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The Agro-Industrial Complex

POTATO WARS

When potato plants bloom, they send up five-lobed flowers that bob in fields like fat purple stars. According to tradition, Marie Antoinette liked the blossoms so much that she put them in her hair. Her husband, Louis XVI, supposedly put one in his buttonhole, inspiring a brief vogue in which the French aristocracy swanned around with potato plants on their clothes. Potatoes belong to the nightshade family, which means they are cousins to tomatoes, eggplant, tobacco, sweet peppers, and deadly nightshade. The tubers are not roots but modified stems that store nutrients underground; the eyes, from which new potatoes sprout, are descended from the leaves that grew on the stem. Potato fruits look like green cherry tomatoes but are full of solanine, a poison that is part of the plant's defense system—it prevents pests from eating the seeds. As a rule modern farmers ignore the seed, instead cutting up tubers and planting the pieces. In a testament to linguistic confusion, tubers used for this purpose are called "seed potatoes."

Today the potato is the fifth most important crop worldwide, surpassed in harvest volume only by sugarcane, wheat, maize, and rice. Originally it came from the Andes—not only *Solanum* *tuberosum,* the potato found in supermarkets, but many other types of potato that are eaten only in Ecuador, Peru, and Bolivia. There are also scores of wild potato species that can be found everywhere from Argentina to the southwestern United States. Despite similarities of name and appearance, not one of these potatoes is related to the sweet potato, which belongs to a different botanical family. The two have long been confused; the word "potato" is derived erroneously from *batata,* the Taino name for sweet potato (and the source of its scientific name, *Ipomoea batatas*). The mix-up rankled the early English botanist John Gerard, who complained in 1597 that "those [who] vulgarly impose names upon plants have little either judgement or knowledge of them." Intending to clear up the matter definitively in his "generall historie of plantes," Gerard used the term "Virginia potato" for the ordinary potato, which is not from Virginia. He called sweet potatoes "common potatoes."*

Potatoes are about three-quarters water and one-quarter starch but have vitamins enough to prevent scurvy if consumed in quantity. For 167 days in 1925 two Polish researchers ate almost nothing but potatoes (mashed with butter, steamed with salt, cut with oil into potato salad). At the end they reported no weight gain, no health problems, and, improbably, "no craving for change" in their diet. Historically speaking, the scientists' regimen was not extreme; two British inquiries in 1839 intimated that the average Irish laborer's per capita daily consumption of potatoes was twelve and a half pounds. Ireland was notorious for its potato habit, but the tubers had become so essential to all of northern Europe that Prussia and Austria fought a "potato war" in 1778–79 in which the two armies spent most of their time scrambling to get food for themselves and deny it to the enemy. Only when every potato in Bohemia had been consumed did hostilities end.

Compared to grains, tubers are inherently more productive.

* Gerard did not contribute to a third source of confusion: the common practice of referring to sweet potatoes as yams. Yams originated in Asia and Africa and belong to yet another biological family.

If the head of a wheat or rice plant grows too big, the plant will fall over, with fatal results. Modern plant breeders have developed wheat and rice varieties with shorter, stronger stalks that can bear heavier loads of grain. But even they could not support something as heavy as an Idaho potato. Growing underground, a tuber is not limited by the rest of the plant—there are no worries about its architecture. In 2008 a Lebanese farmer dug up a potato that weighed nearly twenty-five pounds. Photographs showed a man holding a tuber bigger than his head.

Many scholars believe that the introduction of *S. tuberosum* to Europe was a key moment in history. This is because their widespread consumption largely coincided with the end of famine in northern Europe. (Maize, another American crop, played a similar but smaller role in southern Europe.) More than that, the celebrated historian William H. McNeill has argued, *S. tuberosum* led to empire: "[P]otatoes, by feeding rapidly growing populations, permitted a handful of European nations to assert dominion over most of the world between 1750 and 1950." Hunger's end helped create the political stability that allowed European nations to take advantage of American silver. The potato fueled the rise of the West.

As important in the long run, the European and North American adoption of the potato set the template for modern agriculture—the agro-industrial complex, as it is sometimes called. Celebrated by agronomists for its bounteous harvests and denounced by environmentalists for its toxicity, the agro-industrial complex rests on three pillars: improved crops, high-intensity fertilizers, and factory-made pesticides. All three are entwined with the Columbian Exchange, and with the potato.

Not only did the Columbian Exchange carry the ultra-productive potato to Europe and North America, it also brought ultra-productive Andean potato-cultivation techniques, including the world's first intensive fertilizer: Peruvian guano. Andean peoples had mined it for centuries from great excremental deposits seabirds left on coastal islands. Fertilizer ships crossed the Atlantic by the hundreds, brimming with guano—and, many researchers believe, a fungus-like organism that blighted potatoes, causing a famine in Ireland that by some measures was the worst in the historical record.

Not long after, potatoes fell to the attack of another imported species, the Colorado potato beetle. Panicked farmers turned to the first inorganic pesticide: a widely available form of arsenic, sprayed with enthusiasm over the field. Competition to produce ever-more-effective arsenic compounds launched the modern pesticide industry—the third component of modern agribusiness. Brought together systematically in the 1950s and 1960s, improved crops, high-intensity fertilizers, and artificial pesticides created the Green Revolution, the explosion of agricultural productivity that transformed farms from Illinois to Indonesia—and set off a political argument about the food supply that grows more intense by the day.

SEA OF GENES

In 1853 an Alsatian sculptor named Andreas Friedrich erected a statue of Sir Francis Drake on a marble plinth in the center of Offenburg, a small city in southwest Germany. Friedrich portrayed Drake staring into the horizon in orthodox visionary fashion. His left hand rested on the hilt of his sword. His right gripped a potato. "Sir Francis Drake," the base proclaimed,

disseminator of the potato in Europe
in the Year of Our Lord 1586.
Millions of people
who cultivate the earth
bless his immortal memory.

The statue was pulled down by the Nazis in early 1939, a small piece of the violent frenzy set off by the anti-Semitic riots of

Kristallnacht. Destroying the statue was a crime against art, not history: Drake almost certainly did not introduce the potato to Europe. Even if he *had* introduced it, though, the statue would be misguided. Credit for *Solanum tuberosum* surely belongs most to the Andean peoples who domesticated it.

Geographically, the Andes were an unlikely place for the creation of a major staple food. The second-biggest mountain range on the planet, the chain of peaks forms an icy barrier on the Pacific Coast of South America that is 5,500 miles long and in many places more than 22,000 feet high. Active volcanoes are scattered along its length like molten jewels on a belt. Ecuador alone had seven eruptions in the last century; San José, on Chile's western border, has gone off seven times since 1822. The volcanoes are linked by geologic faults, which push against each other isometrically, trig-

The Offenburg memorial to Sir Francis Drake's introduction of the potato was destroyed by the Nazis.

gering earthquakes, floods, and landslides. Even when the land is seismically quiet the climate is active. Temperatures in the highlands can fluctuate from 75°F to below freezing in the space of a few hours—the air is too thin to hold the heat. Sudden hailstorms splinter windows and drive vehicles off the road. Famously, El Niño—the name itself is an Andean coinage—brings floods to the coast and drought to the high plains. El Niño episodes can last for years.

The main part of the range consists of three roughly parallel mountain chains separated by high tablelands known as the altiplano. The altiplano (average altitude: about twelve thousand feet) holds most of the region's arable land; it's as if Europe had to support itself by farming the Alps. The sheer eastern face of the Andes catches the warm, humid winds from the Amazon, and consequently is beset by rain; the western, ocean-facing side, shrouded by the "rain shadow" of the peaks, contains some of the earth's driest lands. The altiplano between has a dry season and a wet season, with most of the rain coming between November and March. Left to its own devices, it would be covered by grasses in the classic plains pattern.

From this unpromising terrain sprang, remarkably, one of the world's great cultural traditions—one that by 1492 had reached, according to the University of Vermont geographer Daniel W. Gade, "a higher level of sophistication" than any of the world's other mountain cultures. Even as Egyptian kingdoms built the pyramids, Andean societies were erecting their own monumental temples and ceremonial plazas. Contentious imperia jostled for power from Ecuador to northern Chile. Nasca, with its famous stone lines and depictions of animals; Chavín, with its grand temples at Chavín de Huántar; Wari, landscape engineers par excellence; Moche, renowned for ceramics depicting every aspect of life from war and work to sleeping and sex; Tiwanaku, the highest urban complex ever built (it was centered on Lake Titicaca, the highest navigable lake on the planet); Chimor, successor to Moche, with its sprawling capital of Chan Chan—the tally is

enormous. Most famous today are the Inka, who seized much of the Andes in a violent flash, built great highways and cities splendid with gold, then fell to Spanish disease and Spanish soldiers.

The history of the civilizations of the Middle East and Egypt is entwined with the development of wheat and barley; similarly, indigenous societies in Mexico and Central America were founded on maize. In Asia, China's story is written on paper made from rice. The Andes were different. Cultures there were nourished not by cereal crops like these but by tuber and root crops, the potato most important.

Archaeologists have turned up evidence of people eating potatoes thirteen thousand years ago in southern Chile—not the modern *Solanum tuberosum*, but a wild species, *S. maglia*, which still grows on the coast. Geneticists remain uncertain, though, of the exact pathway by which Andean cultures created the domestic potato. Because early Andean natives mainly grew their tubers from seed and apparently planted multiple species of *Solanum* in the same garden, they would have produced countless natural hybrids, some of which presumably gave rise to the modern potato. One often-cited analysis tried to nail down the process; after much study, its author declared that today's potato was bred from four other species, two of which bore the label "unknown." Timing, too, is unclear: archaeologists have established only that Andean peoples were eating wholly domesticated potatoes by 2000 B.C.

Potatoes would not seem obvious candidates for domestication. Wild tubers are laced with solanine and tomatine, toxic compounds thought to defend the plants against attacks from dangerous organisms like fungi, bacteria, and human beings. Cooking often breaks down a plant's chemical defenses—many beans, for example, are safe to eat only after being soaked and heated—but solanine and tomatine are unaffected by the pot and oven. Andean peoples apparently neutralized them by eating dirt: clay, to be precise. In the altiplano, guanacos and vicuñas (wild relatives of the llama) lick clay before eating poisonous plants.

The toxins in the foliage stick—more technically, "adsorb"—to the fine clay particles. Bound to dirt, the harmful substances pass through the animals' digestive system without affecting it. Mimicking this process, Indians apparently dunked wild potatoes in a "gravy" made of clay and water. Eventually they bred less lethal varieties, though some of the old, poisonous tubers still remain, favored for their resistance to frost. Bags of clay dust are still sold in mountain markets to accompany them on the table.

Andean Indians ate potatoes boiled, baked, and mashed as people in Europe and North America do. But they also consumed them in forms still little known outside the highlands. Potatoes were boiled, peeled, chopped, and dried to make *papas secas;* fermented for months in stagnant water to create sticky, odoriferous *toqosh;* ground to pulp, soaked in a jug, and filtered to produce *almidón de papa* (potato starch). The most ubiquitous concoction was *chuño,* made by spreading potatoes outside to freeze on cold nights. As it expands, the ice inside potato cells ruptures cell walls. The potatoes are thawed by morning sun, then frozen again the next night. Repeated freeze-thaw cycles transform the spuds into soft, juicy blobs. Farmers squeeze out the water to produce *chuño:* stiff, Styrofoam-like nodules about two-thirds smaller and lighter than the original tubers. Long exposure to the sun turns them gray-black; cooked into a spicy Andean stew, they resemble gnocchi, the potato-flour dumplings favored in central Italy. *Chuño* can be kept for years without refrigeration, meaning that it can be stored as insurance against bad harvests. It was the food that sustained the conquering Inka armies.

Then as now, farming the Andes was a struggle against geography. Because the terrain is steeply pitched, erosion is a constant threat. Almost half the population cultivates some land with a slope of more than twenty degrees. Every cut of the plow sends dirt clods tumbling downhill. Many of the best fields—those with the thickest soil—sit atop ancient landslides and hence are even more erosion prone than the norm. Problems are exacerbated by the tropical weather patterns: a dry season with too little water, a

rainy season with too much. During the dry season, winds scour away the thin soil. Heavy rainfall in the wet season sheets down hills, washing away nutrients, and floods the valleys, drowning crops.

To manage water and control erosion, Andean peoples built more than a million acres of agricultural terraces. Carved like stairsteps into the hills, the Spanish voyager Pedro Sarmiento de Gamboa marveled in 1572, were "terraces of 200 paces more or less, and 20 to 30 wide, faced with masonry, and filled with earth, much of it brought from a distance. We call them *andenes*"

Using a foot plow, Andean Indians break up the ground in this drawing from about 1615 by Felipe Guaman Poma de Ayala, an indigenous noble. Women follow behind to sow seed potatoes.

(platforms)—a term that may have given its name to the Andes. (Fifteenth-century Indians used more appropriate methods than those ordered by Mao in the twentieth century, and had much better results.)

On the flatter, wetter land around Lake Titicaca indigenous societies built almost five hundred square miles of raised fields: rectangular hummocks of earth, each several yards wide and scores or even hundreds of yards long. Separating each platform from its neighbor was a trench as much as two feet deep that collected water. During the night the trench water retained heat. Meanwhile, the complex up-and-down topography and temperature variation of the surface created slight air turbulence that mixed the warmer air in the furrows and the colder air around the platforms, raising the temperature around the crops by as much as 4°F, a tremendous boon in a place where summer nights approach freezing.

In many places raised fields were not possible and so Indians constructed smaller *wacho* or *wachu* (ridges), parallel crests of turned-up earth perhaps two feet wide, separated by shallow furrows of equal size. Because the Americas had no large domesticable animals—llamas are too small to pull a plow or carry human beings—farmers did all the work with hoes and foot plows, long wooden poles with short hafts and sharp stone, bronze, or copper tips and footrests above the tip. Making a line across the field, village men faced backward, lifting up their foot plows and jabbing them into the soil, then stamping on the footrest to gouge deeper. Step by backward step, they created ridges and furrows. Each man's wife or sister faced him with a hoe or mallet, breaking up the clods into smaller pieces. Placed in holes atop the *wacho* were potato seeds or whole small tubers (each had to have at least one eye, from which the new potato would sprout). Sacred songs and chants paced the labor as the line of workers moved methodically down the field. Breaks were accompanied by mugs of *chicha* (maize beer) and handfuls of coca leaves to chew. When one field was done, villagers moved to the next, until everyone's fields

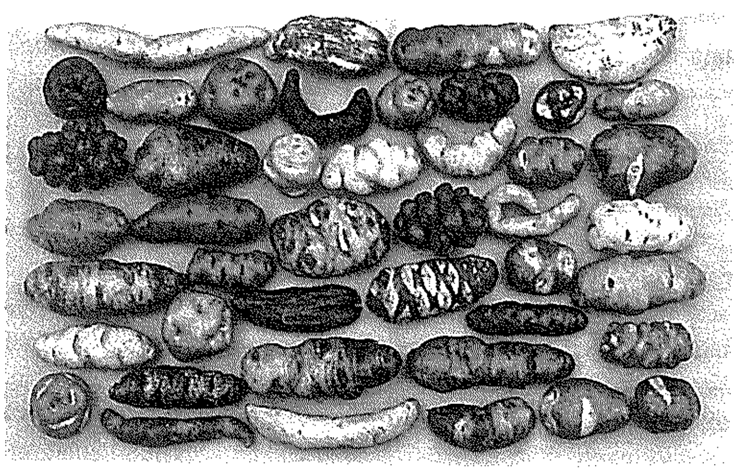
were ready—a tradition of collective work that is a hallmark of Andean societies.

Four or five months later, farmers swarmed into the fields, digging up the tubers and leveling the *wacho* for the next crop—often quinoa, the native Andean grain. Every scrap of the potato plant was consumed except the toxic fruits. The foliage fed llamas and alpacas; the stalks became cooking fuel. Some of the fuel was used on the spot. Immediately after harvest, families piled hard clods of soil into igloo-shaped ovens eighteen inches tall. Inside the oven went the stalks, as well as straw, brush, and scraps of wood (after the Spaniards came, people used cattle manure). Fire heated the earthen ovens until they turned white. Cooks pushed aside the ashes and placed freshly harvested potatoes inside for baking. Villagers in the heights still do this today—the stoves glow in the twilight, dotting the hills. Steam curls up from hot food into the clear, cold air. People dip their potatoes in coarse salt and edible clay. Night winds carry the bakery smell of roasting potatoes for what seems like miles.

The potato roasted by precontact peoples was not the modern spud. Andean peoples cultivated different varieties at different altitude ranges. Most people in a village planted a few basic types, but everyone also planted others to have a variety of tastes, each in its little irregular patch of *wacho*, wild potatoes at the margins. The result was chaotic diversity. Potatoes in one village at one altitude could look wildly unlike those a few miles away in another village at another altitude.

When farmers plant pieces of tuber, rather than seeds, the resultant sprouts are clones; in developed countries, entire landscapes are covered with potatoes that are almost genetically identical. By contrast, a Peruvian-American research team found that families in a mountain valley in central Peru grew an average of 10.6 traditional varieties—landraces, as they are called, each with its own name. Karl Zimmerer, now at Pennsylvania State University, visited fields in some villages with as many as twenty landraces. The International Potato Center in Peru has sampled and preserved more than 4,900. The range of potatoes in a single Andean field, Zimmerer observed, "exceeds the diversity of nine-tenths of the potato crop of the entire United States." (Not all varieties grown are traditional. The farmers produce modern, Idaho-style breeds for the market, though they describe them as bland—they're for yahoos in cities.)

In consequence, the Andean potato is less a single identifiable species than a bubbling stew of many related genetic entities. Sorting it out has given decades of headaches to taxonomists (researchers who classify living creatures according to their presumed evolutionary relationships). Learned studies of cultivated potatoes in Andean fields have divided them, variously and contradictorily, into twenty-one, nine, seven, three, and one species, each further sliced into multiple subspecies, groups, varieties, and forms. Four is probably the most commonly used species number today, though the dispute is anything but resolved. As for *S. tuberosum* itself, the most widely accepted recent study parcels it into eight broad types, each with its own name.



Andean natives bred hundreds of different potato varieties, most of them still never seen outside South America.

The potato's wild relatives are no less confounding. In *The Potato*, a magnum opus from 1990, the potato geneticist J. G. Hawkes proclaimed the existence of some 229 named species of wild potato. That did not lay the matter to rest. After analyzing almost five thousand plants from across the Americas, Dutch researchers in 2008 winnowed Hawkes's 229 species down to just ten fuzzily defined entities—"species groups," as they put it—that bob like low, marshy islands in a morass of unclassifiable hybrids that extends from Central America down the Andes to the tip of South America and "cannot be structured or subdivided" into the classic species in biology textbooks. The description of the wild potato as a trackless genetic swamp was, the Dutch admitted, a view that their colleagues might find "difficult to accept."

None of this was apparent, of course, to the first Spaniards who ventured into the Andes—the band led by Francisco Pizarro, who landed in Ecuador in 1532 and attacked the Inka. The conquistadors noticed Indians eating these round objects and despite their suspicion sometimes emulated them. News of the new food spread rapidly. Within three decades, Spanish farmers as far away as the Canary Islands were growing potatoes in quantities enough to export to France and the Netherlands (then part of the Spanish empire). The first scientific description of the potato appeared in 1596, courtesy of the Swiss naturalist Gaspard Bauhin, who awarded it the name of *Solanum tuberosum esculentum*, which later became the modern *Solanum tuberosum*.

Folklore credits Francis Drake with stealing potatoes from the Spanish empire during a bout of piracy/privateering. Supposedly he gave them to Walter Ralegh, founder of the luckless Roanoke colonies.* (Drake rescued the survivors.) Ralegh asked a gardener on his Irish estate to plant them. His cook is said to have served the toxic berries at dinner. Ralegh ordered the plants yanked from

* Ralegh and his coevals spelled his name in many ways, including Rawley, Ralagh, and Raleigh. Although the last is most common today, he himself generally used "Ralegh."

his garden. Hungry Irish picked them up from the refuse—hence, apparently, the statue of Drake in Germany. On its face, the tale is unlikely; even if Drake snatched a few potatoes while marauding in the Caribbean, they would not have survived months at sea.

The first food Europeans grew from tubers, rather than seed, the potato was regarded with fascinated suspicion; some believed it to be an aphrodisiac, others a cause of fever, leprosy, and scrofula. Ultraconservative Russian Orthodox priests denounced it as an incarnation of evil, using as proof the undeniable fact that potatoes are not mentioned in the Bible. Countering this, the pro-potato English alchemist William Salmon claimed in 1710 that the tubers "nourish the whole Body, restore in Consumptions [cure tuberculosis], and provoke Lust." The philosopher-critic Denis Diderot took a middle stance in his groundbreaking *Encyclopedia* (1751–65), Europe's first general compendium of Enlightenment thought. "No matter how you prepare it, the root is tasteless and starchy," he wrote. "It cannot be regarded as an enjoyable food, but it provides abundant, reasonably healthy food for men who want nothing but sustenance." Diderot viewed the potato as "windy" (it caused gas). Still, he gave it the thumbs-up. "What," he asked, "is windiness to the strong bodies of peasants and laborers?"

With such halfhearted endorsements, it is little wonder that the potato spread slowly outside of the Spanish colonies. When Prussia was hit by famine in 1744, King Frederick the Great, a potato proponent, had to order the peasantry to eat potatoes. In England, farmers denounced *S. tuberosum* as an advance scout for hated Roman Catholicism. "No Potatoes, No Popery!" was an election slogan in 1765. As late as 1862, the British cookbook and household advice writer Isabella Beeton was warning her readers not to drink "the water in which potatoes are boiled." France was especially slow to adopt the new crop. Into the fray stepped nutritionist, vaccination advocate, and potato proselytizer Antoine-Augustin Parmentier, the Johnny Appleseed of *S. tuberosum*.

Trained as a pharmacist, Parmentier served in the army and was captured five times by the Prussians during the Seven Years' War. As a prisoner he ate little but potatoes for three years, a diet which to his surprise kept him in good health. His effort to understand how this could have happened led Parmentier to become a pioneering nutritional chemist, one of the first to try to figure out what is in food and why it sustains the body. When unseasonable rain and snow in 1769 and 1770 led to crop failures in parts of eastern France, a local academy announced a competition for "Plants that Could in Times of Scarcity be Substituted for Regular Food to Nourish Man." Five of the seven entries touted the potato. Parmentier's essay, the most impassioned and well documented, won the competition. It was the beginning of his career as a potato activist.

His timing was good. Four years after the famine, one of the first acts of the newly anointed king, Louis XVI, was to lift price controls on grain. Bread prices shot up, sparking what became known as the Flour War: more than three hundred civil disturbances in eighty-two towns. Throughout the disturbances Parmentier tirelessly advocated the potato as the solution. Proclaiming that France would stop fighting over bread if the French would eat potatoes, he set up one pro-spud publicity stunt after another: persuading the king to wear potato blossoms; presenting an all-potato dinner to high-society guests;* planting forty acres of potatoes at the edge of Paris, knowing that famished sansculottes would steal them. His efforts were successful. "The potato," announced a later supplement to Diderot's *Encyclopedia*, "is the fruit that feeds more than half of Germany, Switzerland, Great Britain, Ireland and many other countries."

In extolling the potato, Parmentier unwittingly changed it.

* Supposedly one guest was Thomas Jefferson, then U.S. ambassador to France. He is said to have liked one potato dish so much that he served it in the White House. In this way Jefferson introduced the United States to French fries.

All of Europe's potatoes descended from a few tubers sent across the ocean by curious Spaniards. From a genetic point of view, the European stock had been created by dipping a teaspoon into the sea of genes in Peru and Bolivia. Parmentier was urging his countrymen to cultivate this limited sample on a massive scale. Because potatoes are grown from pieces of tuber, he was unknowingly promoting the notion of planting huge areas with clones—a true monoculture. The potato fields he was envisioning were thus radically different from their Andean forebears. One was a crazy gumbo, its ingredients unclear; the other was an orderly array of identical parts.

The effects of this transformation were so striking that any general history of Europe without an entry in its index for *S. tuberosum* should be ignored. Hunger was a familiar presence in the Europe of the Little Ice Age, where cold weather killed crops even as Spanish silver drove up prices. Cities were provisioned reasonably well in most years, their granaries monitored by armed guards, but country people teetered on a precipice. When harvests failed, food riots ensued; thousands occurred across Europe between 1400 and 1700, according to the great French historian Fernand Braudel. Over and over, rioters, often led by women, broke into bakeries, granaries, and flour mills and either stole food outright or forced merchants to accept a "just" price. Ravenous bandits swarmed the highways, seizing grain convoys to cities. Order was restored by violent action.

Braudel cited an eighteenth-century tally of famine in France: forty nationwide calamities between 1500 and 1778, more than one every decade. This appalling figure actually understates the level of scarcity, he wrote, "because it omits the hundreds and hundreds of *local* famines." France was not exceptional; England had seventeen national and big regional famines between 1523 and 1623. Florence, hardly a poor city, "experienced 111 years when people were hungry, and only sixteen 'very good' harvests between 1371 and 1791"—seven bad years for every bumper year.

The continent could not feed itself reliably. It was caught in the Malthusian trap.

As the sweet potato and maize did in China, the potato (and maize, to a lesser extent) helped Europe escape Malthus. When the agricultural economist Arthur Young toured eastern England in the 1760s he saw a farming world that was on the verge of a new era. A careful investigator, Young interviewed farmers, recording their methods and the size of their harvests. According to his figures, the average yearly harvest in eastern England from an acre of wheat, barley, and oats was between 1,300 and 1,500 pounds. By contrast, an acre of potatoes yielded more than 25,000 pounds—about eighteen times as much.* Growing potatoes especially helped England's poor, Young believed. "It is to be wished, that all persons who have it in their power to render this root more common among them, would exert themselves in it." Potatoes, he proclaimed, "cannot be too much promoted."

Potatoes didn't replace grain but complemented it. Every year, farmers left fallow as much as half of their grain land, to replenish the land and fight weeds (they were plowed under in summer). Now smallholders could grow potatoes on the fallow land, controlling weeds by hoeing. Because potatoes were so productive, the effective result was, in terms of calories, to double Europe's food supply. "For the first time in the history of western Europe, a definitive solution had been found to the food problem," the Belgian historian Chris Vandenbroeke concluded. (The German historian Joachim Radkau was blunter: the key environmental innovations of the eighteenth century, he

* This comparison overstates the case. Compared to grains, potatoes have more water, which is nutritionally useless. In the past potatoes were about 22 percent dry matter; wheat, by contrast, was about 88 percent. Thus the 25,620 pounds/acre yield of potatoes found by Young was equivalent to 5,636 pounds/acre of dry matter. Similarly, wheat's 1,440 pounds/acre yield would be 1,267 pounds/acre of dry matter. For this reason, it is fairer to say that potatoes were about four times more productive than wheat.

wrote, were "the potato and coitus interruptus.") Potatoes (and, again, maize) became to much of Europe what they were in the Andes—an ever-dependable staple, something eaten at every meal. Roughly 40 percent of the Irish ate no solid food other than potatoes; the figure was between 10 and 30 percent in the Netherlands, Belgium, Prussia, and perhaps Poland. Routine famine almost disappeared in potato country, a two-thousand-mile band that stretched from Ireland in the west to Russia's Ural Mountains in the east. At long last, the continent could, with the arrival of the potato, produce its own dinner.

Although the potato raised farm production overall, its greater benefit was to make that production more reliable. Before *S. tuberosum*, summer was usually a hungry time, with stored grain supplies running low before the fall harvest. Potatoes, which mature in as little as three months, could be planted in April and dug up during the thin months of July and August. And because they were gathered early, they were unlikely to be affected by an unseasonable fall—the kind of weather that ruined wheat harvests. In war-torn areas, potatoes could be left in the ground for months, making them harder to steal by foraging soldiers. (Armies in those days did not march with rations but took their food, usually by force, from local farmers.) Young's interview subjects used most of their potatoes for animal feed. In bad years, they had been forced to choose whether to feed their animals or themselves. Now they didn't have to make the choice.

The economist Adam Smith, writing a few years after Young, was equally taken with the potato. He was impressed to see that the Irish remained exceptionally healthy despite eating little else: "The chairmen, porters, and coal-heavers in London, and those unfortunate women who live by prostitution—the strongest men and the most beautiful women perhaps in the British dominions—are said to be, the greater part of them, from the lowest rank of people in Ireland, who are generally fed with this root." Today we know why: the potato can better sustain life than any other food when eaten as the sole item of diet. It has all essential nutrients except vitamins A and D, which can be supplied by milk; the diet of the Irish poor in Smith's day consisted largely of potatoes and milk. And Ireland was full of poor folk; England had conquered it in the seventeenth century and seized much of the best land for its own citizens. Many of the Irish were forced to become sharecroppers, paid for their work by being allowed to farm little scraps of wet land for themselves. Because little but potatoes could thrive in this stingy soil, Ireland's sharecroppers were among Europe's most impoverished people. Yet they were also among its most well nourished, because they ate potatoes. Smith drew out the logical consequences: if potatoes ever became, "like rice in some rice countries, the common and favourite vegetable food of the people," he wrote, "the same quantity of cultivated land would maintain a much greater number of people." Ineluctably, Smith believed, "Population would increase."

Smith was correct. At the same time that the sweet potato and maize were midwifing a population boom in China, the potato was helping to lift populations in Europe—the more potatoes, the more people. (The worldwide population boom was a sign and effect of the onset of the Homogenocene.) In the century after the potato's introduction Europe's numbers roughly doubled. The Irish, who ate more potatoes than anyone else, had the biggest boom; the nation grew from perhaps 1.5 million in the early 1600s to about 8.5 million two centuries later. (Some believed it reached 9 or even 10 million.) The increase occurred not because potato eaters had more children but because more of their children survived. Part of the impact was direct: potatoes prevented deaths from famine. The greater impact, though, was indirect: better-nourished people were less likely to die of infectious disease, the era's main killer. Norway was an example. Cold climate had long made it vulnerable to famine, which struck nationwide in 1742, 1762, 1773, 1785, and 1809. Then came the potato. The average death rate changed relatively little, but the big spikes vanished. When they were smoothed out, Norwegian numbers soared.

Such stories were recorded all over the continent. Hard hit by the shorter growing seasons of the Little Ice Age, mountain hamlets in Switzerland were saved by the potato—indeed, they thrived. When Saxony lost most of its agricultural land to Prussia in 1815, refugees filled its towns. To keep up with the rising numbers, farmers ripped out wheat and rye and planted potatoes. The potato harvest was enough to feed Saxony's growing population but not enough for good nutrition—there wasn't enough milk. Farmers in central Spain cut down olive and almond trees and planted potatoes. Village prosperity rose, followed by village numbers. And so on.

Just as American crops were not the only cause of China's population boom, they were not the only reason for Europe's population boom. The potato arrived in the midst of changes in food production so sweeping that some historians have described them as an "agricultural revolution." Improved transportation networks made it easier to ship food from prosperous areas to places with poor harvests. Marshlands and upland pastures were reclaimed. Shared village land was awarded to individual families, dispossessing many smallholders but encouraging the growth of mechanized agriculture (the new owners could be guaranteed of keeping the returns if they invested in their farms). Reformers like Young popularized better cultivation methods, especially the use of manure from stables as fertilizer. Farmers learned to plant fallow fields with clover, which recharges the soil with nutrients. First domesticated by the Moors in Spain, clover helped prevent Europeans from destroying their pastureland soil by overgrazing. The advances were not confined to agriculture. American silver let Europeans build ships to increase trade, raising living standards. Some improvements occurred in the continent's governance and even in its abysmal hygiene standards. As in China, the Little Ice Age began to wane.

In 2010 two economists at Harvard and Yale attempted to account for such factors by comparing events in parts of Europe that were similar except for their suitability for potatoes; any systematic differences, they argued, would be due to the new crop. According to the two researchers' "most conservative" estimate, *S. tuberosum* was responsible for about an eighth of Europe's population increase. Put baldly, the figure may not seem high. But the continent's long boom had many causes. One way to think of this calculation is to say that it suggests the introduction of the potato was as important to the modern era as, say, the invention of the steam engine.

THE GUANO AGE

It was said that the islands gave off a stench so intense that they were difficult to approach. They were a clutch of dry, granitic mounds thirteen miles off the Peruvian shore, about five hundred miles south of Lima on the west coast of South America. Almost nothing grew on them. Called the Chincha Islands, they were never inhabited by Indians—not for long, anyway. Their sole distinction is their population of seabirds, especially the Peruvian booby, the Peruvian cormorant, and the Peruvian pelican. The birds are attracted by the strong coastal current, which pulls cold water from the depths. Phytoplankton feast on the nutrients that rise with the water. Zooplankton eat the phytoplankton and in turn are the primary food of the anchoveta fish, a cousin to the familiar anchovy. Anchoveta live in vast schools that are preyed upon by other fish. Predators and prey both are preyed upon by the Peruvian booby, cormorant, and pelican. All three have nested on the Chincha Islands for millennia. Over time they have covered the islands with a layer of guano as much as 150 feet thick.

Guano makes excellent fertilizer. Fertilizer is, at base, a mechanism for providing nitrogen to plants. Plants need nitrogen to make chlorophyll, the green substance in their leaves that absorbs the sun's energy for photosynthesis. Nitrogen is also a key building block for both DNA and the proteins for which DNA is the template. Although more than three-quarters of the atmosphere is made up of nitrogen gas, from a plant's point of view nitrogen is scarce—the gas is made from two nitrogen atoms that cling to each other so tightly that plants cannot split them apart for use. In consequence, plants seek nitrogen from the soil, where it can be found in forms that they can break down: ammonia (NH_3, or one nitrogen atom and three hydrogen atoms), nitrites (compounds that include NO_2, a group of one nitrogen atom and two oxygen atoms), and nitrates (compounds that include NO_3, a group of one nitrogen atom and three oxygen atoms). All are in less supply than farmers would like, not least because bacteria in the soil constantly digest nitrates and nitrites, turning the nitrogen back into unusable nitrogen gas. Land that has been farmed repeatedly always risks nitrogen depletion.

Unlike mammalian urine, bird urine is a semisolid substance. Because of this difference, birds can build up reefs of urine in a way that mammals cannot (except, occasionally, for big colonies of bats in caves). Even among birds, though, Chincha-style guano deposits—heaps as big as a twelve-story building—are uncommon. To make them, the birds must be relatively large, form big flocks, and defecate where they live (gulls, for instance, release their droppings away from their breeding grounds). In addition, the area must be dry enough not to wash away the guano. The waters off the Peruvian coast receive less than an inch of rain a year. The Chinchas, the most important of Peru's 147 guano islands, house hundreds of thousands of Peruvian cormorants, the most prolific guano producers. According to *The Biogeochemistry of Vertebrate Excretion*, a classic treatise by G. Evelyn Hutchinson, a cormorant's annual output is about thirty-five pounds. Arithmetic suggests that the Chincha cormorants alone produce thousands of tons per year.

Centuries ago Andean Indians discovered that depleted soils could be replenished with guano. Llama trains carried baskets of Chincha guano along the coast and perhaps into the mountains. The Inka parceled out guano claims to individual villages, levying penalties for disturbing the birds during nesting or taking guano allocated to other villages. Blinded by the shine from Potosí silver, the Spaniards paid little attention to conquered peoples' excremental practices. The first European to observe guano carefully was the German polymath Friedrich Wilhelm Heinrich Alexander von Humboldt, who traveled through the Americas between 1799 and 1804. A pioneer in botany, geography, astronomy, geology, and anthropology, Humboldt had an insatiable curiosity about everything that crossed his path, including the fleet of native guano boats that he saw skittering along the Peruvian coast. "One can smell them a quarter of a mile away," he wrote. "The sailors, accustomed to the ammonia smell, aren't bothered by it; but we couldn't stop sneezing as they approached." Among the thousands of samples Humboldt took back to Europe was a bit of Peruvian guano, which he sent to two French chemists. Their analysis showed that Chincha guano was 11 to 17 percent nitrogen—enough to burn plant roots if not properly applied. The French scientists touted its potential as fertilizer.

Few took their advice. Supplying European farmers with guano would involve transporting large quantities of excrement across the Atlantic, a project that understandably failed to enthuse shipping companies. Within several decades, though, the picture changed. Agricultural reformers throughout Europe had begun to worry that the ever-more-intense agriculture necessary to feed growing populations was exhausting the soil. As harvests leveled off and even decreased, they looked for something to restore the land: fertilizer.

At the time, the best-known soil additive was bone meal, made by pulverizing bones from slaughterhouses. Bushels of bones went to grinding factories in Britain, France, and Germany. Demand ratcheted up, driven by fears of soil depletion. Bone dealers supplied the factories from increasingly untoward sources, including the recent battlefields of Waterloo and Austerlitz. "It is now ascertained beyond a doubt, by actual experiment upon an extensive scale, that a dead soldier is a most valuable article of commerce," remarked the London *Observer* in 1822. The newspaper noted that there was no reason to believe that grave robbers were limiting themselves to battlefields. "For aught known to the contrary, the good farmers of Yorkshire are, in a great measure, indebted to the bones of their children for their daily bread."

From this perspective, avian feces began to seem like a reasonable item of commerce. A few bags of guano appeared in European ports in the mid-1830s. Then Justus von Liebig weighed in. A pioneering organic chemist, Liebig was the first to explain plants' dependence on nutrients, especially nitrogen. In his treatise *Organic Chemistry in Its Application to Agriculture and Physiology* (1840), Liebig criticized the use of bone fertilizer, which has little nitrogen. Guano was another story: "It is sufficient to add a small quantity of guano to a soil consisting only of sand and clay, in order to procure the richest crop of maize." Liebig was enormously respected; he was an avatar of the Science that had brought new, productive crops like the potato and maize, and new ways of thinking about agriculture and industry. *Organic Chemistry* was quickly translated into multiple languages; at least four English editions appeared. Sophisticated farmers, many of them big landowners, read Liebig's encomium to guano, flung down the book, and raced to buy it. Yields doubled, even tripled. Fertility in a bag! Prosperity that could be bought in a store!

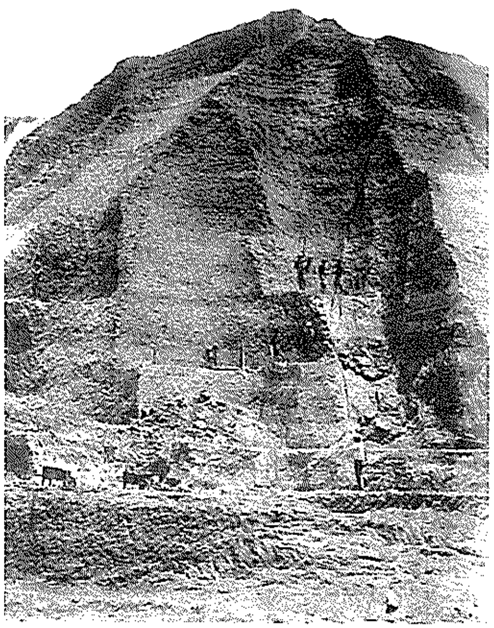
Guano mania took hold. In 1841, Britain imported 1,880 tons of Peruvian guano, almost all of it from the Chincha Islands; in 1843, 4,056 tons; in 1845, 219,764 tons. In forty years, Peru exported about 13 million tons of guano, receiving for it approximately £150 million, roughly $13 billion in today's dollars. It was the beginning of today's input-intensive agriculture—the practice of transferring huge amounts of crop nutrients from one place to another, distant place according to plans dictated by scientific research.

Hoping to take maximum advantage of the guano rush, Peru nationalized the Chinchas. Soon it discovered that nobody wanted to work on the islands. Except for birds, their only inhabitants were bats, scorpions, spiders, ticks, and biting flies. Not a single plant grew on their barren slopes. Worse, the islands had

no water; every drop had to be shipped in. Because the land was blanketed in guano, miners worked, ate, and slept on shelves of ancient excrement. So little rain fell that the soluble materials in the guano never washed away—it remained studded with crystals of ammonia nitrate, which broke in corrosive clouds around miners' shovels. Powdery and acrid, the guano went into miners' carts, which were pushed up rails to a depot atop one of the seaside cliffs. From the cliff, men dumped tons of excrement through a long canvas tube directly into the bellies of vessels below. Slamming into the hold, guano dust exploded from the hatchways, shrouding the ship in a toxic fog. Workers wore masks made from hemp smeared with tar, one visitor noted,

> but the guano mocks at such weak defenses. . . . [T]hey are unable to remain below longer than twenty minutes at one time. They are then relieved by another party, and return on deck perfectly naked, streaming with perspiration, and with their brown skins thickly coated with guano.

The government could have paid high wages to get workers to endure these terrible conditions, but that would have cut into profits. Instead it stocked the islands with a mix of convicts, army deserters, and African slaves. This arrangement proved unsatisfactory: the convicts and deserters killed each other, and the slaves were so valuable that their mainland owners did not wish to part with them. In 1849 Peru gave up trying to run the mines itself and awarded an exclusive concession to Domingo Elías, Peru's biggest cotton grower and one of its principal slave owners. Politically savvy and manically ambitious, Elías had been prefect of Lima; during a time of civil unrest, he briefly declared himself ruler of the nation. In return for the monopoly, Elías was supposed to mine guano with his own slaves, but he, too, was reluctant to take them away from his cotton fields. He induced the government to subsidize merchants who imported immigrants. Promi-



Thousands of Chinese slaves mined the guano of Peru's Chincha Islands, shown here in 1865, for export to Europe as fertilizer. The islands, home for millennia to seabirds, were covered with a layer of guano as much as 150 feet deep.

nent among these subsidized importers was Domingo Elías. By the time the law passed his agents were already in Fujian, waving labor contracts in the faces of illiterate villagers.

In standard indenture practice, the contracts promised the Chinese would pay for their passage by working, typically for eight years, in the newly discovered California gold fields. (The actual destination, the guano archipelago, was not mentioned.) The ruse was plausible: agents for U.S. firms were in Fujian at the same time, telling a similar lie as they sought indentured servants to build railroads. People who signed the bogus Peruvian contract were conducted to bleak human warehouses in Amoy (now called Xiamen, on an island across the river from Yuegang) and, later, Macao. People who refused to sign often were kidnapped and shipped to the same warehouses. In these dark confines slavers burned the letter *C*—for California, their ostensible destination—into the backs of their ears. No longer were the men described as workers. Their new name was *zhuzai,* little pigs. "None were let outside," wrote the Shanghai historian Wu Ruozeng. "Those who resisted were whipped; any who tried to escape were killed."

Peru was not the only destination in the mid-century Chinese diaspora. A quarter of a million or more *zhuzai,* almost all of them men, ended up—more or less willingly, more or less knowingly—in Brazil, the Caribbean, and the United States. But Peru represented the worst passage, the direst conditions, the most dreaded destination. Ultimately at least 100,000 Chinese were taken there. Conditions en route can be compared to those in the transatlantic slave trade. Perhaps one out of eight *zhuzai* died. As on the Atlantic slave ships, revolts were common. Eleven mutinies are known to have occurred on Peru-bound vessels; at least five bloodily succeeded.

Most of the Chinese ended up working in the sugar and cotton plantations on the coast. Some built the railroads that the Peruvian government was constructing with guano money. At any given time between one and two thousand were on the Chincha Islands. In classic divide-and-conquer fashion, Elías forestalled rebellion by setting his African slaves as overseers over his Chinese slaves and holding both to strict deadlines. Spasms of cruelty, slave upon slave, were the inevitable result. Guano miners swung their picks up to twenty hours a day, seven days a week, to fulfill their assigned daily quotas (as much as five tons of guano); two-thirds of their pay was deducted for room (reed huts) and board (a cup of maize and some bananas). Failure to meet the daily quota was rewarded with a five-foot rawhide whip. Minor infractions were punished by torture. Escape from the islands was impossible. Suicide was frequent. One overseer told a *New York Times* correspondent that

> more than sixty had killed themselves during the year, . . . chiefly by throwing themselves from the cliffs. They are buried, as they live, like so many dogs. I saw one who had been drowned—it was not known whether accidentally or not—lying on the guano, when I first went ashore. All the morning, his dead body lay in the sun; in the afternoon, they had covered it a few inches, and there it lies, along with many similar heaps, within a few yards of where they were digging.

So many Chinese died that the overseers marked off an acre of guano as a cemetery.

Journalistic exposés of guano slavery created an international scandal that gave the Lima government an excuse to eject Elías and renegotiate the guano contract with someone else, thus procuring a second round of bribes. Fulminating against the evils of official corruption, Elías sought to regain his lucrative concession by twice staging a coup d'état. Both attempts failed. In 1857 he tried the legal route, running for president without success.

All the while guano flowed to Europe and North America. In addition to signing an exclusive mining concession with Elías, Peru had awarded a monopoly on shipping guano internationally to a company in Liverpool. With demand outstripping supply, Peru and its British consignees were able to charge high prices. Their customers reacted with fury to what they viewed as extortion. Decrying the "powerful monopoly" on guano, the British *Farmer's Magazine* laid out its readers' demands in 1854. "We do not get anything like the quantity we require; we want a great deal more; but at the same time, we want it at a lower price." If Peru insisted on getting a lot of money for a valuable product, the only fair solution was invasion. Seize the guano islands!

From today's perspective, the outrage—threats of legal action, whispers of war, editorials about the Guano Question—is hard to understand. But agriculture was then "the central economic activity of every nation," as the environmental historian Shawn William Miller has pointed out. "A nation's fertility, which was set by the soil's natural bounds, inevitably shaped national economic success." In just a few years, agriculture in Europe and the United States had become dependent on high-intensity fertilizer—a dependency that has not been shaken since. Britain, first to adopt guano and by far the largest user, was both the most dependent and the most resentful. Much as oil buyers today begrudge the member nations of OPEC, Peru's British customers ranted about the guano cartel. They were apoplectic as Peru's guano barons sauntered around Lima in the latest Parisian fashions, bejeweled trollops on their arms.

Britons were almost entirely silent about Peru's British agents in Liverpool, who used their share of the Peruvian monopoly profits to construct one of the biggest houses in England. Americans were not silent. They fumed as the British gave priority to their British customers, leaving Americans at the end of the guano line. Spurred by their fury, Congress passed the Guano Islands Act in 1856, authorizing its citizens to seize any guano islands they saw. The biggest loads came from Navassa, an island fifty miles west of Haiti, which the United States took in 1857.

After the Civil War its workforce consisted largely of freed slaves. Conditions gradually deteriorated; the former slaves rebelled twice, killing some of their jailers, and the enterprise fell apart in a cloud of scandal. Under the aegis of the Guano Islands Act, merchants claimed title to ninety-four islands, cays, coral heads, and atolls between 1856 and 1903. The Department of State officially recognized sixty-six as U.S. possessions. Most proved to have little guano and were quickly abandoned. Nine remain under U.S. control today.

Guano set the template for modern agriculture. Ever since Liebig, farmers have treated the land as a medium into which they dump bags of chemical nutrients. The nutrients are shipped from far-off places or synthesized in distant factories. Farming is the act of transferring those external nutrients to crops in the field: high volumes of nitrogen go in, high volumes of maize and potatoes go out. Because the harvests in this system are enormous, the crops are no longer vehicles for local subsistence, but products destined for an international market. To maximize output, they are grown in ever-larger, single-crop fields—industrial monoculture, as it is called.

Today scholars often describe the "Green Revolution" after the Second World War—the combination of high-yield crops, agricultural chemicals, and intensive irrigation—as the moment when humankind triumphantly escaped, at least for a while, the limits set by small-scale farms and local resources. But as the Amherst College historian Edward D. Melillo has argued, the arrival of guano ships in Europe and the United States marked an earlier, equally profound Green Revolution, the first in a series of technological innovations that transformed life across the planet.

Before the potato and maize, before intensive fertilization, European living standards were roughly equivalent with those today in Cameroon and Bangladesh; they were below Bolivia or Zimbabwe. On average, European peasants ate less per day than hunting-and-gathering societies in Africa or the Amazon.

Industrial monoculture with improved crops and high-intensity fertilizer allowed billions of people—Europe first, and then much of the rest of the world—to escape the Malthusian trap.* Incredibly, living standards doubled or tripled worldwide even as the planet's population climbed from fewer than 1 billion in 1700 to about 7 billion today.

Along the way guano was almost entirely replaced by nitrates mined from vast deposits in the Chilean desert. The nitrates in turn were replaced by artificial fertilizers, made in factories by a process invented and commercialized in the early twentieth century by two Nobel-winning German chemists, Fritz Haber and Carl Bosch. No matter what their composition, though, fertilizers remain just as critical to agriculture, and through agriculture to contemporary life. In a fascinating 2001 study of the impact of factory-made nitrogen, Vaclav Smil, the University of Manitoba geographer, estimated that two out of every five people on earth would not be alive without it.

By any measure these were amazing accomplishments. Yet like all human endeavors the rise of intensive agriculture had its downside. The guano trade that launched modern agriculture was also the beginning, via the Columbian Exchange, of one of its worst pitfalls: the intercontinental transport of exotic pests. Proof will never be found, but it is widely believed that the guano ships carried a microscopic hitchhiker: *Phytophthora infestans. P. infestans* causes late blight, a plant disease that exploded through Europe's potato fields in the 1840s, killing as many as two million people, half of them in Ireland, in what came to be known as the Great Hunger.

* This may understate the impact. The historian Kenneth Pomeranz has argued that "some of the most intensely farmed soils of Europe (including in England) faced serious depletion by the early nineteenth century." If guano had not arrived, Pomeranz believes, the consequences may not have been simply remaining at the same level but a full-scale disaster across much of the continent.

THOROUGHLY MODERN FAMINE

The name *Phytophthora infestans* means, more or less, "vexing plant destroyer," a censure that is wholly deserved. *P. infestans* is an oomycete, one of seven hundred or so species sometimes known as water molds. From a biologist's point of view, oomycetes can be thought of as cousins to algae. From a gardener's point of view, *P. infestans* looks and acts like a fungus. It sends out tiny bags of six to twelve spores that are blown on the wind, usually for no more than twenty feet, occasionally for as much as half a mile or even further. When the bag lands on a susceptible plant, it hatches, so to speak, releasing what are technically known as zoospores: mobile, two-tailed cells that slowly swim through moisture on the leaf or stem, looking for the tiny respiratory holes called stomata. If the day is warm and wet enough, the zoospores germinate, sending long, threadlike filaments through the stomata into the leaf. Extensions from the filaments infiltrate leaf cells, hijacking the mechanisms inside; the plant ends up nourishing the invader, rather than itself. The first obvious symptoms—purple-black or -brown spots on the leaves—are visible in about five days. By that time it is often too late. Filaments lace through much of the plant. The oomycete is already generating new bags of spores.

Water is the blight's friend—zoospores cannot germinate on dry leaves. Rain washes zoospores from the leaves onto the soil, letting them attack roots and tubers as much as six inches below the surface. Especially vulnerable are the tuber's eyes. *P. infestans* strikes from the outside in, turning the potato's outer flesh into dry, grainy, red-brown rot. Extensions of blight reach like dark claws toward the center of the tuber. Because the boundary between diseased and healthy tissue is indistinct, the entire potato must usually be thrown away. Care must be taken with disposal: a single infected tuber can generate a million spores.

P. infestans preys on members of the nightshade family: potatoes, tomatoes, eggplants, sweet peppers, and weeds like hairy nightshade and bittersweet nightshade. When shocked European researchers first observed the carnage in potato fields, they naturally assumed the agent responsible came from Peru, the land of potatoes. Seventy years ago most changed their minds. Typically biologists view a species's "center of diversity"—the place where it has the widest array of forms—as its ancestral home. Mexico has hundreds of varieties of maize seen nowhere else, suggesting that the species originated there. Africans are more genetically diverse than Caucasians or Asians; Africa is the cradle of humankind. And so on. In central Mexico, *P. infestans* seemed more varied than anywhere else. Notably, the species occurs in two types—one could think of them as male and female, except that oomycetes have no sexual characteristics—that can combine their DNA, creating an egg-like entity known as an oospore. In other words, *P. infestans* can reproduce both asexually and "sexually," with the quotation marks as a reminder that these creatures are not male and female.* But only in Mexico did the oomycete reproduce sexually, because the rest of the world lacked one of the two forms. Scientists argued that this and other types of diversity indicated that *P. infestans* originated in Mexico—even though there is no evidence of *S. tuberosum* there until the eighteenth century. Alexander von Humboldt, visiting Mexico in 1803 with his samples of guano, made the first certain observation of a potato in Mexico. Humboldt assumed that Spaniards had imported the tuber from the Andes. The potato blight had existed for millennia, in this view, before it encountered a potato. A final detail:

* Reproducing both sexually and asexually sounds odd to big, clumsy mammals like us, but it is a canny survival strategy in much of the microworld (malaria-causing *Plasmodium* parasites reproduce both ways, for example). Asexual reproduction is useful in good times, because it produces offspring that are exactly as well adapted genetically to their environment as their parents. Sexual reproduction is valuable when the environment changes, because the sexual shuffling of genes creates variability, which helps the offspring survive in altered circumstances.

because blight was spotted in the United States before Europe, some researchers suggested that it spread there first, then hopped a boat across the Atlantic.

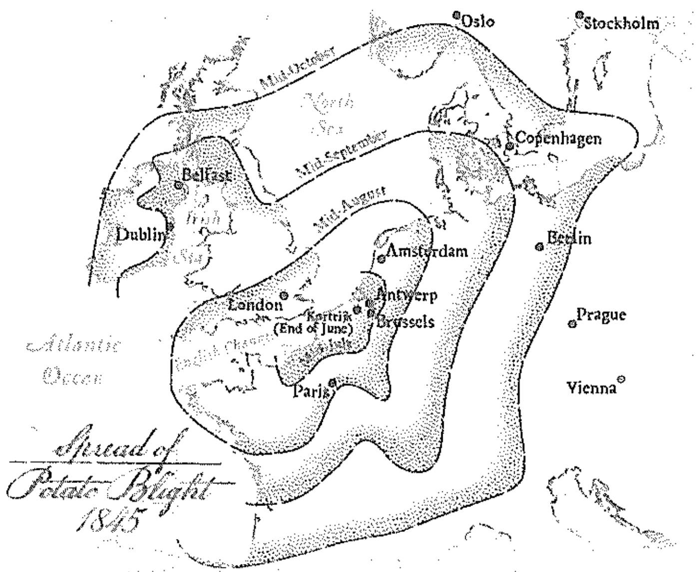
In a series of experiments culminating in 2007, a team led by University of North Carolina plant geneticist Jean Ristaino overturned these ideas. Ristaino's team used the tools of DNA analysis to examine blight from 186 infected potatoes in herbariums, the botanical storehouses in museums. The youngest sample was from 1967; three were collected in Europe in 1845–47, the time of the Great Hunger. Ristaino's scheme was complex in detail, but simple in principle. Because *P. infestans* usually reproduces asexually, the progenitor oomycete and its offspring usually have identical genetical endowments, except for the infrequent occasions when a mutation scrambles DNA. Organisms with similar DNA patterns belong, as geneticists say, to the same "haplogroup." If two individuals belong to the same haplogroup, it is molecular evidence that they share a recent ancestor. Similarly, different haplogroups are a sign of the lack of a recent common ancestor. Ristaino's team found that potato blight from the Andes had a greater number of haplogroups than Mexican blight—it was fundamentally more diverse. Moreover, DNA from the old blight in herbariums—samples preserved for as long as a century and a half—was nearly identical to DNA from Andean blight. "The U.S. and Irish populations were not genetically differentiated from the Peruvian populations," the scientists wrote. Blight from the Andes "initiated epidemics first in the U.S. and then Ireland that led to the famine."

Most likely the blight traveled from Peru to Europe aboard a guano ship to Belgium, probably to Antwerp, the area's most important port. Farmers in the adjacent province of West Flanders were having trouble with their potatoes. In what would now be described as a demonstration of the power of evolution, European plant pathogens—viruses and fungi—were adapting to the new crop. In July 1843 the provincial council of West Flanders voted to import new varieties of potato from North and South America, hoping some would prove to be less susceptible to the diseases. No record exists of their origins or the means by which they were shipped. It would be odd, though, if the South American potatoes had not come from the Andes.

Almost certainly the potatoes made the journey on a guano ship. Between 1532 and 1840 few ships passed directly from Peru to Europe, because Spain, protective of its silver in Potosí, tightly controlled traffic. As Potosí ran out of ore, the silver ships sailed less frequently. In the 1820s Bolivia and Peru gained their independence and Spanish shipping there closed down altogether. European ships were then free to sail to Lima, but few did: the new nations had little to offer and were politically chaotic to boot. In its first two decades, Peru had more than one change of government per year; it also fought five foreign wars. A direct shipping line between Peru and Britain did not open until 1840. It carried guano. As guano frenzy set in, ships by the score sailed from Europe to the Chincha Islands. One traveler there in 1853 saw 120 vessels clustered about the guano docks. Another, later voyager saw 160. Chances are high that one of these ships unknowingly carried blighted potatoes to Belgium—and infected a continent.

Field trials of West Flanders's new potatoes began in 1844. That summer a nearby French botanist observed a few potato plants with strange, bruise-dark spots. The following winter was extremely cold, which should have killed any blight spores or eggs in the soil. But the experimenters may have stored a few contaminated potatoes and unknowingly planted them the next spring. In July 1845 the West Flanders town of Kortrijk, six miles from the French border, became the launchpad for Europe's first widespread epidemic of potato blight. Carried by windblown spores, the oomycete hopscotched to farms around Paris by August. Weeks later, it was in the Netherlands, Germany, Denmark, and England. Governments panicked and ordered more potatoes from abroad.

Blight was first reported in Ireland on September 13, 1845. By mid-October the British prime minister was privately describ-



ing the epidemic as a national disaster. Within another month between a quarter and a third of the crop had been lost. Cormac Ó Gráda, an economist and blight historian at University College, Dublin, has estimated that Irish farmers planted about 2.1 million acres of potatoes that year. In two months *P. infestans* wiped out the equivalent of between half and three-quarters of a million acres in every corner of the nation. The next year was worse, as was the year after that.

Recall that almost four out of ten Irish ate no solid food except potatoes, and that the rest were heavily dependent on them. Recall, too, that Ireland was one of the poorest nations in Europe. At a stroke, the blight removed the food supply from half the country—and there was no money to buy grain from outside. The consequences were horrific; Ireland was transformed into a post-apocalyptic landscape. Destitute men lined the roads in their rags, sleeping in crude shelters dug into roadside ditches. People ate dogs, rats, and tree bark. Reports of cannibalism were frequent

In early 1847 the *Illustrated London News* asked the artist James Mahoney to tour the famine-wracked Irish countryside. His articles and illustrations depicted a landscape of ruins and starving beggars—and did much to bring the crisis to the attention of the English public.

and perhaps accurate. Entire families died in their homes and were eaten by feral pets. Disease picked at the survivors: dysentery, smallpox, typhus, measles, a host of ailments listed in death records as "fever." Mobs of beggars—"homeless, half-naked, famishing creatures," one observer called them—besieged the homes of the wealthy, calling for alms. So many died that in many western towns the bodies were interred in mass graves.

As resources vanished, life became a struggle of all against all. Starving men stole into fields to steal turnips from the ground. Farmers dug mantraps in their fields to stop them. Landlords evicted tenants in huge numbers, tore down their homes, then went bankrupt themselves. Neighbor fought neighbor for food and shelter. Crime levels exploded, the murder rate almost doubling in two years. Some hungry people stole to put food on the table, others to be fed while incarcerated. In one case two men released from prison were sent back the next day for trying "to break into jail." The only violent crime to decline was rape, because potential perpetrators lacked the energy.

Hundreds of thousands of desperate people fled the country in what became known as "coffin ships." One passenger remembered bodies "huddled together without light, without air, wallowing in filth and breathing a fetid atmosphere, sick in body, dispirited in heart." The ships marked their passage with a trail of dead slid into the sea. Most migrants went to the United States and Canada. Multitudes of sick and starving filled the quarantine area at Grosse Île, in the St. Lawrence River by Quebec. A mass grave there contains thousands of bodies. They died an ocean away from Ireland but were as much victims of *P. infestans* as if they had never left.

Britain mounted the biggest aid program in its history, but it was catastrophically insufficient—largely, Irish nationalists charge, because London treated the crisis as a chance to expand its efforts to transform Ireland's "primitive" subsistence farming to export-oriented agriculture. Instead of simply providing food, the British pulled people off the farm, massed them in work-

houses, and fed them from soup kitchens; meanwhile, the farms were consolidated into bigger, more export-friendly units. Other critics point to the export of food from Ireland during the famine: 430,000 tons of grain in 1846 and 1847, the two worst years. "The Almighty indeed sent the potato blight," nationalist leader John Mitchel thundered, "but the English created the famine."

Examples of British callousness were indeed thick on the ground. Some politicians welcomed the depopulation, which would, one cabinet minister's agent promised, "give us room to become civilized." Others said that giving food to soup kitchens actually did harm; if "large numbers would have perished of starvation," one banking official reasoned, "the material relations of the survivors would have been re-established."

England's defenders retort that although anti-Irish politicians said awful things they were ignored. In practice, the starving had to be massed if they were to be fed; delivering huge amounts of food to scattered families is not easy, even today. The exporters, moreover, were mainly Irish farmers who sold pricy meat and grain to buy cheap food for their families. Failure to accomplish the unprecedented, however dire the consequences, is not a moral lapse—or so the argument goes.

No matter what degree of culpability should be assigned to Britain, the consequences of the famine to Ireland are indisputable: it broke the nation in half. At a million or more fatalities, it was one of the deadliest famines in history, in terms of the percentage of population lost. A similar famine in the United States today would kill almost forty million people. Only the famine of 1918–22 in the Soviet Union may have been worse. Within a decade of the blight another two million fled Ireland. Many more followed in subsequent decades, inexorably driving its population down. The nation never regained its footing. As late as the 1960s its population was half what it had been in 1840. Today Ireland has the melancholy distinction of being the only nation in Europe, and perhaps the world, to have fewer people within the same boundaries than it did more than 150 years ago.

LAZY BEDS

The Great Hunger left such a scar in Ireland that historians could barely bring themselves to look at it for more than a century. Since the 1970s, though, the famine has been the subject of hundreds of books and articles. In all the outpour, though, surprisingly little attention has been devoted to its cause, *P. infestans*—unfortunately, because the oomycete was the protagonist in the first calamity of modern commodity agriculture.

P. infestans came to Ireland with surprising alacrity and overtook the country with puzzling speed. Ireland, an island nation, is eight hundred miles away from West Flanders. Between them are the North Sea and the Irish Sea. Blight spores are fragile: a single hour of exposure to the ultraviolet radiation in sunlight is enough to cut their likelihood of germinating by 95 percent. Even a light rain knocks them from the air. A widely cited ecological model suggests that as a practical matter they cannot surf the winds further than twenty to thirty miles. After tests in Washington State, three scientists concluded that in perfect conditions—strong winds, cool temperatures, no direct sunlight or rain—blight spores might be able to move seventy miles, though fewer than 5 percent would survive. Except around Northern Ireland, the Irish Sea is wider than seventy miles. If the researchers are correct, blight spores could only have been blown to Ireland by traveling from southeast to northwest England, then floating over the North Channel to Belfast—a remarkable journey. (Technically, they are not spores but "sporangia," the bags of spores released by blight, but I am ignoring this distinction for the moment.)

Rain fell, sometimes heavily, on twenty-four of the thirty days after September 13, 1845, when the blight was first reported in Ireland. Yet despite the rain *P. infestans* swept across the country, striking with a remorselessness not seen anywhere else. Something about Ireland was uniquely vulnerable—but what? One part of the answer was the sheer number of potatoes, a fat target for the blight. Another part was the uniformity of the crop. According to Ó Gráda, the blight historian, about half of Ireland was dominated by a single, outstandingly productive variety: the Lumper. Many Irish lived in clusters of farmhouses called *clachans* surrounded by tightly packed, communally owned farmland. Encircled by clones of a single variety of a single tuber species, the *clachans* of western Ireland were among the most uniform ecosystems on the planet.

Irish farmers for centuries had grown crops by cutting out blocks of sod, flipping them upside down, and piling them into long, broad ridges separated by deep furrows—"lazy-bed" farming, as the system was known. (The name may come from an occasional English epithet for the potato: the "lazy root.") Typically four feet wide, the ridges loomed a foot or more above the furrows. They looked strikingly like *wacho*, the ridged fields in Andean societies. Like *wacho*, they were built in boggy soils; the ridges warmed up more quickly in the morning and retained heat longer in the evening than the surrounding flatlands, an advantage in cold places like the Andes and Ireland. Constructed from several layers of sod, the ridges represented concentrations of good soil; farmers could plant them densely, which naturally stifled weeds. Because the ridges were not plowed, they had intact root systems that resisted erosion; the roots also ensured that grass returned quickly after harvest, restoring nutrients.

Unaware of these advantages, eighteenth-century agricultural reformers denounced the lazy-bed/*wacho* method as inefficient, an unproductive obstacle to modernization. Activists like Andrew Wight and Jethro Tull wanted farmers to release soil nutrients by deep, thorough plowing; to plant every possible bit of terrain; to charge the land with fertilizer (manure and then, when it became available, guano); to protect growing crops with ruthless weeding; and to maximize yields by efficient harvesting. Believers in technology, they viewed the newest factory-made harrows, drillers, and harvesters as God-given tools to accomplish these goals. Because these machines needed level land—they couldn't climb up and down ridges—the lazy-beds had to go. On top of everything else, reformers said, the furrows between the ridges were a waste of space.

Wacho occupied a swath of northern Europe that reached from France to Poland and included Britain, Ireland, Scandinavian countries, and Baltic states. As the new methods took hold after about 1750, they disappeared. *Wacho* had almost vanished from Ireland by 1834, when reform enthusiast Edmund Murphy took a cross-country "professional tour" between Dublin on the east coast and Galway on the west, taking "particular notice of the potato crop." Seeing few lazy-beds in areas where they had once been ubiquitous, he crowed that they were "completely superseded. . . . Nothing shows the rapid improvement in agriculture which is at present extending in this country more clearly."

To examine the consequences of the shift to modern cultivation methods, Michael D. Myers, then at the University of Texas in Austin, experimentally created six fields in Northern Ireland: three lazy-beds and three of the level fields that replaced them. He discovered that the simple ridges and furrows created a complex geography, with surprisingly sharp temperature and humidity differences between the top of the ridge and the bottom of the furrow. Plant-disease specialists describe the temperature and humidity conditions that favor *P. infestans* in terms of "blight units"—the higher the number of blight units, the better the chance that blight zoospores on potato leaves will be able to germinate. Myers's lazy-beds had roughly half as many blight units as the level fields. Blight spores were less likely to germinate in the comparatively warm, dry conditions atop the ridges. Because water drained into the furrows, it flowed away and beneath the growing tubers, carrying zoospores away from them. In addition, they had fewer noxious weeds and needed less fertilizer.*

Murphy, denouncer of lazy-beds, took his professional tour because disease had been striking Ireland's potatoes. This was in 1834, a decade before the blight; the diseases he was concerned with were viruses, bacteria, nematodes, and so on—ordinary pests that were adapting to the new crop. As the pests evolved, they caused crop failures; fourteen occurred between 1814 and 1845. (None of these incidents was anywhere as severe as the Great Hunger.) Myers, the University of Texas researcher, came to believe these failures were due in part to the abandonment of lazy-bed cultivation, which inadvertently fostered plant disease. (It is worth noting that the Andes did not have such widespread potato epidemics.) The blight was simply the latest and worst pathogen to take advantage of the new scientific agriculture: one kind of potato, on a terrain shaped for technology, rather than biology.

The Great Hunger was the first truly contemporary agricultural disaster. Without the improvements wrought by modern science and technology, the blight would have had far less impact. Alarmed by the blight, governments in France, Belgium, Britain, and the Netherlands quickly asked biologists for help. But in its surge and sweep it was like nothing they had ever seen.

* The campaign against lazy-bed farming may not have been reformers' only contribution to destruction. *P. infestans* exploded across Europe so fast that one wonders whether the blight was accidentally distributed by human action. Ecological models suggest that blight is "more likely to be spread by people than by passive dispersal through the atmosphere." At least one new product suddenly appeared in farms across much of Europe in the early 1840s: guano. On the passage from Lima to Liverpool, one can easily imagine blighted potatoes spilling from a broken barrel, spreading spores into the loose mass of guano in the hold. Blight spores can survive in soil for as much as forty days. If the soil were infected toward the end of the trip, that would allow more than enough time to distribute it. Ireland had been the site of much guano experimentation. By 1843, trials had occurred in at least eleven of its thirty-two counties. Farmers were swapping and borrowing samples with equal vim the next year. It is tempting to wonder whether *P. infestans* was less imported with the guano than imported *in* the guano. (Another pest, the potato cyst nematode, invaded Japan in exactly this way.) After the blight hit, some of Ireland's most progressive farmers advocated a means for returning potato yields to normal: higher doses of guano. All through the Great Hunger the fertilizer ships came.

Many Andean peoples have long grown potatoes in parallel ridges called *wacho* (bottom, in Bolivia near Titicaca), a practice that has been shown to discourage fungal diseases by drying wet soil. Lazy-bed cultivation, as it was called in English, was common in Ireland (top, in northern Ireland in the 1920s) until the early nineteenth century. Recent research suggests the abandonment of lazy-beds helped potato blight race through the countryside, exacerbating the great Irish famine.

During the next forty years, researchers attributed the blight to ozone, air pollution, static electricity, volcanic action, smoke from steam locomotives, excessive humidity or heat, gases from the recently introduced sulfur match, an emanation from outer space, various insects (aphids, ladybugs, tarnished plant bugs), and the potato's own internal debilitation. Edward Hitchcock, a renowned natural historian at Amherst College, assigned blame to an "atmospheric agency, too subtle for the cognizance of our senses." A few thought the cause was a fungus, but they were shouted down. No useful countermeasures were proposed. The plea for help went out to Science, but Science couldn't answer.

"WAR UPON THE BEETLES"

In August 1861 beetles invaded a ten-acre garden in northeastern Kansas that belonged to a potato farmer named Thomas Murphy. His name was appropriate: Murphy, a common Irish surname, was also a slang term for potatoes. Murphy's potatoes—Murphy's Murphys—were overrun by so many beetles that he could barely see the leaves through the swarm of tiny glittering bodies. He knocked the insects from the plants into a basket, he wrote later, and "in a very short time gathered as many as two bushels of them"—remarkable, given that each insect was barely a third of an inch long. In a different context, perhaps, Murphy might have thought the beetle was beautiful, with its yellow-orange body and its forewings marked tigerishly with thin black stripes. But they were devouring his potato plants as fast as they came up.

Murphy had never seen the beetle before its hordes suddenly attacked his potatoes. Nor had his neighbors who also were visited by it, or the farmers in Iowa and Nebraska whom it invaded that summer. The insect marched steadily north and east, expanding its range by fifty to a hundred miles a year, shocking potato growers at every step. It reached Illinois and Wisconsin in 1864; Michigan, by 1870. Seven years later it was attacking potatoes from Maine to North Carolina. The little insects swarmed potato fields in such profusion, according to one widely repeated story, that they stopped nearby trains. Their bodies covered the tracks in a layer deep enough to make the wheels slip "as if oiled, so that the locomotive was powerless to draw the train of cars." Strong winds blew the beetles into the sea, from which they washed ashore in a glittering, yellow-orange carpet that fouled beaches from New Jersey to New Hampshire. Farmers had no idea where the creature had come from or how to stop it from eating their potato fields to the ground.

The Great Hunger still a vivid memory, Europeans cringed to hear the reports of potato devastation. Companies produced thousands of small insect models to help farmers identify Murphy's beetle. Germany imposed what may have been the world's first-ever agricultural quarantine, against U.S. potatoes, in 1870; France, Russia, Spain, and the Netherlands followed suit. Great Britain, which had the most to fear, did not ban U.S. potatoes—it didn't want to set off a trade war. Traveling in ship holds, the beetle kept appearing in European fields, only to be expunged. The First World War distracted governments from the task of monitoring insect movements. Seizing the moment, the beetle established a beachhead in France, then moved east. Today it occupies a swath of Europe that reaches from Athens to Stockholm. In the Americas its realm extends from south-central Mexico to north-central Canada. Many biologists fear that it will spread into East and South Asia, completing a round-the-world journey.

Murphy's beetle is known to entomologists as *Leptinotarsa decemlineata* and to gardeners as the Colorado potato beetle. It is not from Colorado. Nor at first did it have any interest in potatoes. It originated in south-central Mexico, where its diet centered on buffalo bur (*Solanum rostratum*), a weedy, knee-high potato relative with leaves that somewhat resemble oak leaves. From the human point of view, the plant is annoyingly spiny, with barbed seedpods that stick in hair and clothes and are hard to remove without gloves. Biologists believe that buffalo bur was confined

to Mexico until Spaniards, agents of the Columbian Exchange, carried horses and cows to the Americas. Quickly realizing the usefulness of these foreign mammals, Indians stole as many as they could, sending them north for their families to ride and eat. Buffalo bur apparently came along, tangled in horse manes, cow tails, and native saddlebags. The beetle followed in its path, hopping along a chain of corrals and stock pens. After arriving in Texas, the bur also could have been carried by bison, which migrate from south to north in the spring. By 1819 the beetle had arrived in the Middle West, where a naturalist observed it feeding on buffalo bur along the Missouri River. In this area it first encountered the cultivated potato.

Chance intervened. In Mexico the beetle, specialized on buffalo bur, finds it easy to ignore the delights of *S. tuberosum;* placed on a potato leaf, it will seek sustenance elsewhere. But one midwestern beetle in the mid-nineteenth century was born with a tiny mutation—perhaps, according to one suggestive study, a slight shift at a particular spot in its second pair of chromosomes, a snippet of DNA that flipped end to end. The mutation was not enough to make the beetle look different or affect its ability to reproduce. But it may have been enough to widen its focus from buffalo bur to a relative, the potato.

"The progeny of one pair, if unmolested for a year, would amount in the aggregate to over 60,000,000 of individuals," the *New York Times* calculated in 1875. The actual figure is more like sixteen million, but the point is valid—a single genetic accident in a single individual was enough to generate a worldwide problem. The beetle is the potato's most devastating pest to this day. "One of the worst features of the present visitation," the newspaper continued, "is that the Colorado beetle is noted for its permanency, and rarely abandons localities until it has ravaged them for several seasons in succession. . . . Under such circumstances, the only resource is to commence an aggressive war upon the beetles."

War with what weapon? Farmers tried everything they could think of: picking off and crushing beetles with special pincers; trying to find less-attractive potato varieties; encouraging the insect's natural predators (ladybirds, soldier beetles, certain species of tiger beetle); moving potato fields every season, thus avoiding beetles overwintering (an insect version of hibernation) in the soil; surrounding their plots with buffalo bur, "so as to concentrate the insects, and thus more readily destroy them"—here I am quoting Charles Valentine Riley, founder and longtime head of the U.S. Entomological Commission. An Iowa man touted his horse-drawn beetle remover, which raked the insects into a box dragged behind. Potato growers doused plants with lime, sprinkled sulfur, spread ashes, sprayed with tobacco juice. They mixed coal tar with water and splashed that on the beetles. Some farmers reportedly tried wine. Others tried kerosene. Nothing worked.

Insects have bothered farmers since the first planting of crops in the Neolithic era. But large-scale industrial agriculture changed the incentives, so to speak. For millennia the potato beetle had made do with the buffalo bur scattered through the Mexican hills. By comparison, an Iowa potato farm—hundreds of orderly rows of a single type of a single species—was an ocean of breakfast. By adapting to the potato, the beetle could command many more resources for reproduction than it had ever possessed before; its numbers naturally exploded. So did those of other pests—the potato blight is a notable example—that were able to take advantage of the same opportunities. Each of the massive new farms was a fabulous storehouse of riches for the species that could exploit it.

Those farms were ever more similar, a hallmark of the Homogenocene. Because growers planted just a few varieties of a single species, pests had a narrower range of natural defenses to overcome. If a species was able to adapt to the potatoes in one place, it would not have to adapt to those in others. It could simply jump from one identical food pool to the next—a task that was easier than ever, thanks to modern inventions like railroads,

As this cover illustration on an 1877 number of the London newspaper supplement *Funny Folks* suggests, British farmers feared the arrival of the Colorado potato beetle.

steamships, and refrigeration. Not only did industrial agriculture present insects with a series of rich, identical targets; these faster, denser transportation networks made it ever easier for faraway species to exploit them. In 1898, L. O. Howard, Riley's successor, calculated that at least thirty-seven of the seventy worst insect pests in the United States were recent imports (he wasn't sure of the origins of six others).

The late nineteenth century was, in consequence, a time of insect plagues. The boll weevil, slipping over the border from Mexico, wiped out so much cotton in the South that the governor of South Carolina proclaimed a day of public prayer and fasting to fight the bug. The cottony cushion scale, an Australian insect, swept through California's citrus industry. A European import, the elm leaf beetle, ravaged elm trees in U.S. cities; Dutch elm disease, introduced from Asia despite the name, would arrive later and more or less wipe out all elms east of the Mississippi. Returning the favor, the United States exported phylloxera, an aphid that wrecked vineyards in most of France and Italy.

For the wine industry, the solution was discovered by Riley, the Entomological Commission head: grafting European grape vines onto U.S. grape roots, which resist the aphid. For decades afterward, most French and many Italian grapevines had American roots. For the potato, the solution was more consequential: Paris Green.

Paris Green's insecticidal properties were supposedly discovered by a farmer who finished painting his shutters and in a fit of annoyance threw the remaining paint on his beetle-infested potato plants. The emerald pigment in the paint was Paris Green, made largely from arsenic and copper. Developed in the late eighteenth century, it was common in paints, fabrics, and wallpaper. Farmers diluted it heavily with flour and dusted it on their potatoes or mixed it with lots of water and sprayed.

Paris Green was a simple, reliable solution: buy the pigment, mix in flour or water according to the manufacturer's instructions, apply it with a sprinkler or dust box, and watch potato beetles die. To potato farmers, Paris Green was a godsend. To the nascent chemical industry, it was something that could be tinkered with and extended and improved. If arsenic killed potato beetles, why not try it on other pests? Why not spray Paris Green to combat cotton worm, apple cankerworm, apple codling moth, elm leaf beetle, juniper webworm, and that plague of blueberries, the northern walkingstick? Arsenic killed them all. It was a godsend to cotton farmers reeling from the boll weevil. Eager scientists and engineers invented foggers and pumpers, sprayers and dusters, pressure valves and adjustable brass nozzles. The dust changed to liquid; the copper-arsenic mix changed to a lead-arsenic mix and then a calcium-arsenic mix.

If Paris Green worked, why not market another arsenic-containing pigment, London Purple? Why not other chemicals for other agricultural problems? In the mid-1880s a French researcher discovered that the "Bordeaux mixture"—copper sulfate, used to keep children from eating fruit—would kill downy mildew on grapevines. Given a new chemical weapon, researchers pointed it at other pests and hoped it would prove as deadly as Paris Green. Quickly they found that copper sulfate was—oh, happy day!—the long-sought remedy for potato blight. Spraying potatoes with Paris Green, then copper sulfate, would eliminate both the beetle and the blight.

From the beginning, farmers knew that Paris Green and copper sulfate were toxic. Even before the discovery of its insecticidal properties, many people had got sick from living in homes with wallpaper printed with Paris Green. The thought of spraying food with this poison made farmers anxious. They dreaded the prospect of letting pesticides and fungicides build up in the soil. They worried about exposing themselves and their workers to dangerous chemicals. They were alarmed by the cost of all the technology. All of these fears came true, but all could be adjusted for, at least in part. For a long time, farmers didn't know about the most worrisome issue of all: inevitably, the chemicals would stop working.

Colorado potato beetles are, genetically speaking, unusually diverse, which means that they have an unusually wide range of resources in their DNA. When their populations confront new threats—pesticides, for instance—some individuals are likely to be unaffected by them. To farmers' misfortune, this means that the species can quickly adapt. As early as 1912 a few beetles showed signs of immunity to Paris Green. Farmers didn't notice, though, because the pesticide industry kept coming up with new arsenic compounds that kept killing potato beetles. By the 1940s growers on Long Island found themselves having to use ever-greater quantities of the newest arsenic variant, calcium arsenate, to maintain their fields. Luckily for them, Swiss farmers spent the Second World War testing an entirely new type of pesticide on the potato beetle: DDT, a chemical bug killer with unprecedented range and sweep. Farmers bought DDT and exulted as insects vanished from their fields. The celebration lasted about seven years. The beetle adapted. Potato growers demanded new chemicals. The industry provided dieldrin. It lasted about three years. By the mid-1980s, each new pesticide in the eastern United States was good for about a season.

In what critics call the "toxic treadmill," potato farmers now treat their crops a dozen or more times a season with an ever-changing cavalcade of deadly substances. Many writers have decried this, perhaps none more elegantly than Michael Pollan in *The Botany of Desire*. As Pollan observed, large-scale potato farmers now douse their land with so many fumigants, fungicides, herbicides, and insecticides that they create what are known, euphemistically, as "clean fields"—swept free of life, except for potato plants. (In addition, the crops are sprayed with artificial fertilizer, usually once a week during growing season.) If rain doesn't fall for a few days, the powders and solutions can build up on the surface of the soil, creating a residue that resembles the aftermath of a chemical-warfare test. In my area, the Northeast, I have met farmers who claimed not to allow their children to walk around their fields. One doesn't have to be an organic fanatic to wonder about the prospects of a system that turns the production of food into a toxic act.

Worse still, many researchers believe that the chemical assault is counterproductive. Strong pesticides kill not only target species but their insect enemies as well. When the target species develop resistance, they often find their prospects better than before—everything that had previously kept them in check is gone. In this way, paradoxically, insecticides can end up *increasing* the number of harmful insects—unless farmers control them with yet more chemical weapons. "Secondary pests," insects that previously were controlled by some of the species killed off by insecticides, also profit. Here, too, industry has a solution: more pesticides. "A number of new chemistries are expected to appear

on the market in the near future," one research team announced in the *American Journal of Potato Research* in 2008. But

> there is no reason to believe that any of them will break the seemingly endless insecticide–resistance–new-insecticide cycle that is so characteristic of Colorado potato beetle management. . . . Despite all the scientific and technological advances, the Colorado potato beetle continues to be a major threat to potato production.

Blight, too, has returned. Swiss researchers were dismayed in 1981 to discover that the second type of *P. infestans* oomycete, previously known only in Mexico, had found its way to Europe. Because the blight was now capable of "sexual" reproduction, it had greater genetic diversity—more resources, that is, to adapt to chemical control. Similar introductions occurred in the United States. In both cases the new strains were more virulent, and more resistant to metalaxyl, the chief current anti-blight treatment. No good substitute has yet appeared. In 2009, as I was writing this book, potato blight wiped out most of the tomatoes and potatoes on the East Coast of the United States. Driven by an unusually wet summer, it turned gardens all around me into slime. It destroyed the few tomatoes in my garden that hadn't been drowned by rain. Accurately or not, one of my neighbors blamed the attack on the Columbian Exchange. More specifically, he charged that blight had arrived on tomato seedlings sold in big-box stores. "Those tomatoes come from China," he said.