn from scientists after its release in autumn 2012, doubt about much of what Mr. Ilagan had heard began to prick at his mind.

"Come to find out, the kind of rats they used would get tumors anyway," he told his staff. "And the sample size was too small for any conclusive results."

Sensitive to the accusation that her bill was antiscience, Ms. Wille had circulated material to support it. But in almost every case, Mr. Ilagan and his staff found evidence that seemed to undermine the claims.

A report, in an obscure Russian journal, about hamsters that lost the ability to reproduce after three generations as a result of a diet of genetically modified soybeans had been contradicted by many other studies and deemed bogus by mainstream scientists.

Mr. Ilagan discounted the correlations between the rise in childhood allergies and the consumption of G.M.O.s, cited by Ms. Wille and others, after reading of the common mistake of confusing correlation for causation. (One graph, illustrating the weakness of conclusions based on correlation, charted the lock-step rise in organic food sales and autism diagnoses.)

Butterflies were disappearing, but Mr. Ilagan learned that it was not a toxin produced by modified plants that harmed them, as he had thought. Instead, the herbicide used in conjunction with some genetically modified crops (as well as some that were not) meant the milkweed on which they hatched was no longer found on most Midwestern farms.

He heard many times that there were no independent studies of the safety of genetically modified organisms. But Biofortified, which received no funding from industry, listed more than a hundred such studies, including a 2010 comprehensive review sponsored by the European Union, that found "no scientific evidence associating G.M.O.s with higher risks for the environment or for food and feed safety than conventional plants and organisms." It echoed similar statements by the World Health Organization, the National Academy of Sciences, the Royal Society of Medicine and the American Association for the Advancement of Science.

A blog post on the website of NPR, a news source Mr. Ilagan trusted, cataloged what it called "Top Five Myths of Genetically Modified Seeds, Busted." No. 1 was a thing he had long believed: "Seeds from G.M.O.s are sterile."

One of the more alarming effects of G.M.O.s that Ms. Wille had cited was suicides among farmers in India, purportedly driven into debt by the high cost of patented, genetically modified cotton seeds.

Biotechnology companies, she said, "come in and give it away cheap, and then raise prices."

Mr. Ilagan with Alberto Belmes, one of the growers of genetically modified papayas whose views helped change Mr. Ilagan's mind. Jim Wilson/The New York Times

Monsanto's cotton, engineered with a gene from bacteria to ward off certain insects, had "pushed 270,000 farmers to suicide" since the company started selling it in India in 2002, the activist Vandana Shiva said in a Honolulu speech Ms. Wille attended.

But in Nature, a leading academic journal, Mr. Ilagan found an article with the subhead "GM Cotton Has Driven Farmers to Suicide: False."

According to the Nature article, peer-reviewed research in 2011 found that suicides among farmers were no more numerous after the new seeds were introduced than before. And a 2012 study found that farmers' profits rose because of reduced losses from pest attacks.

"There's farmers committing suicide because of the whole debt issue, but it's not because of the G.M.O. issue," Mr. Ilagan said he concluded in mid-August.

Still, it was hard not to be spooked by material emailed by constituents and circulated on Facebook: images of tomatoes with syringes stuck in them and of pears and apples stapled together, warnings of children harmed by parents serving genetically modified food. The specter of genetic contamination still haunted him. And his mother, who had always served papaya at home, had stopped because of her new concerns about the Rainbow variety.

Learning From a Researcher

The scientists at the national agriculture research center here were not accustomed to local Council representatives dropping by unannounced.

But one day in August, Mr. Ilagan recalled, when he turned up in search of someone who could answer questions about genetic contamination, he found a molecular biologist willing to help.

"It's kind of a loaded term," the councilman remembered the scientist, Jon Suzuki, saying. "What they're talking about is cross-pollination, which is something that happens all the time within species."

The councilman knew little about how food was grown. He enlisted in the Air National Guard immediately after high school and abandoned his first semester of community college classes when he decided to run for the Council seat.

Dr. Suzuki gave him a tutorial on plant reproduction, Mr. Ilagan recalled, explaining that with the wind, insects and animals spreading pollen and seeds, cross-pollination can never be entirely avoided.

But, Mr. Ilagan learned, by staggering planting times and ensuring a reasonable distance between crops, it is usually possible to avoid large-scale mingling. Also, plants have different fertilization methods: The Rainbow papaya, for instance, was largely self-fertilizing. If it is planted about 12 feet away from other varieties, the chance of cross-pollination is exceedingly low.

"But what about the papaya contaminating" — Mr. Ilagan recalls correcting himself — "cross-pollinating with a pineapple?"

This was the part he had trouble explaining to himself. Was the virus gene from the papaya also in Ms. Barr's macadamia nuts and the organic coffee farmer's beans?

Dr. Suzuki paused.

"With plants of different species — it's kind of like how you don't cross a cat with a dog and expect to have offspring," he said.

"Duh!" exclaimed Mr. Ilagan. "I should have realized that."

In the following weeks, Mr. Ilagan sometimes called Dr. Suzuki with his question du jour. For instance, do weeds near genetically modified crops turn into "superweeds" because of a rogue gene?

The scientist, he recalled, helped him understand that "superweeds" were weeds that had evolved resistance to a widely used herbicide — most likely faster than they would have if farmers had not used it so much on crops genetically engineered to tolerate it.

Biotechnology firms were already selling seeds that tolerated other, less benign herbicides, Mr. Ilagan learned. But that was a different problem from the specter conjured by a woman at one of the hearings, who said that "G.M.O.s are cross-pollinating with weeds that now can't be controlled."

Asked about the danger of moving genes among species where they had not originated, Dr. Suzuki explained that for millenniums, humans had bred crops of the same species to produce desired traits. But with the advent of genetic engineering, it became possible to borrow a feature from elsewhere on the tree of life. An example Mr. Ilagan later learned about was the rice being tested in the Philippines. Modified with genes from bacteria and corn, it can provide Vitamin A, the deficiency of which is a scourge of the world's poor.

That did not mean genetically engineered food could never cause harm. But the risks of such crops could be reliably tested, and they had so far proved safe. "With scientists, we never say anything is 100 percent certain one way or another," Dr. Suzuki said. "We weigh conclusions on accumulated knowledge or evidence — but often this is not satisfactory for some."

Silencing the Scientists

On Oct. 1, Mr. Ilagan voted to block the bill from moving out of committee, shortly after a day of what Ms. Wille and Brenda Ford, another Council member who was a proponent of the ban, had described as expert testimony.

The Rainbow papaya is genetically modified to resist a virus that devastated other papaya varieties on Hawaii.
Jim Wilson/The New York Times

At the hearing on Sept. 23, he had grown increasingly uneasy as his fellow Council members declined to call several University of Hawaii scientists who had flown from Oahu, instead allotting 45 minutes to Jeffrey Smith, a self-styled expert on G.M.O.s with no scientific credentials.

One University of Hawaii at Manoa biologist, Richard Manshardt, responded to a question from Ms. Ford about the effect on honeybees of corn engineered to resist pests: none, he said, because the protein it produced affected only certain insect groups, and was not toxic to bees.

"I don't agree with the professor," Ms. Ford told her colleagues.

Many University of Hawaii scientists had already registered their opposition to the bill, in written and oral testimony and letters in the local papers.

If the ban passed, local farmers could not take advantage of projects underway at the university and elsewhere, they noted, including drought-tolerant crops and higher-yield pineapple plants. Genetic engineering is a precise technique that "itself is not harmful," the dean of the school's College of Tropical Agriculture and Human Resources, Maria Gallo, wrote in one op-ed.

But Ms. Wille had largely dismissed the opinions of university researchers, citing Monsanto contributions to the university. In 2012, she noted, the company made a one-time donation of $600,000 for student scholarships at the College of Tropical Agriculture and Human Resources, an amount that the college said represented about 1 percent of its annual budget that year.

"It is sad that our state has allowed our university departments of agriculture to become largely dependent upon funding grants from the multinational chemical corporations," Ms. Wille told reporters, suggesting that the university's professors were largely a "mouthpiece for the G.M.O. biotech industry." She did, however, rely on the opinion of a specialist in organic agriculture practices at the university, Hector Valenzuela, who supported the bill.

Mr. Smith, known for "Genetic Roulette," a movie he produced based on his book of the same title that had been shown at one of the island's "March Against Monsanto" events, appeared at the hearing by Skype from Arizona.

He praised the Council for stepping in where he believes that federal regulatory agencies have failed, and suggested that the Rainbow papaya could harm people because of a protein produced by the viral gene added to it, adding that no human or animal feeding studies had ever been conducted on the fruit.

Mr. Ilagan was genuinely curious to hear the author's take on his own latest realization: Each genetically modified organism was different, and came with its own set of trade-offs.

“I don’t see a blanket ban,” he told his staff that week. “It seems like it should be a case-by-case thing.”

“Aloha, Mr. Smith,” Mr. Ilagan said when he had his turn. “Or is it Dr. Smith?”

“No, Jeffrey’s fine,” Mr. Smith said over Skype.

“In your world,” Mr. Ilagan asked, “is there any room for any G.M.O.?”

Mr. Smith replied that there was not.

In the afternoon, Dr. Gonsalves, who led the development of the Rainbow papaya, was given time to respond to Mr. Smith’s allegations. He laid to rest a lingering question about papaya safety that had troubled Mr. Ilagan.

He explained that any papaya infected by the ringspot virus contains the protein Mr. Smith had mentioned as potentially dangerous in the genetically modified Rainbow. Moreover, plant viruses do not infect people. “Everyone was eating virus-infected papaya in the 1990s,” Dr. Gonsalves said. “And now you want to do feeding studies?”

With one member absent, only one other Council member joined Mr. Ilagan in opposing the bill. The Council deferred a decision on creating a task force to discuss the implications of banning genetically modified organisms.

Ms. Wille assured her colleagues that, upon the bill’s passage, she would support the formation of such a group. But it was better not to delay, she said: “I want to draw a line in the sand until we can take a closer look.”

Angry Voters

The response to Mr. Ilagan’s vote was swift and unambiguous.

He was mocked on Facebook and pilloried in letters from constituents. “You have been influenced by the contrived arguments from the pro-G.M.O. interests,” one letter read. “Many of my fellow Puna residents will seriously consider more progressive candidates for the next Council term.”

“Greggor, what do you think you’re doing?” his campaign manager, Kareen Haskin, 70, a close family friend, asked him. “The main thing I told people was you would listen to them.”

He told her that though a vocal minority supported the ban, many other constituents knew little about the complex issue. “I have to do what’s right for them, too.”

Farmers outside the County Council chamber listened to a discussion about the ban.
Jim Wilson/The New York Times

He told Ms. Haskin what he had learned about health and environmental aspects of genetic engineering. But as he had found often happened in conversations about G.M.O.s, the subject quickly shifted. “We don’t want corporations to own all the seeds,” she said.

Mr. Ilagan was as opposed as Ms. Haskin was to big businesses controlling a market, in part by using patents that prohibit farmers from replanting or selling their seeds. But banning crops because they were made with genetic engineering would not change the patent laws, he told her.

Mr. Ilagan had been alarmed by testimony from farmers who said they could be sued by Monsanto and other patent-holders when patented seeds ended up in their fields by accident. But he found there was no evidence that Monsanto had ever initiated such a lawsuit.

“I’m still trying to voice this out,” he said, “but to me it just seems symbolic. Like doing something that seems good, but not really achieving what you want to achieve.”

Ms. Haskin took his hand. “You have to vote for this bill,” she pleaded. “What about all the pesticides being sprayed on our food?”

The conversation, he noticed, had turned again.

Emotional Testimony

The Council meeting on Oct. 15 started with public testimony that lasted more than seven hours.

Again, Mr. Ilagan found himself touched by the emotion of the crowd. A mother brought her 8-year-old to testify. Mr. Brewer, the eco-hostel owner, was in the audience with his wife, who is deaf, signing so she could follow the debate. Invoking the Hawaiian word for "land," several speakers — not necessarily of Hawaiian descent — begged for "our aina" to be preserved. "Our island can be the uncontaminated seedbed for the world," one said.

Those in favor of the bill outnumbered those opposed by more than five to one.

Lukas Kambic, a biology major at the University of Hawaii at Hilo, sought to use his own experience to counter the anecdotes others voiced that night. "My mom ate organic food exclusively and did yoga all the time, and she died of a brain aneurysm," Mr. Kambic said. "According to the logic of people here, she was killed by organic food and yoga."

The room was silent.

Knowing that the final vote on the ban was yet to come, Mr. Ilagan voted "no" after the hearing. Then nearly 1,000 people quickly signed a petition demanding that he change his vote at the final hearing, scheduled for Nov. 18. For the first time in his career as councilman, he began to consider voting "kanalua" — yes, with reservation.

In early November, he sought to escape with a friend to a condo in Kona, only to be accosted at the pool by a voter demanding answers.

And on Nov. 14, Mr. Brewer, the veteran who runs an eco-hostel, visited him in his office. They discussed Mr. Brewer's conviction that cross-pollination by G.M.O.s would do unknown harm to the environment and detract from the island's image.

"We need all the votes we can get to override" a possible veto by the mayor, Mr. Brewer said. "Do you think you can vote for this bill, Greggor?"

Mr. Ilagan still had questions of his own. One scientist he had spoken to said the built-in pesticide in corn should not worry him, because many plants contain their own natural pesticides. "I still want to track that down," he told his staff. "What is an example of a natural pesticide?"

Maybe, he thought, he would join the long-promised task force, which would weigh the implications of banning G.M.O.s on the island and report back to the Council.

The final hearing on the bill was not unlike the first. Superweeds were mentioned. Indian suicides. Contamination.

Ms. Wille urged a vote for the ban. “To do otherwise,” she said, “would be to ignore the cries from round the world and on the mainland.”

“Mr. Ilagan?” the Council member leading the meeting asked when it came time for the final vote.

“No,” he replied.

The ban was approved, 6 to 3.

The mayor signed the bill on Dec. 5.

At the Council meeting on Dec. 17, Ms. Wille’s motion to create a committee to study the impact of banning genetically modified organisms on the island was not seconded, and she withdrew it. Stunned, Mr. Ilagan briefly considered making his own motion to form a task force. But he could see he would not have enough support.

It was time to move on. A fast-growing subdivision in his district needed a community park. Last week, Mr. Ilagan turned his focus to drumming up support for the bond issue he would need from the county to plan and design it.

A version of this article appears in print on January 5, 2014, on page A1 of the New York edition with the headline: On Hawaii, a Lonely Quest for Fact.

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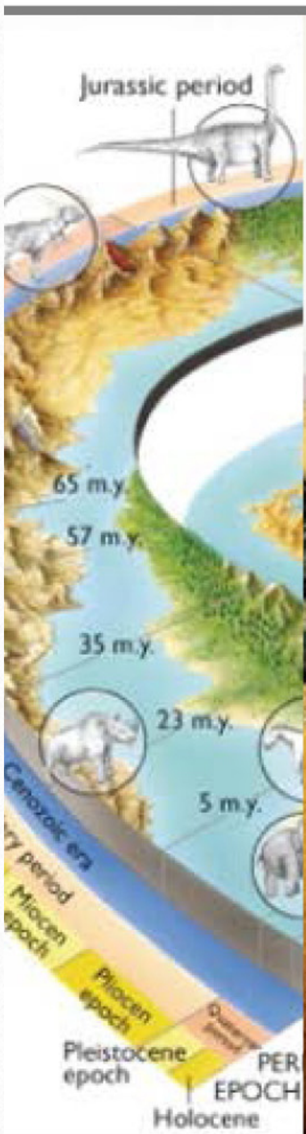
Jurassic period
65 m.y.
57 m.y.
35 m.y.
23 m.y.
5 m.y.
Cenozoic era
Miocen
epoch
Pliocen
epoch
Pleistocene
epoch
EPOCH
Holocene