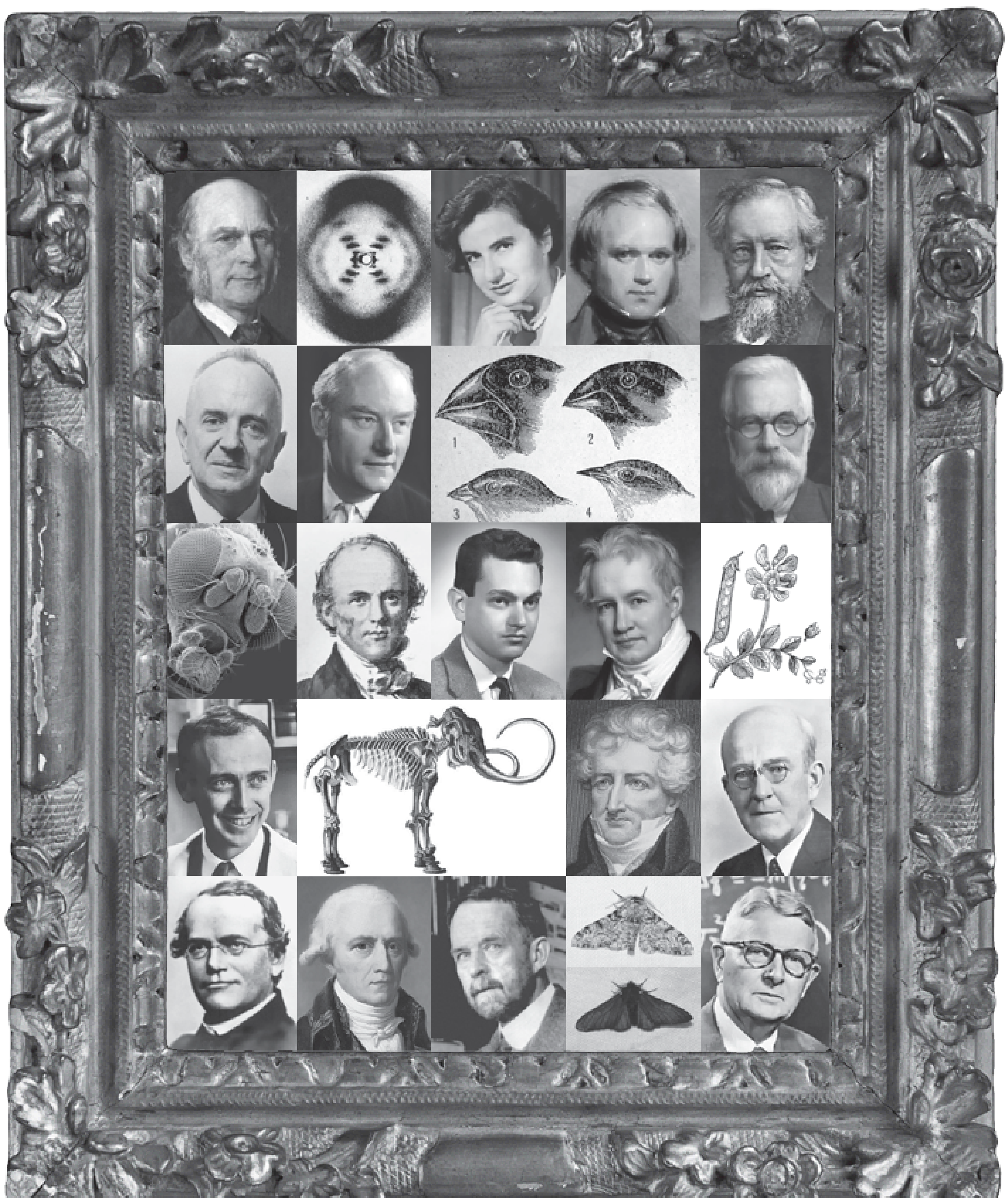
LAND REPORT

THE LAND INSTITUTE · SPRING 2012



THE LAND INSTITUTE

MISSION STATEMENT
When people, land and community are as one, all three members prosper; when they relate not as members but as competing interests, all three are exploited. By consulting nature as the source and measure of that membership, The Land Institute seeks to develop an agriculture that will save soil from being lost or poisoned, while promoting a community life at once prosperous and enduring.

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Thousands of new perennial grain plants live year-round at The Land Institute, prototypes we developed in pursuit of a new agriculture that mimics natural ecosystems. Grown in polycultures, perennial crops require less fertilizer, herbicide and pesticide. Their root systems are massive. They manage water better, exchange nutrients more efficiently and hold soil against the erosion of water and wind. This strengthens the plants' resilience to weather extremes, and restores the soil's capacity to hold carbon. Our aim is to make conservation a consequence, not a casualty, of agricultural production.

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Contents photo: Beetle and *Silphium integrifolium*, by Scott Bontz.

THE NEXT STEP

SCOTT BONTZ

Trevally off of Costa Rica. They can hunt singly, but are more successful together. This observation comes from scientists, who reach

In the essay “Societies as Organisms,” Lewis Thomas tells how social insects such as bees behave like “the most social of all social animals,” the one with the strongest attachments to kind, *Homo sapiens*. Some people aren’t comfortable with that comparison. Thousands of insects swarming to act as one, larger creature seems alien. But ants farm fungi. Ants raise aphids as livestock. Termites “throw up columns and beautiful, curving, symmetrical arches.” Each hive and colony works as a society. None turns to central authority; they mysteriously gather to a critical mass for action. They consult accumulated knowledge in their genes. Thomas compares this to scientific papers. In the journals of scientific societies, fragmentary and usually modest findings of workers in lab and field accumulate, collate, correct, and build. John M. Ziman says this has been “the secret of Western science since the 17th century, for it achieves a corporate, collective power that is far greater than one individual can exert.”

For the sciences of evolutionary biology and ecology, that encyclopedia grows

world-changing effects through shared accumulation of their findings. Jason Buchheim photo.

large but usually toward only more exploration. Scientists at The Land Institute say now has come a critical moment for the amalgam's wholesale, holistic *application*. They call this the "fourth synthesis," after Charles Darwin's theory of evolution, then the theory's melding with the science of inheritance, and eventually the cracking of life's genetic code. They mean making agriculture work more like a natural culture and economy, with grain crops that are perennials growing in mixtures, as does most natural vegetation, to save the soil and nutrients that farming has lost from the start but finally can't live without.

The scientists have been at it for three decades. What they seek is a radical change from the annual monocultures that make most of humanity's food. To ready their crops and figure how to grow them may take three decades more. Meanwhile, population grows and soil erodes. Recently Britain's Royal Society, the US National Research Council, and even the US Agriculture Department have come to see the need and voice support for perennial grains. The Land Institute now proposes a 30-year, $1.64 billion effort enlisting more than 160 scientists on five continents. For comparison: federal ethanol subsidies reached that figure in four months.

The time required is no cause for discouragement, says Wes Jackson, president of The Land Institute. For an established grain crop, breeding a new variety takes almost a decade. With modern knowledge of genetics and modern computing power, his scientists hope to accomplish with perennials what for annuals, in the hands of farmers with no labs, took millennia. And in far less time than that, the worldview born of the organism of ideas has seen three big developments to support the institute scientists' plan for a fourth.

1 Charles Darwin pulls together geology, ecology, and biology to recognize all life as related, and a result of never-ending competition.

"It is difficult for a modern person to appreciate the unity of science and Christian religion that existed at the time of the Renaissance and far into the 18th century," the German-American scientist Ernst Mayr wrote in "The Growth of Biological Thought." Nature's apparent harmony and purpose served as convincing proof of God. "The science of the day" was natural theology. Galileo thought that a god who governs the world with eternal laws inspires trust and faith at least as much as one who forever intervenes, Mayr said, and this idea gave rise to the birth of science as we know it.

Mechanistic laws fit reasonably well the physical model of spheres revolving across the heavens. But life was something else. The diversity of form and action among plants and animals didn't fit limited basic rules. "Everything in the living world seemed to be so unpredictable, so special, and so unique that the observing naturalist found it necessary to invoke the creator, his thought, and his activity in every detail of the life of every individual of every kind of organism," Mayr said. This didn't fit with conception of a ruler as someone who supervises workers but doesn't perform all of their tasks. For two centuries scientists tried to resolve this dilemma.

As these searchers explained more things once considered inexplicable except by intervention or special laws from God, theology and science began to conflict. And, Mayr said, "Nothing signaled the emancipation of science from religion and philosophy more definitely than the Darwinian revolution." Edward J. Larson, in "Evolution: The Remarkable History of a Scientific Theory," wrote, "Darwin's theory ripped through science and society, leaving little unchanged by its force." With 19th century evolutionary thinking, we became interconnected competitors rather than separate creations.

Millions of Americans still deny Darwin's idea that all life forms trace from a common ancestor. Less well known is that though scientists soon accepted evolution in the form of a branching tree, they fought for decades about how it happened. Did mutation suddenly create new species? Or did new organisms appear through long winnowing from variation across populations? The decisive resolution was named biology's "modern synthesis," and it didn't come until a decade beginning in the mid-1930's. Larson said that "often quite a bit of erasing is required before anyone can write something new on the board."

Aristotle's conclusion that species were immutable and eternal held into the 19th century, even with a scientist who piled up enough old bones to conclude that there had been species which are no longer with us, and to see the form of each precisely fitting a function. This was Georges Cuvier, who Larson said was the first scientist with a suitably complete collection of past and present mammals to make definite distinctions among them, and who founded the modern science of paleontology. "Before Cuvier, few people found many fossils anywhere. He found them everywhere and gave them new meaning," Larson said. The Frenchman separated as species Asian and African elephants, and the skeletons of both from mammoth fossils. Before him, European naturalists typically held that no species died out, that fossils were "sports," or remnants of something still living. Cuvier, born in 1769, at 27 had found so many extinct species that he read from them of "a world previous to ours, destroyed by some kind of catastrophe." But though he considered form so much a result of function that he could infer a whole animal from one part, he could not accept that environment determined form, and he adamantly opposed organic evolution.

Larson saw behind this view Cuvier's Protestant religion and political conservatism. Other traditionalists of the time also instinctively opposed the idea that species evolve, which would make change normal. "It had a revolutionary taint," Larson said. It was embraced by social radicals like Jean-Baptiste Lamarck, whose concept that organisms inherit traits acquired by their parents during life carried well into the 20th century, even to young Ernst Mayr. In "Nature's Economy: A History of Ecological Ideas," Donald Worster wrote that, more than is supposed, scientific ideas are rooted in "cultural subsoil," and validated by personal and social needs.

Through the history of biology and evolution come scientists who advance ideas that eventually lead to cutting down older ideas that the innovators themselves hold dear. As it was for Cuvier, so it was for Charles Lyell, who with predecessor James Hutton established the science of geology. Trained as a lawyer, and looking at fossils and regions of volcanoes and earthquakes, Lyell dismantled the notion that catastrophes on the scale of the biblical flood had wiped Earth clean of species, to be followed by divine replacements, and that with humans finally on the scene, those days were over. He argued for "uniformitarianism," for a much older planet that continues slow, cyclic change. But though he saw how conditions would favor different species at different places and times, he didn't see the species themselves changing, and he stressed humans' unique place in creation. T. H. Huxley later observed that Lyell was "doomed to help the cause he hated."

When in 1831 Charles Darwin boarded a ship called the Beagle to serve as naturalist for a five-year expedition round the world, another geologist, Adam Sedgwick, gave to the 22-year-old a reading list. Absent was Lyell's controversial "Principles of Geology." But Capt. Robert FitzRoy had a copy, and Darwin was into it when the southwest sailing Beagle reached the Cape Verde Islands off Africa. It helped translate for him the message in a cliff built with layers of volcanic rock, shells, and coral: catastrophic events would've destroyed the strata. Current geologic forces working over enough time could make the islands. He wrote in his "Beagle Diary," "It has been for me a glorious day, like giving to a blind man eyes."

"For Darwin, uniformitarianism greatly lengthened the time available for evolution to operate, and illustrated the cumulative power of small changes," Larson said in his history of evolution science. Darwin, who bred pigeons and saw how his selections effected change through generations, later wrote in his notebooks, "It is a beautiful part of my theory, that domesticated races of organisms are made by precisely [the] same means as species – but [the] latter far more perfectly & infinitely slower." He also wrote, "I always feel as if my books came half out of Lyell's brains."

Lyell was not his only strong influence, and Darwin was far past the Cape Verde cliffs before he assembled an explanation of evolution. First he hiked and observed the geology, flora, fauna, and cultures of South America, including the Fuegians, whom he considered the lowest of humanity, and not so distant from apes. He read the works of another European who'd explored there, Alexander von Humboldt, who studied geography and interaction of plants and animals under the influence of climate. The holistic Humboldt taught Darwin and others to look at nature comparatively, environmental historian Worster said: to see each region as a unique ecological assemblage dependent on local conditions. Darwin was made "giddy" by the undulations that 200 miles away leveled Concepcion, Chile, and he wrote, "An earthquake like this at once destroys the oldest associations; the world, the very emblem of all that is solid, moves beneath our feet like a crust over a fluid; one second of time conveys to the mind a strange idea of insecurity, which hours of reflection would never create." He wondered over the similarities and differences among finch species in the Galapagos Islands, their similarities to birds 600 miles east in Ecuador, and their differences with birds in like environment but a continent and ocean way in Africa. Back in England, he thought about the sometimes subtle but defining differences among the Galapagos finches. He perceived some species as more closely related than had been thought. He observed the orangutan's expressiveness and intelligence, and in his notes dared a man to boast of preeminence. In how human lovers kiss and almost bite, he guessed of ancestry like the dogs. He found our minds "no more perfect than the instincts of animals." Working through the form of variety over geography and time, he suggested that all life came from one source. And in 1838, through Thomas Malthus's "Essay on the Principle of Population," he found a means.

Malthus said that all species make too many offspring for available food, and limits prescribe "waste of seed, sickness, and premature death." Darwin saw that if individuals within a species differ, weaker members would lose in competition and fail to reproduce, and those better suited to where they live would pass along their beneficial adaptations to the next generation. Over time the resulting complex of small changes in answer to complex, changing, and diverse environments could evolve new organisms. He saw "a force like a hundred thousand wedges," and he called it natural selection.

Darwin and Malthus were men of a culture leading radical remake of the world, Victorian Britain. This too influenced Darwin's ideas. Economics enables philosophical change, Larson said, and colonialism and industrialism led the English elite to equate change with progress, and to see ascendency as a natural result of superior science and technology. "In the unknown interlocking movements of the human mind," Janet Browne wrote in 'Charles Darwin: Voyaging,' natural selection intuitively seemed the right answer to a man thoroughly immersed in the capitalist world of the early 19th century United Kingdom. Worster went further and said Darwin's ideas, with emphasis on "competitive scrambling for place," could not have arisen among Hopis, Hindus, or even continental Europeans. His time and culture, and his ambition to be among its scientific elite, placed him to see what the human mind previously has missed – even, as Worster said, they limited his view and in some ways distorted it.

Darwin combined biology with geology, paleontology, and history. He made biology not just about physical laws, but about connected and continual development. Others before him, including Lamarck and Darwin's grandfather, Erasmus, had argued for evolution. But it was Charles Darwin – and his contemporary and countryman, Alfred Russel Wallace, working independently and today enjoying far less attention – who outlined the means of selection from populations, and drew the populations branching from one ancestral tree.

We can call it a great scientific synthesis. But Darwin never knew what caused the variation that provides for selection. And the branches of biology that grew after his revolutionary "On the Origin of Species" was published in 1859 didn't see the selection for the trees.

2 Biologists diverge and quarrel until a more perfect union is formed by mathematicians, and a man at home in both field and lab.

The diversity of opinion among evolutionists for 80 years after "Origin," Mayr said, was extraordinary. Each biological branch and country had its own tradition. Germany embraced evolution quickly, but almost universally rejected natural selection. That idea found acceptance with no experimental biologist in Britain. But within 10 years biologists there welcomed evolution by descent with modification. The conversion took longer in the United States, which at the time had few biologists and paleontologists, and where the debate fell to writers, theologians, and philosophers. Change came after the death in 1879 of Harvard's Swiss-born, charismatic, and influential Louis Aggasiz, who opposed Darwin even after Lyell guardedly accepted the idea of species shifts. France turned slowest among Western nations to accept evolution. Russia proved the most welcoming, including of natural selection, until the end of the 1920's and the rise of Trofim Lysenko, who threw his nation back to Lamarck's idea that life experience imbues heritable traits, and who by applying it to agriculture brought famine.

Even before the culture storm when "Origin" knocked *Homo sapiens* off of its pedestal, biology was splitting into camps: those interested in anatomy and physiology, and the field naturalists. By the 1840's the camps talked past one another. Mayr said that after 1859, the functional biologists explored laws and quantity, like physicists. The evolutionary biologists asked about history and selective value, more like behavioral and social science. The two competed for talent and resources, and they fought over theory. Among evolutionists after 1880 came further branching. Some saw heritable traits acquired over lifespan. Some saw what an organism passes on as set from the start. Darwin mostly went this way, but allowed for some trait acquisition by "pangenesis," with cells throughout the body picking up hereditary material and sending it by blood to reproductive cells. A German named August Weismann would have none of this "soft inheritance." He adopted an uncompromising selectionism, which came to be called neo-Darwinism. Weismann was first to advocate sexual recombination's extraordinary power to create genetic variability for natural selection to act on – that this was the very purpose of sex. Biology also split into specific fields, distancing experimentalists, who looked into cells, and naturalists working with whole organisms.

Fossils and crushed shells make Monument Rocks a chalky epitaph to Kansas as ocean millions of years ago. Similar layers in a cliff off

The experimentalists missed seeing the importance of diversity, but with better microscopes they leapt in exploration of cells. They witnessed and came to understand fertilization. And though they didn't yet speak of genes, a word born in 1913, they concluded that hidden in the nucleus was an organism's genetic material.

Looking at a species and seeing continuous variation within a range, biologists before the turn of the century thought of inherited traits as "blended." The daughter of a long-necked mother giraffe and a normal-necked father would turn out only somewhat long necked. And when that somewhat-long-necked daughter mated with a normal-necked male, their offspring got necks only a little bit long. Generations of breeding would average away the long neck. Like might attract like and preserve a range of neck length. But this could not expand the range, and so allow natural selection to gradually transform a species. A fluke outside the range, a "discontinuous variance," might appear. But as polymath and Darwin critic Fleeming Jenkins said, it would be "swamped by numbers, and after a few generations its peculiarity will be obliterated."

Swamped by such thinking about blended inheritance was an 1866 paper by a monk in Moravia. Gregor Mendel bred thousands of pea plants, to observe traits including height, seed shape, and flower color.

Africa helped Charles Darwin to see how life is a result of long evolution. Ron Schott photo.

These were traits that did *not* blend. Petals were purple or white, never pink. When white was bred to white, the offspring all were white. The offspring of purple by white all were purple. But self-pollination by the new purple generation made offspring at a ratio of roughly three purple to one white. Mendel saw that each trait is controlled by two "heritable factors," what later were called alleles. If these differ, one is dominant, and shows in the organism. One is recessive and won't appear unless both of an individual's alleles are recessive. And parents deliver alleles to offspring randomly.

Darwin reportedly had Mendel's paper, and forayed independently and briefly with breeding the same pea species. Mendel had "Origin" in his 20,000-volume library. (He became his monastery's abbot.) But Darwin didn't make the connection of his theory with Mendel's finding, and Mendel wasn't interested in evolution. "If Darwin had read Mendel's paper, or if Mendel had had the facilities and opportunity to extend his work, the whole history of evolutionary studies might well have been very different," wrote John Timson, for the Galton Institute.

This organization took its name from Darwin's cousin, Francis Galton. Galton was the man who made fingerprinting almost infallible for identification. He also thought virtually everything quantifiable, assessed womanly beauty with a pocket scale, and campaigned for eugenics to keep the British great. Whatever one might think of his social values, he was brilliant with numbers. With Weismann and Dutch botanist Hugo de Vries, Larson said, Galton got biologists to think in statistical terms about hard heredity and "discontinuous variations."

De Vries and two other scientists each working independently rediscovered Mendel in 1900. They saw how each parent's contribution of a dominant or recessive allele to make a gene was not an infinitely discrete blending of ingredients, but a discontinuous shuffling of directions. Mendel had been fortunate as the groundbreaker to find traits that were determined simply, such as pea flower color, by one gene. But most traits involve multiple genes, and combinations can make variations across a species, such as height in humans, appear continuous. Swedish biologist Herman Nilsson-Ehle calculated that if 10 genetic factors affect a trait, variations might number 60,000. The fineness of those increments could *look* like blending.

The Mendelian view fit well for those who still saw sudden change – mutation – as the only event necessary to make a new species, even without Cuvier's catastrophes. T. H. Huxley, Darwin's contemporary and "bulldog" in defense of evolution by common descent, stuck with this idea of sudden innovation rather than accept natural selection from continuous variation in form. "Nature does make jumps now and then," he said. Decades later, de Vries said individual variation is irrelevant to evolution, that natural selection is inconsequential, that all evolutionary change is due to sudden, large mutations, and that species have periods of being changeable and periods when they are not. Mayr called de Vries a brilliant physiologist and geneticist, who offered the most sensible and prophetic discussion of the problems of inheritance before 1900. But he said the botanist violated all canons of science when he perceived wild variation in flower color and stem shape in his study plants as mutation leaps, when they were only normal variation in highly complex hybrids. De Vries said species-creating mutation didn't follow Mendelian principles, and his ideas were prominent in biological thinking until 1910. A leading textbook summed: "Species arise by mutation, a sudden step." Zoologist William Bateson considered it a marvel that natural selection ever appeared acceptable.

But Bateson and others who began calling themselves geneticists thought a species could arise without ignoring Mendel. Freed of blending's limits and mean, they said that a genetically based variation, if dominant, could avoid swamping and sweep through a population. They saw that even a recessive mutation could persist.

Still, they thought natural selection at most culls grossly unfit changes, and that self-propagating mutations could bring evolution without complement. And despite enthusiasm for Mendelism, Larson said, these scientists rejected genes as material particles on chromosomes, speculating instead about immaterial waves or energy states.

A Kansan with grasshopper cells under the microscope found otherwise. Walter Sutton would soon quit genetics to be a surgeon. But while in college just after Mendel's rediscovery, he pointed out that hypothetical Mendelian factors behave like chromosomes, coming in mated pairs, with one mate from each parent. German biologist Theodor Boveri had shown in sea urchins that embryo development required all chromosomes. Perhaps, the men noted independently, chromosomes carry Medelian factors.

Proof came from another man who ignored natural selection. Thomas Hunt Morgan was a strict empiricist, who thought attempts of explanation outside laboratory tests were mere speculation. Morgan and his students confined their study to the "flyroom" at Columbia University. But in it they bred fruit flies by the tens of thousands. And in one pedigreed group of the red-eyed *Drosophila melanogaster* appeared a single white-eyed male. Mating the precious white-eye with its red-eyed sisters, Morgan found that although first generation progeny were all red-eyed, in generation two appeared more white-eyed males. The white eye was a recessive trait that must have come from a sudden change in a red-eye gene. It also must have been on one of the chromosomes that determine sex, since the white eye didn't appear in females. Morgan soon found other sex-linked recessive mutations, for stunted wings and yellow color. He saw that the changes stuck through succeeding generations unless there was another mutation, one that reversed the first. These changes are rare. Genes are almost completely stable. Mayr said this was final proof for "hard inheritance" and against the passing along of acquired traits. Morgan won the Nobel Prize, the first for an American biologist.

Morgan was "brilliantly successful" where de Vries, Bateson, and others had failed, Mayr said, by looking in the lab for the simplest possible explanation rather than speculating on laws of inheritance and trying to figure the physiology of genes – though he rightly called them "like beads on a string." And what he found was not de Vries' wholesale mutation of new species, but change bit by bit. But lab scientists still ignored natural selection. "Nature makes new species outright," Morgan said.

Naturalists, in actual fields and streams, continued to find this unacceptable. Over 50 years they had made great progress observing the nature of species and geographic variation. Most importantly, they'd developed thinking about variation not just as it occurred in individuals, but in populations. If a population ranges around a hypothetical norm, and more individuals survived at one end of that range than at the other, then the norm would shift – perhaps to make a new species. Darwin and Wallace, the other originator of natural selection theory, already saw this way. But they lacked the statistical power to demonstrate.

The idea that Darwinism and Mendelism equals evolution came as early as 1902, Larson said, but bitter rivalry delayed development for two decades. Naturalists saw the important dimensions of geographic space and time, but held wrong ideas about inheritance. Experimentalists discerned the value of gene frequency in closed, one-dimensional gene pools, but ignored populations. Mayr called the result a "deplorable communication gap." A resolution was reached through the universal language of math.

J. B. S. Haldane was a discipline crosser who explained how enzymes work according to thermodynamic law and illustrated the chemistry of respiration. He also analyzed shifts in a species called the peppered moth. This insect had been studied around Manchester since 1848. At that time, less than 1 percent of the moths were black. Then the industrial revolution decimated lichens that had camouflaged lighter moths from birds. By 1898, 99 percent of the moths were black. Haldane calculated that without selection by the birds, mutation from speckled to black would have been required in one in five moths – a rate impossibly high. But he said the switch could have occurred by selection if darker color improved chance of survival 50 percent. He said that even a slight competitive advantage would, like compounding interest builds a bank account, come to dominate a population over generations. He didn't prove that natural selection drove evolution. The darker moths were not new species. But he encouraged thinking about extrapolation.

Like Galton, Haldane advocated eugenics. He suggested that reproduction be limited to the best thousandth of humanity. Perhaps seeing himself in that cream was Ronald A. Fisher, who fathered nine children, and for whom Larson said the aim of "breeding better Britons" was one of two life-shaping traits. The other was a "stunning facility for mathematics." Fisher saw that the way to unify biology lay in discerning by math what in variation came from genes and what came from environment, and statistically understanding how multiple genes make the variation across a species population seemingly continuous. He showed that the greater the benefit from particular genes in a given environment, the faster their frequency would increase in a population. Change the environment so that different genes become more helpful, and the gene frequency will shift. Evolution acts through gene selection to continuously and finely adapt organism to environment.

The dozens of calculations in Fisher's groundbreaking 1918 paper, "The correlation between relatives on the supposition of Mendelian inheritance," ran up to five lines, and beyond many biologists. But they found understanding through a metaphor from cartography.

With Haldane and Fisher, American Sewall Wright is considered a co-founder of population genetics. In trying to understand evolution, the English mathematicians stressed large, genetically varied populations. Wright focused on small, genetically restricted ones, inbreeding guinea pigs and shorthorn cattle at the Agriculture Department and the University of Chicago. In addition to his own challenging math, he imagined a contour map called the "adaptive landscape." In it, natural selection drives populations up slopes toward peaks whose elevation designates fitness. At a species' geographic fringe a subpopulation might become isolated and be small enough that inbreeding increases expression of recessive traits. This change pushes the group dangerously down the fitness slope, and away from kinship with the mother population. But if it survives and expands, further random genetic changes and natural selection lifts the subpopulation back toward peak fitness – perhaps even above the original elevation. If the instigating isolation disappears and the groups reconnect, now they are so different that they cannot or will not intermate. They are separate species. Competition pushes them toward even greater genetic division, as they pick different foods and niches. Or the upstart topples the old school.

Fisher and Wright quarreled, and evolutionary biologists today fault metaphor details. But for a man who enjoyed the unusual vantage of standing in both the naturalist and geneticist camps, the adaptive landscape was, in his own words, love at first sight. Theodosius Dobzhansky said Wright's picture was not just imaginary: "On the contrary, it is very frequently encountered in nature." Dobzhansky became the man most credited with finally knitting biology's modern synthesis.

The Soviets shrouded Russian genetics from outsiders. But until state support of the Lamarckian ideologue Lysenko, it developed along lines parallel with the United States and Britain. In the 1920's Russia might have had more geneticists that the rest of continental Europe put together, Mayr said. Among them, Sergei Chetverikov pioneered the idea that recessive mutations create hidden reservoirs of genetic diversity on which selection can act when conditions warrant. He could have been recognized as a co-founder of population genetics. He led in seeing traits inherited not from one gene but their aggregate, and that no gene has a constant value for fitness, because how it acts depends on surrounding genes. Visits to Chetverikov's Moscow lab influenced Dobzhansky's thinking, which began with observation of nature as a boy, when he collected butterflies, and continued as a teen-ager studying beetles. The Ukrainian moved on to study fruit flies in Leningrad, and upon moving to the United States in 1927, he landed in Morgan's "flyroom."

Then, most biologists assumed that the genes of all species members were practically identical. This could be seen in lab populations. But when Dobzhansky traveled from Canada to Mexico to study wild fruit flies, he found that each population bore chromosome markers distinguishing it from other populations. He realized that what separated species were not cookie-cutter genes, but sex: a species is simply a group whose members reproduce among themselves. Dobzhansky ran fly experiments showing genes carried by one species clash with the genes from another species. But within a species can be considerable gene variance to select from.

In "Genetics and the Origin of Species," in 1937, Dobzhansky translated the abstract population genetics theorems of Haldane, Fisher, Wright, and Chetverikov into a working, popularizing explanation of how that genetic variation feeds evolution. He highlighted the variability hidden in recessive genes and the effect of isolation, and could see the results as a naturalist. In his preface, L. C. Dunn said the book symbolized "something which can only be called a Back-to-Nature Movement." And as the synthesis shifted more attention from genetics to natural selection, Dobzhansky tried to show that having two different alleles rather than two identical ones – genetic diversity – benefited both the individual and the population.

Variety is not just the spice of life, it's the engine. From the first strings of nucleic acid to millions of species, evolution built an economy of increasing power. It is like the capitalist juggernaut, but unlike our industrialism it runs on energy dependable for billions of years, and with a recycling program to match. Mayr the scientist stressed that variation characterizes all nature. He called diversity the basis of ecosystems, the cause of competition and symbiosis, and what makes natural selection possible. Diversity has occupied man's mind from the start, he said. Hunter-gatherers are preoccupied with natural variation, and expert on those parts of it important to their lives.

The variety of life has made life productive, but each species can do only so much with what's around it. So each fills a spot where another comes short, even growing shoulder to shoulder with others, as in a prairie. "Commensalism," early ecologist Eugenius Warming of Denmark called it: several species sit at the same table to eat, but rather than fight over a common dish, they complement each other's diet, each feeding on what the other doesn't want.

The key is not just niche-filling, but interlocking; not just the economical, but an economy. "The bedrock idea upon which Darwin built, though he never isolated it as such, was that all survival on earth is socially determined," Worster said. "Nature is 'a web of complex relationships,' he wrote, and no individual organism or species can live independently of that web." Even the most insignificant creatures are important to the welfare of conjoining species. Gilbert White, amateur naturalist and an inspiration for ecology, saw this as early as 1789 in "The Natural History of Selborne": "Thus nature, who is a great economist, converts the recreation of one animal to the support of another!"

Two centuries later, in the essay "Ecology, the Subversive Science?" Robert

London's Abney Park was a garden cemetery in Charles Darwin's days. Now it is a nature reserve. Men set stones; plants and weather

E. Ulanowicz tried to shake ecology free of a Newtonian perception of living systems as closed, deterministic, and "reversible" mechanisms. He saw that how species relate is not entirely predictable, and can evolve structures with effects larger than their players, such as bacteria and legumes trading nitrogen for sugar to build fertile soil. He said this long, elaborate history cannot be rewritten: a species or an ecosystem gone is gone forever. But an emergent structure affecting the world around it can outlast participants within it when they are replaced by others, just as we remain who we are even while all of the atoms and cells in us come and go. Conversely, unlike in the Newtonian view of seeing all change working from the bottom up, change can come from the top. So ecologists think not just of genes and species, but of their system, such as the forest and grassland, or agriculture, the common replacement for each.

But for the third chapter leading to that view – for the unpredictable, primary source of biological variation over 3 billion years on Earth – look nearer the bottom, for when two molecules stray from established place.

3 The search for the nuts and bolts of heredity finds that we and the millions of other species are writ by a common handful of chemical letters.

Scientists as early as the late 1800's suggested that cells held genetic material in complex compounds called nucleic acids, but the idea didn't gain favor. Frederick Griffith steered back toward it in 1928 while working for the British health department with the germ that causes pneumonia. One

make with them soil and life. Tom Simonite photo.

strain of pneumococcus was virulent, the other not, with predictable results in laboratory mice. The virulent strain could be made harmless by killing it with heat. But when the dead bacteria were injected along with the nonvirulent strain, mice died. Griffith thought the dead germ had passed to the other type its lethal trait; in the blood of the dead mice, the virulent strain was alive. American Oswald T. Avery suspected that Griffith hadn't controlled the experiment well enough. But he replicated the results, and by process of elimination of cell chemicals, reported in 1944 that the means of "transformation" was through one: deoxyribonucleic acid. "How could this seemingly simple molecule carry the entire information in the nucleus of the fertilized egg to control the species-specific development of the resulting organism?" Mayr said. Laboratories raced for the answer.

Briton Rosalind Franklin advanced the search by making a skilled X-ray photograph of crystallized DNA. Without her permission, colleague Maurice Wilkins shared the unpublished picture with James Watson, who later wrote that "my mouth fell open and my pulse began to race." The image revealingly indicated arrangement of facing spirals. Coupling that key to Austrian-American Erwin Chargaff's discovery in the 1940's of how DNA apportioned molecules of adenine, cytosine, guanine, and thymine, Watson and Francis Crick built a model with the four chemicals paired as rungs, A with T and C with G, connecting the double helix. And in 1961, American Marshall Nirenberg discovered that the molecule pairs work in triplets, or codons, each like a letter in a code.

The code makes for thousands of biological compounds. Most are aggregates of limited number of elements, mainly carbon, hydrogen, oxygen, sulfur, phosphorous, and nitrogen. But they have extraordinarily specific and often unique properties. For building with them, the possible sequence of codons makes for near infinite variety: millions of species, and among them uniquely varying individuals. The code's universal basis supports Darwin's idea of a common ancestor for organisms from bacteria to blue whales. Its arrangements among species show the branching connections.

In humans the code has stretched to about 3 billion base pairs of AT and CG. Even with scripts much shorter, and with some of the code dedicated to detection and correction, there are typos. One pair out of place is a mutation. The result might be inconsequential, or it might be fatal. Or it might add a neck vertebra for giraffe's edge at nibbling tree leaves. This comes with a tradeoff in speed or nimbleness. Mayr emphasized that the whole organism is what matters for success – "Selection cannot produce perfection" – and that the results of sexual recombination are far more important than mutation. But mutations are beginnings.

"For those not studying biology at the time in the early 1950's, it is hard to imagine the impact the discovery of the structure of DNA had on our perception of how the world works," E. O. Wilson, ant scientist and promoter of "sociobiology," wrote in his autobiography, "The Naturalist." "If heredity can be reduced to a chain of four molecular letters – granted, billions of such letters to prescribe a whole organism – would it not also be possible to reduce and accelerate the analysis of ecosystems and complex animal behavior?" Larson said, "This surprisingly simple, highly elegant structure shed new light on the mechanics of evolution by suggesting how genetic reproduction, inheritance, and variations operated at the molecular level." And: "Traditional ways of studying evolution suddenly seemed terribly old-fashioned."

The new ascendant of biology was the workings of molecules. This has served as a license to, in the words of Richard Levins and Richard Lewontin, place priority on parts over wholes. There is little wrong with being reductive so long as it doesn't lead to seeing the world as like the method. Some scientists, including Mayr and Wilson, thought molecular genetics too narrow to cover all aspects of evolution. "For a full understanding of living phenomena every level must be studied but … the findings made at lower levels usually add very little toward solving the problems posed at the higher levels," Mayr said. He went on to quote the painter Georges Braque: "I do not believe in things, I believe only in their relationships."

4 More than a century and a half of growing and merging scientific knowledge could shake up agriculture as it has the field of medicine.

Each of the previous changes that scientists at The Land Institute call the three syntheses – Darwin, Dobzhansky, DNA – catalyzed investigation and understanding. They changed worldviews. And the last of them is used in medicine and industry. "But agriculture gained little, and has withdrawn more than ever from its ecological context," wrote the institute's Wes Jackson and Stan Cox, with colleague Tim Crews, in a proposal for a "fourth synthesis." "For example, crop rotations and animals on the farm have declined. In the central US ecologically impoverished annual grain monocultures continue to present a striking contrast with the remaining islands of native prairie. In spite of all of our accumulated knowledge, numerous studies of soil erosion and water contamination attest to this dire gap."

In Central America came a study that the scientists cite for an example of tying everything together for agriculture. Over decades there, slash and burn farming with ever shorter recovery by the forest means fewer nutrients left for crops. Yields fall, while soil erosion and nutrient leaching rise. Jack Ewel and colleagues built in Costa Rica an artificial community with as many species of plants and in the same proportions – herbs, trees, and so forth – as the complex natural community. Some were domesticated, some wild, but none were native to the site. The natural community that Ewel had planted for comparison changed rapidly, and beat the mimic in production of biological mass. But by the fifth year productivity of the mimic came to more than 90 percent of the model. In a pest outbreak, the mimic fared worse than the natural vegetation. But both communities lost leaf tissue to insects at about the same rate. Within two years, the rates of nutrients leaching from the soil were indistinguishable. The mimic was as water-tight as the model. An adjacent plot of bare soil lost water 50 percent faster. Nitrogen faded 10 times faster.

The gains came from an arrangement too diverse and demanding for a farmer. But Ewel concluded that simpler communities might provide many of the same benefits with the right plants. Diversity helps slow pests and can cut fertilizer needs. Agriculture might enjoy most of the advantages of a native economy with as few as two perennial crops, Land Institute scientists say, a cereal and a legume to fix nitrogen.

But to develop those crops and economies for the world's diverse lands will require more than what can come from the institute, which is dealt the particularities of the good soil and hard temperate climate of central Kansas. Places widely vary, and crops must vary to fit right and work well. The institute's 30-year plan would enlist about 20 institutions across some 10 nations. It would employ not just plant breeders, but molecular geneticists, modelers, cropping system specialists, soil scientists, pathologists, and entomologists. Each would be a member of a network working with the same crop, able to share seed and data.

John Ziman called similar information-building by journal publication of fragments of scientific work possibly the "key event in the history of modern science." What Land Institute scientists see would be less fragmented, more intentional. Its success could use less of the time-consuming conflict waded through from the parlor of the Victorian naturalist to the steps of the double helix. It could use more of the kind of cooperation described by one of T. H. Morgan's flyroom colleagues, Alfred H. Sturtevant. "There can have been few times and places in scientific laboratories with such an atmosphere of excitement and with such a record of sustained enthusiasm," Sturtevant wrote. "This was due in large part to Morgan's own attitude, compounded of enthusiasm combined with a strong critical sense, generosity, open-mindedness, and a remarkable sense of humor."

That lab's results, and those of thousands of other scientists over more than two centuries, support what The Land Institute and a few others are working for. And now these plant researchers enjoy techniques of precision and speed far beyond those known to Sturtevant in the early 20th century, or even Mayr at its end. That "most social of all social animals" could for the first time join agriculture and the natural economic culture in a beautiful, balanced arch.

Now, if the cooperation of some thousands of millions of cells in our brain can produce our consciousness, a true singularity, the idea becomes vastly more plausible that the cooperation of humanity, or some sections of it, may determine what Comte calls a Great Being. – J. B. S. Haldane

BEDFELLOWS AND COMMUNITIES

WES JACKSON, STAN COX, AND TIM CREWS

The discipline of agronomy is coping as well as it can in areas where nature's ecosystems have been impaired or destroyed. Grain agriculture has been a 10,000-year-old success story, but only on its own terms and at an incalculable ecological and human cost. It has "progressed" by way of single solutions to single problems, too often ignoring natural and social contexts. Agronomic successes in industrial societies, however, have depended on fossil fuel subsidies provided by an industrial, growth-oriented economy. The demand for more production at any cost too often has dominated. A shift to the ecosystem approach of perennial polycultures will show the current agronomic tradition to be incompatible with sustainable food production.

During the last few decades, the third synthesis – that of ecology/evolutionary biology and molecular science and engineering – has failed to make the changes that will be possible with polycultures of perennial grains. The genetic engineers and genomics scientists, in part because they are unencumbered by previous agricultural-research, are now seeing perennialism as a good idea. They see this not only because perennialism is a solution that was arrived at through natural selection over vast amounts of time in multiple taxonomic groups, but also because it holds the promise of improving several important agronomic functions – which is also to say that it might be profitable to agribusinesses. For the time being, there seems to be an overlap of interests between those who want to work and think within the limits of ecosystems, and those who are looking to mine ecological ideas that, from an industrial perspective in 2012, appear valuable.

How long will these bedfellows get along? Once we have perennial crops, will genetic engineers and ecological researchers, working together, accept the evolutionary constraints in constructing a multiple-species perennial-cropping system? [Crop threats such as] nematodes, mycorrhizae, and predatory mites have arrived at their current state by trying many alternative evolutionary pathways. There is no reason to expect that their behaviors will be ideal in service of the narrowly defined goals of agriculture. However, if we decide to trust natural selection and ecosystem development to provide answers to countless questions we don't even know to ask, then the processes and functioning of natural ecosystems will guide the design of *plant communities* as the basis of agricultural production.

By adding perennial grains to the human inventory of crops we will accelerate the necessary fourth synthesis – necessary because soil is as much of a non-renewable resource as oil, and for future food supply, soil is far more important.

From "The Next Synthesis," a proposal for a world effort to develop perennial grains grown in mixtures.

Workers for Gurukula Botanical Sanctuary attach orchids to a tree in what was clear-cut forest. Gurukula's Suprabha Seshan, a former Land Institute intern, calls the restoration 3-D gardening. Photo courtesy of the sanctuary.

ECOSYSTEM GARDENING

SCOTT BONTZ

In an Indian forest so wet that tree branches host orchids which never touch the ground, a dozen women in saris as brilliant as the flowers comb ground clear-cut for plantations, and climb the trees marked to fall next. Their mission is botanical search and rescue. They take plants home to nurture, and return them to repair damage. "Rainforest etiquette in a world gone mad," is how Suprabha Seshan described the operation at Gurukula Botanical Sanctuary.

In modern society, etiquette is almost a prison, Seshan said during a late October visit to The Land Institute, where she was an intern. In nature, she said, etiquette is attunement. "We've lost the code of behavior of plants and animals and humans," she said. Gurukula means family of the teacher, and in this case the teacher is nature. The effort begun by a German dropout has foster-mothered more than 1,600 species, compiled 30 years of notes about the plants and their ecosystems, and increasingly shifts the plants out of rehab to restore land. Gurukula's search is as much a spiritual as scientific, Seshan said. The world has many botanical gardens. She said only Gurukula is a botanical sanctuary.

Seshan was from Bangalore, 13 degrees from the equator and then a city of 4 million, when in 1990 she visited Scotland's sparsely populated Orkney Islands in the North Sea. She was on a wilderness search and, for the Royal Society for the Protection of Birds, surveying local feelings about conservation. In a little Orkney bookstore she found a selection from middle ground. "Meeting the Expectations of the Land" introduced her to the idea of agriculture mimicking natural ecosystems. She already knew of one of the writers, Wendell Berry. She hadn't known of another, Wes Jackson. But after phone calls she signed up for a yearlong internship at his Land Institute. Aside from on the bus from New York, she saw nothing else of the United States. But in Kansas she soaked up the philosophy of looking to nature for answers about how to farm and live. And when she took this thinking back to India, Seshan said, "It was shocking to me that there, 300 kilometers from my hometown, the same questions were being asked." At Gurukula is where she has stayed, supplying education, public relations, administration, and activism.

On Halloween, three days after her return to The Land Institute, demographers reckoned that Earth's human population reached 7 billion. There's a good chance that the milepost baby was born in India, with more than one-sixth of the world's people and growing at about 1.4 percent annually. The nation has almost four times as many people as the United States on about one-third the land area. Seshan's pictures of the country around Gurukula show an often still naturally beautiful mountain landscape. But shot through it are plantations, growing population, and hydroelectric power projects that break up habitat, overgraze grassland, overharvest native flora, and introduce invasive species. "The pressure on the wild is enormous when all that's left are small pockets … a few hundred acres here, a few hundred there," she said. Despite conservation work, habitat loss and poaching since the 1990's have cut by more than half the nationwide wild population of Bengal tigers, to about 1,700. And the land around Gurukula can no longer support indigenous people who for millennia were self-reliant. Seshan said rice is brought to them, furthering their alienation from the land.

The wild that's left in that land fits Gurukula. The Western Ghats, a range running 1,000 miles along the west edge of the subcontinent to its southern tip, is considered one of the world's most threatened but biologically rich regions, with 5,000 floral species, 600 of them used for herbs or medicine, plus 1,000 ferns and mosses. Kerala, one of five states along the range, and Gurukula's home, has 600 kinds of trees. Seshan described block mountains graced varyingly with grasslands, dwarf woods, dry deciduous forest, bamboo breaks up to 60 feet tall, and rainforest fogged in for eight months of the year. That's where orchids perch. "It's an amazing world up there," Seshan said.

To this in 1968 came a young German, Wolfgang Theuerkauf. He was disenchanted with the hippies and the reds, and just wanted to be alone and live simply. But he has since become one of India's leading orchid specialists, Seshan said, and the sanctuary he established has under its care 700 orchid species. Gurukula has restored to land more than 400 plant species, including 100 kinds of trees. The sanctuary has grown to 62 acres as supporters bought up land around the original 15-acre trust of Theuerkauf and his Indian colleagues.

About a dozen local women at a time work for the sanctuary. They learn ecology, and how to grow the plants. The work seems to take a female attitude, Seshan said. The sanctuary allows women to explore life outside India's status quo. They've seen no college, but Seshan said two have become experts at finding and distinguishing species among the region's great diversity, and then nurturing and finally restoring the plants to wrecked land.

The sanctuary's database is not secondhand compilation of other collections, but the product of 30 years of its workers' own observation on the ground. "We keep good track of our plants," and must know them well, Seshan said. What looks like a weed to some might be the rarest plant in the mountains. Sanctuary work has grown from search and rescue to documentation and study, and to education and consultation. Gurukula talks with botanists around the world, and advises the Indian forest service on restoration. It tells how to strengthen biodiversity, restore ecosystems, and still meet human needs. It teaches farmers about the plants and how to raise them. Seshan said that the most important education is with children, and that most learning comes when people visit the sanctuary. "The best teaching tool is the place itself," she said.

Though the human population keeps expanding, Gurukula increasingly plants out rescued species rather than just sustain them at home. The sanctuary wants entire habitat reconstruction, not just plants in pots. "Is this a forest or is this a garden?" Seshan said while showing a picture of native plants richly restored to land that had been scraped raw. "We want them to merge," she said. "We're called ecosystem gardeners."

This is not all nature for nature's sake. Lichens of the Western Ghats are used for medicine and dyes. Fewer than 100 of the flowering plants that contribute to herbs and medicine have been domesticated, and just 50 to 60 can be raised at crop scale, Seshan said. The rest can't grow well without the supporting environment of the native stage. India has about 17,000 floral species, she said, and about 8,000 of these have human uses. So, for a model and direct support of their lives, humans would do well to look out for nature. "What everyone can do is take care of the land, bring it back to health," Seshan said.

Freed of pressure, the land will come back on its own. Seshan showed pictures of rainforest springing back. But pressure is on, and she said, "The worse the pressure, the longer it will take." So Gurukula rescues orchids from felled trees and climbs to place them in branches of the living.

At the Land

THE WILD SUNFLOWER ALSO RISES

Seed size and seeds per stalk on Maximilian sunflower, a perennial native to prairie, increased again in the latest three-year cycle of selection begun in 2002 by Land Institute researcher David Van Tassel. Even considering the limitations of his comparison – populations of different sizes and genetic structure, grown in different locations and years, and with different spacing and harvesting methods – Van Tassel said progress is clear. Measurement showed that single-seed weight since the program's start is up 50 percent, and seed weight per stalk has roughly doubled each cycle. Seed weight harvested per ground area has quadrupled. In early years the average seed per stalk was dragged down by most plants yielding poorly. Now more stalks yield nearer the middle of the range and make a flatter curve.

In 2007, Van Tassel found a plant growing stalks with a single head, like a commercial sunflower. Wild Maximilian branches profusely. With breeding from this anomaly seed size has increased, presumably because of the bigger heads that come with fewer branches. The total seed weight per stalk in these plants is lower than in Van Tassel's improved, normal-branching populations, but he hedges his bets by taking more than one path. Single-head stalks initially suffered greater sterility. But there were enough plants of decent fertility to pick from, so by 2011 sterility fell, and some per head yields broke records in Van Tassel's books. Yield of annual crop sunflower remains several times higher, but the gap narrows.

This year Van Tassel is adding to his tools statistical method being refined by Lee DeHaan, The Land Institute's developer of intermediate wheatgrass, another wild perennial. Wheat breeder Shuwen Wang is showing both of his fellow researchers how to speed selection by reading their plants' chromosomes.

PRESENTATIONS

The December issue of Scientific American magazine devoted a page to perennial grains in a collection called "10 World Changing Ideas." In the cover story of the October 20 science magazine Nature, use of perennial grains is among tactics offered to meet the world's growing food demand while avoiding further degradation of land by agriculture. The analysis, "Solutions for a Cultivated Planet," is by a dozen scientists from North America and Europe. Land Institute staff members spoke in Texas, New York, Colorado, Indiana, California, Georgia, and Iowa. Upcoming events: May 11, Claremont, California. May 19, Deerfield, Illinois. June 11-13, Fayetteville, Arkansas. August 8, Winnipeg, Manitoba. September 13-14, Lisle, Illinois. The Land Institute will present its annual Prairie Festival September 28-30. For more, call 785-823-5376 or see Calendar at www.landinstitute.org.

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In the time when Dendid created all things,

He created the sun,
And the sun is born, and dies, and comes again;

He created the moon,
And the moon is born, and dies, and comes again;

He created the stars,
And the stars are born, and die, and come again;

He created man,
And man dies, and never comes again.

– Old song of the Dinka people in Sudan,
as presented in “The Unwritten Song,”
edited by Willard Trask

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