ENERGY

THE FALSE PROMISE OF BIOFUELS

The breakthroughs needed to replace oil with plant-based fuels are proving difficult to achieve

By David Biello

Photograph by Levi Brown

RANGE FUELS WAS A RISKY BUT TANTALIZING BET. The high-tech start-up, begun by former Apple executive Mitch Mandich, attracted millions of dollars in private money plus commitments for up to $156 million in grants and loans from the U.S. government. The plan was to build a large biofuels plant in Soperton, Ga. Each day the facility would convert 1,000 tons of wood chips and waste from Georgia's vast pulp and paper industry into 274,000 gallons of ethanol. "We selected Range Fuels as one of our partners in this effort," said Samuel Bodman, then secretary of energy, at the groundbreaking ceremony in November 2007, "because we really believe that they are the cream of the crop."

That crop has spoiled in the ground. Earlier this year Range Fuels closed its newly built biorefinery without selling a drop of ethanol. Turning biomass into a commercially viable, combustible liquid is tougher than anticipated, the company has found. As expensive equipment sits idle, the firm is searching for more funding to try to solve the problem.

Range Fuels is not the only biofuels company to fall short. Cilion in Goshen, Calif., Ethanex Energy in Basehor, Kan., and others have gotten out of the business of making biofuels from plant matter because it is too expensive. Despite the best hopes of scientists, CEOs and government policy makers, hundreds of millions of dollars in government money, more than two dozen U.S. start-ups financed by venture capital and decades of concentrated work, no biofuel that can compete on price and performance with gasoline is yet on the horizon.

This failure is particularly discouraging because only a few years ago biofuels seemed like an ideal solution to two big U.S. problems: dependence on oil and climate change. Terrorism and soaring oil prices had made Middle Eastern oil a particular liability, and rising average global temperatures underscored the need to find alternative fuels for automobiles and airplanes. Because biofuels come from plants, which absorb carbon dioxide from the atmosphere as they grow, burning biofuels in vehicles would in theory slow the buildup of greenhouse gases, compared with burning fossil fuels.

The notion that biofuels technology is not living up to expectations may seem odd, given the rapid expansion in recent years of corn ethanol. U.S. production went from 50 million gallons in 1979 to 13 billion gallons in 2010. A government mandate to supply 10 percent of the country's passenger vehicle fuel drove that enormous growth, however, and the product has been affordable only because of massive federal subsidies. Ethanol yields little if any net savings in carbon dioxide emissions. Furthermore, making those 13 billion gallons consumed roughly 40 percent of the nation's corn crop, cultivated on 32 million acres of farmland, pushing up food prices and feeding an enormous "dead zone" in the Gulf of Mexico, where the Mississippi River dumps all the fertilizer that runs off midwestern cornfields.

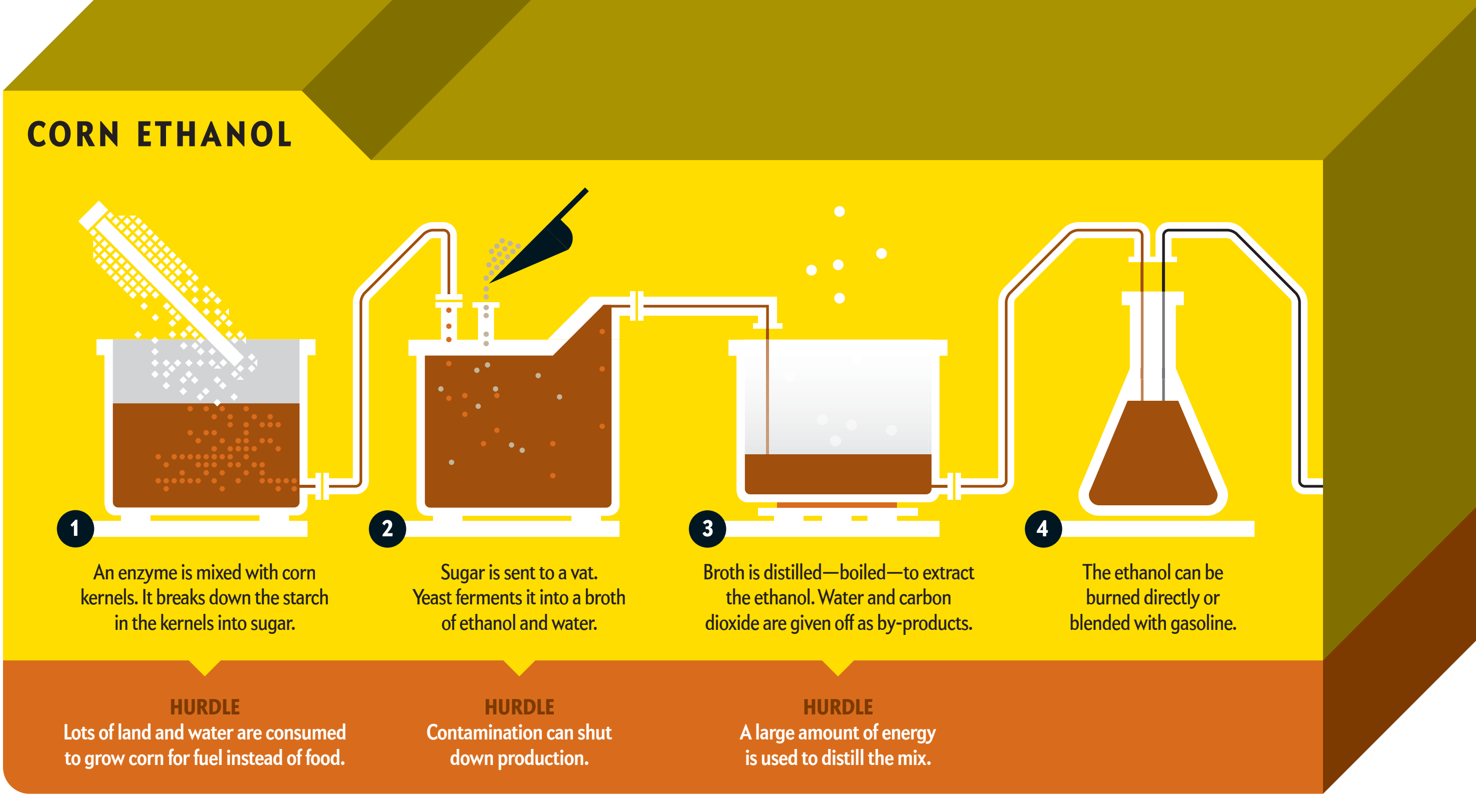
More advanced biofuels made with different processes promised to remedy these flaws. Ethanol could be brewed from sugar derived from the husks and

IN BRIEF

Despite extensive research, biofuels are still not commercially competitive. The breakthroughs needed, revealed by recent science, may be tougher to realize than previously thought.

Corn ethanol is widely produced because of subsidies, and it diverts massive tracts of farmland needed for food. Converting the cellulose in cornstalks, grasses and trees into biofuels is proving difficult and expensive. Algae that produce oils have not been grown at scale. And more advanced genetics are needed to successfully engineer synthetic microorganisms that excrete hydrocarbons.

Some start-up companies are abandoning biofuels and are instead using the same processes to make higher-margin chemicals for products such as plastics or cosmetics.



stalks of the corn plant, rather than the edible kernel, or from similarly fibrous material in grasses or even trees (as in the case of Range Fuels). These plant parts consist of cellulose, which is not used as food for humans nor as feed for animals and therefore would not affect food prices. Liquid fuels could also be harvested from algae, which more efficiently turn water, CO_2 and sunlight into fats that can be converted into hydrocarbons or, more effective still, from genetically engineered microorganisms that could directly excrete hydrocarbons.

None of these advanced biofuels is working at commercially meaningful scales today, however. According to the U.S. Environmental Protection Agency's Renewable Fuel Standard, by 2011 the U.S. was supposed to be producing 100 million gallons of cellulosic ethanol a year. Instead in 2010 the EPA rolled back the 2011 goal to just 6.5 million gallons, and it is unclear whether even that amount will be reached.

Recent experience suggests that the scientific or industrial improvements needed to solve the challenges to making advanced biofuels practical may be extremely difficult to attain. The goal of producing 36 billion gallons of biofuels annually by 2022, set by the U.S. government as a significant solution to energy independence and climate change, looks to be an even more distant prospect. "It's not a simple problem," says microbiologist Timothy Donohue, director of the Great Lakes Bioenergy Research Center in Madison, Wis., one of three Department of Energy labs dedicated to advanced biofuels. "It's no less challenging than doing things with stem cells or other major scientific initiatives this country has embarked on."

CORN ETHANOL: SIMPLY INSUFFICIENT

SO FAR CORN ETHANOL is the only biofuel to reach commercial scale in the U.S., thanks to subsidies that topped $5.68 billion in 2010 alone, according to the White House's Office of Management and Budget. Fermentation is the core technology for making ethanol from corn. Humans have spent the past 9,000 years refining techniques for exploiting enzymes and yeast to ferment sugars derived from corn kernels, sugarcane or other plants into ethanol. To scale up U.S. production over the past decade, an extensive infrastructure of corn mills, stainless-steel fermentation tanks and other equipment has sprung up like mushrooms after rain throughout the Midwest.

Unfortunately, corn ethanol is not very energy-efficient and is therefore not carbon-neutral. Lots of energy is required to distill (basically, boil off) ethanol from the soup of water and yeast in which it has been fermented—energy typically supplied by burning fossil fuels such as natural gas or coal. After all that trouble, a gallon of ethanol supplies a vehicle with only two thirds of the energy in a gallon of gasoline.

Those energy inputs cost money, too, and corn ethanol may never compete on price with gasoline without subsidies. Greater production is also limited by fertile land. In October 2010 the Congressional Research Service reported that if the entire record U.S. corn crop of 2009 was used to make ethanol, it would replace only 18 percent of the country's gasoline consumption. "Expanding corn-based ethanol … to significantly promote U.S. energy security is likely to be infeasible," the researchers concluded.

J. Craig Venter, co-founder of would-be algae producer Synthetic Genomics, puts an even sharper point on the land problem. Replacing all U.S. transportation fuels with corn ethanol, he calculates, would

Lots of energy is required to distill ethanol from the soup of water and yeast in which it has been fermented, energy typically supplied by burning fossil fuels.

Illustrations by Carl DeTorres

require a farm three times the size of the continental U.S.

CELLULOSE: TOUGH TO BREAK DOWN

OF COURSE, using the nation's entire corn crop to make fuel would leave none as food—for people or livestock. That is one reason researchers and policy makers have turned their attention to cellulosic ethanol, produced not from the starchy corn kernel but from the rest of the corn plant—the stover, or "waste"—which would not adversely affect the food supply.

The energy that could be harvested from waste cellulose is potentially huge. According to Oak Ridge National Laboratory, the U.S. could generate 1.4 billion tons of cellulosic material such as corn stover, 80 percent of which could be converted to biofuel, displacing 30 percent of U.S. transportation fuel.

Finding a way to efficiently break down a plant's cell walls is the central challenge. First, there is lignin, the chemical compound that supports a plant's cell wall against gravity and that makes wood indigestible for animals. Then there is the hemicellulose, a long, interlocking complex sugar fiber bonded to the lignin supports that wards off attacking enzymes. Inside these walls is a fibrous core of cellulose—long chains of glucose molecules, simple carbohydrate sugars that hold the energy that will become a biofuel.

One inspiration for breaking through the organic barriers comes from leaf-cutter ants. At the Great Lakes Bioenergy Research Center, leaf-cutter ants mill about in plastic bins, growing fungus caves that turn leaf material into the oils and amino acids that the insects actually eat. Certain microbes in the ants' digestive tract chew up the initial harvest into scraps. Worker ants transfer those scraps into the compost caves. Another set of microbes that the ants deposit converts the scraps, with the addition of water, into lipid droplets. In essence, the ants build an external gut for turning cellulose into fuel—a small model, perhaps, for a biofuels factory.

The lab's goal, Donohue says, "is to either use those microbes themselves or isolate the genetic material that encodes their enzymes and use it in an industrial process to take plant cell walls apart."

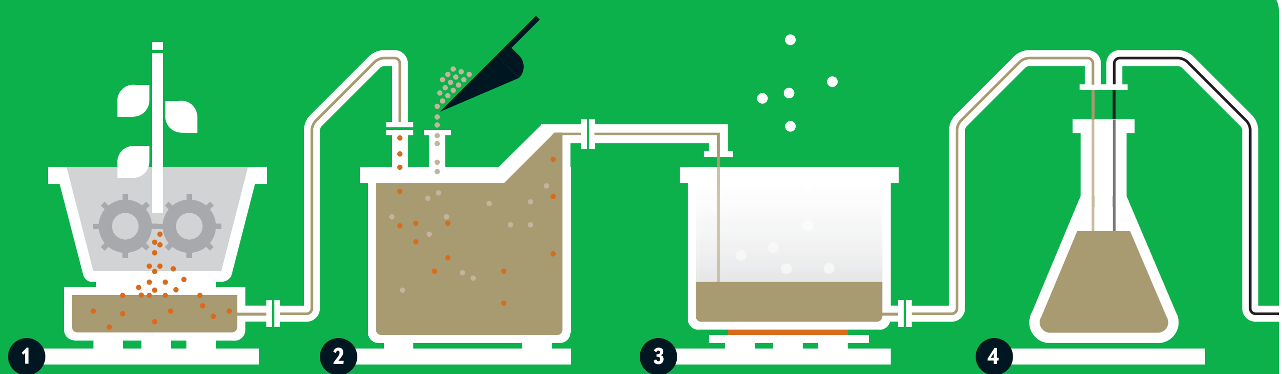
Inspiration also comes from cows, which break down cells by crushing grass between their powerful teeth and washing it in a bath of saliva. In the cow's gut, a slew of microbes ferment the fibrous cud into lipids—the fatty building blocks of fuels. To mimic a cow's chewing, scientists have tried blasting cell walls with steam or bathing them in liquids made up of charged molecules. HCL Cleantech in Oxford, N.C., dissolves plants in concentrated hydrochloric acid to get at the cellulose inside, then recycles the acid to try to keep costs down.

Yet another approach is to use a family of enzymes known as cellulases, such as the enzyme in a termite's gut that turns wood into food. Only one such enzyme is commercially available—from Danish company Novozymes. It costs roughly 50 cents a gallon—more than 10 times the price of enzymes used in traditional ethanol fermentation. "Enzyme costs have to come down, or there will be no industry," admits Cynthia Bryant, Novozymes's manager for global business development.

Codexis in Redwood City, Calif., is trying to build a more affordable enzyme by screening thousands of natural versions and combining their parts into a hybrid that works better in a factory than in nature. The company is also tweaking the genes that cause living cells to create enzymes, hoping to end up with a superenzyme of sorts.

Even a superenzyme will inevitably be slow to break down cellulose because the biological interactions require time to work, making high-volume production difficult. But what if energy crops such as corn or switchgrass could produce these cellulose-splitting enzymes themselves? The enzymes would hide within the plant cell, waiting for heat or some other industrial trigger to set them off, allowing the cellulose to quickly and easily degrade into its component sugars.

CELLULOSIC ETHANOL



1 Acids, enzymes or other methods break down plant matter (cellulose) such as cornstalks or grasses into its constituent sugars.

2 Sugar is sent to a vat. Yeast ferments it into a broth of ethanol and water.

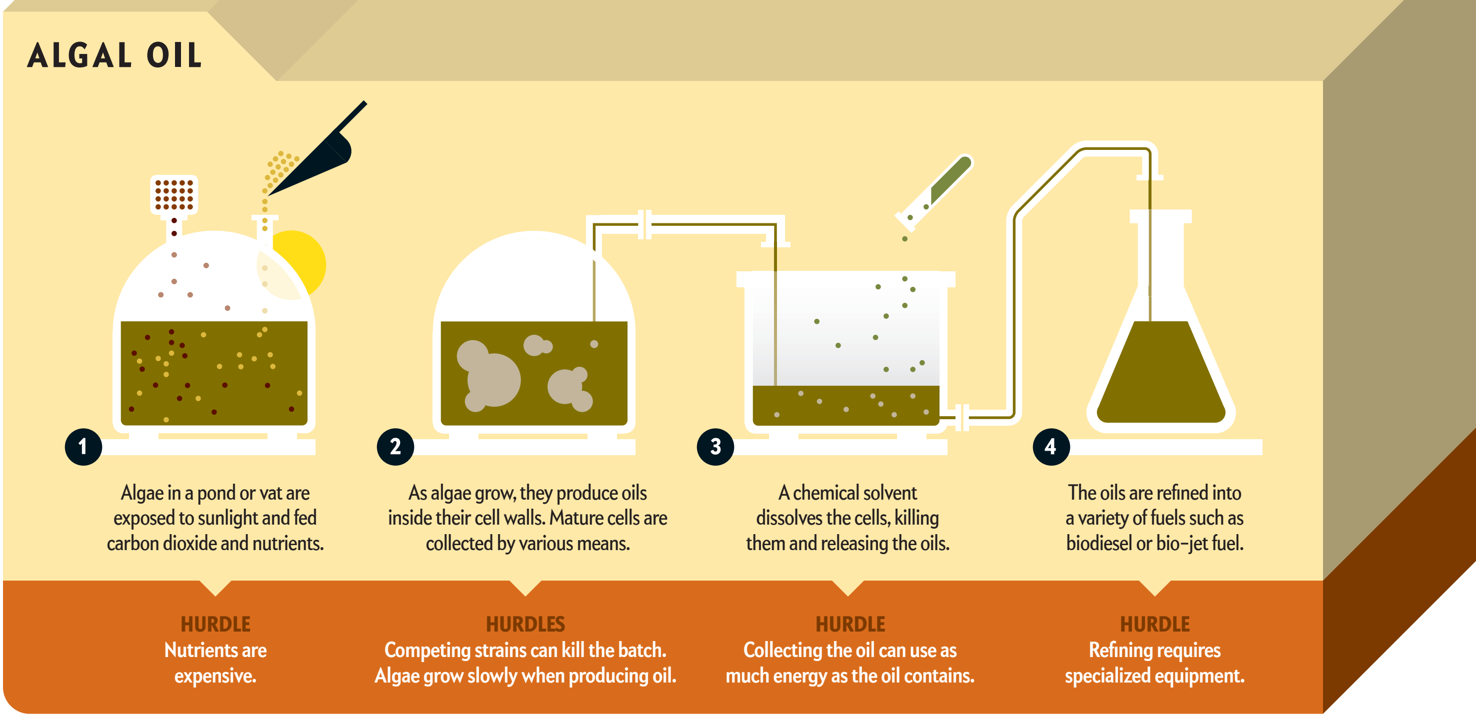
3 Broth is distilled to extract the ethanol. Water and carbon dioxide are given off as by-products.

4 The ethanol can be burned directly or blended with gasoline.

HURDLE Cellulose is difficult and expensive to break down.

HURDLE Contamination can shut down production.

HURDLE A large amount of energy is used to distill the mix.



Swiss agribusiness giant Syngenta has already devised a way to embed enzyme-making capabilities into corn kernels, allowing the kernels themselves to convert starch to sugar when exposed to the right temperature, moisture and acidity concocted in a factory. The U.S. Department of Agriculture has approved the process over objections from environmentalists and food producers such as the North American Millers' Association, and Syngenta's seeds containing the enzyme will go on sale this year.

This work proves the principle, but it does not solve the problems of using corn for fuel rather than food. As an alternative, Agrivida in Medford, Mass., hopes to apply its own version of the technology to cellulose from corn stover or dedicated energy crops such as switchgrass.

Inbred enzymes alone may not make cellulosic ethanol affordable. The sugars that are unlocked "better be one-third the cost of a barrel of oil," says chemist Patrick R. Gruber, CEO of biotech company Gevo in Englewood, Colo., given the cost of then refining the sugar into liquid fuel. Indeed, Gevo and other companies, such as Virent in Madison, Wis., have concluded that even with historically high gasoline prices, advanced biofuels cannot compete as a fuel. The companies are de-emphasizing ethanol as a product, and instead they are altering their processes to turn sugars—whether from cellulose or sugarcane—into industrial chemicals such as precursors for plastics in bottles, which now command prices as much as 10 times higher than fossil fuels.

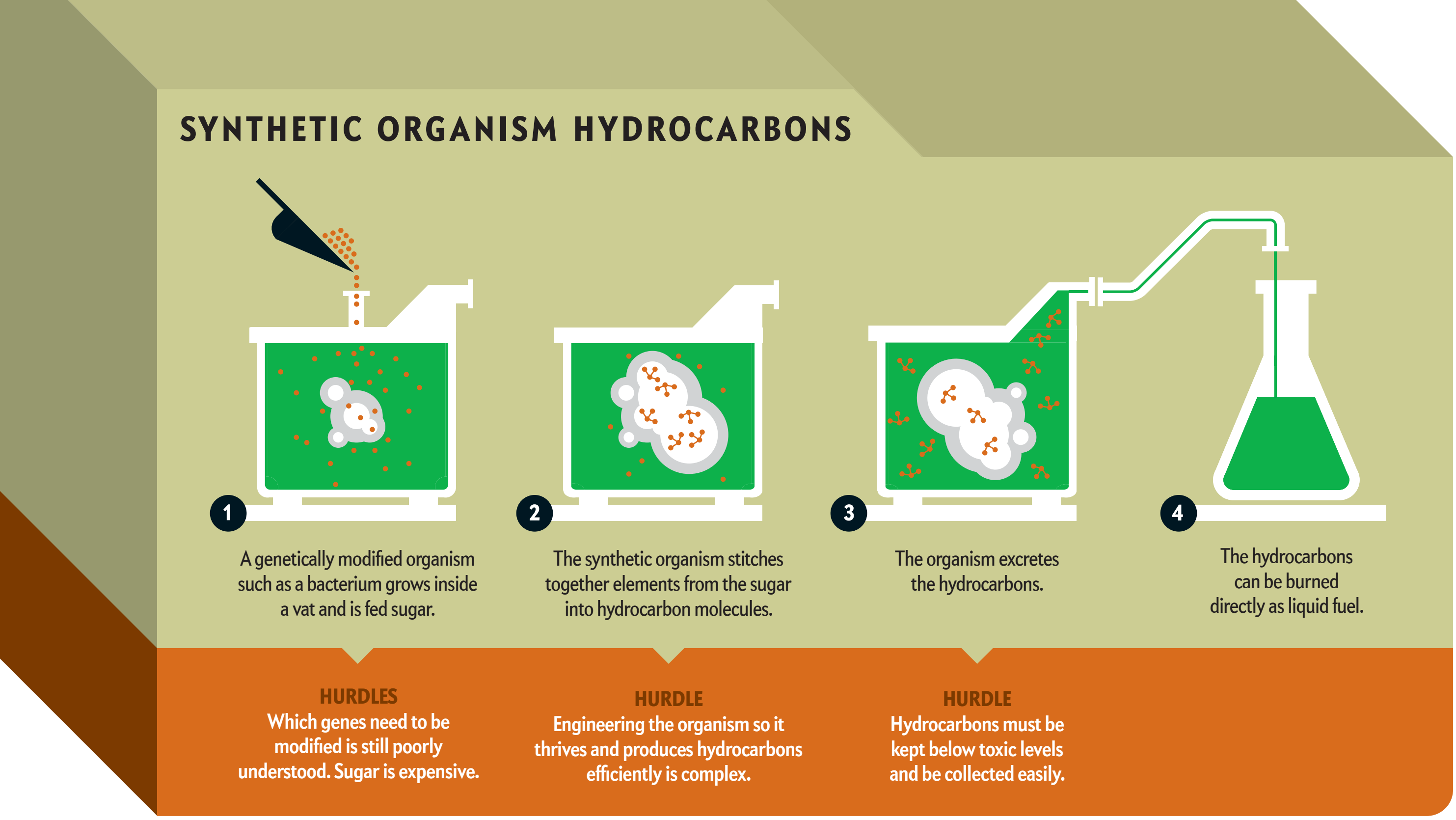
Even if sugar from cellulose somehow became competitive, the approach would impose a significant environmental and agricultural burden. Corn stover is typically left on farmland after harvest, where it improves the soil's fertility as it decomposes. Baling it up and hauling it away may accelerate soil degradation, rendering the soil incapable of growing crops. "I am not convinced that we fully understand the consequences of taking all this biomass out of the system," says Jeffrey Jacobs, vice president of biofuels and hydrogen business for Chevron Technology Ventures in San Ramon, Calif. Some scientists estimate that only 80 million tons of cellulosic material could be safely removed from U.S. fields, which, if converted to ethanol, would supply only 3 percent of U.S. gasoline demand.

Seeking a cheaper feedstock, oil companies such as Royal Dutch Shell in the Netherlands are investing in ethanol fermented from sugarcane rather than from stover. Sugarcane delivers more energy, is easier to grow and has an existing production infrastructure in Brazil thanks to more than 40 years of government effort. That country now supplies roughly seven billion gallons of ethanol from sugarcane annually. Shell has formed a joint venture dubbed Raizen with Brazilian ethanol maker Cosan to produce 581 million gallons of sugarcane ethanol a year, according to Shell's global manager of bioinnovation Jeremy Shears. That much growth in production would exacerbate the leveling of Brazilian natural habitats, which in turn could promote clearing of the Amazon rain forest. "The thing that's going to destroy the planet is not crop-based biofuels, where everybody seems to accept there are limits. It's unlimited cellulosic-based biofuels," notes agricultural expert Timothy D. Searchinger of Princeton University. "We're talking about a gigantic, gigantic effect on world land use and biodiversity."

Even if a superenzyme is found, it will inevitably be slow to break down cellulose because the reactions require time to work, making volume production difficult.

ALGAE: DIE OR BE KILLED

AS AN ALTERNATIVE, some scientists have opted to work with the one photosynthetic organism that does a much more effi-



cient job than rooted plants of turning incoming photons into stored chemical energy: pond scum.

Microscopic algae are the titans of photosynthesis. Certain strains can harness 3 percent of the incoming sunlight to make plant matter, as opposed to roughly 1 percent for corn or sugarcane. Their greenish tint comes from chlorophyll, a pigment that captures sunlight to break water into hydrogen and oxygen. The organisms combine the hydrogen with carbon dioxide to make cell walls, food and stockpiled fats—plant oil.

Algae can be grown in the desert instead of on arable land, nourished with undrinkable briny water or even sewage, so the approach does not displace food crops or consume precious freshwater. The efficient process promises as much as 4,270 gallons of oil per acre, depending on conditions. Replacing all U.S. transportation fuels with algal oil "would take a farm roughly the size of Maryland," notes Synthetic Genomics's Venter, compared with his estimate of farmland three times the size of the continental U.S. for corn ethanol. "That's a pretty big difference," Venter quips. "One's doable, and the other's just absurd."

Sapphire Energy in San Diego is testing the algal waters in a series of oval ponds spread across 22 desert acres near Las Cruces, N.M. The company plans to build 300 more acres of ponds near Columbus, N.M. That facility would be the country's first integrated algae production plant, for which Sapphire has secured a $50-million grant from the USDA and a $54.5-million loan guarantee from the DOE. The algae would grow in brine from salt aquifers underneath New Mexico, and the oil would be shipped to a refinery in Louisiana.

The problems facing algal biofuels producers are manifold, however. If they grow algae in open ponds, how do they prevent the organisms from falling prey to predators, disease or contamination by natural strains? If they grow algae inside bioreactors, how do they justify the equipment expense and keep the algae from sticking to the innards? How do they afford nutrients such as the nitrogen and phosphorus required to promote the algae's growth? Ultimately, once they have grown the algae, how do they skim off and tear apart the mature algal cells to get the oil without using as much or more energy than that oil could provide? Few algae companies have produced useful quantities of oil, much less profits.

The biggest challenge may be the fact that producing hydrocarbons is algae's defense against long periods without sunlight or nutrients. When in this stress mode, however, the tiny plants grow slowly. Scientists will have to go against the basic biological mechanisms of these cells to engineer them to respond to stress yet grow quickly.

Sapphire has surveyed 4,000 algal strains and chosen 20 to try to enhance. If all goes well, the Columbus facility would manufacture one million gallons of algal oil a year, which could then be refined into diesel or jet fuel. The dead algal cells would be recycled into the process as nutrients rather than sold as animal meal or other products; that biomass "is expensive, and we need it," says Tim Zenk, vice president for corporate affairs at Sapphire. "You can't add a lot of nutrients to the system and make any money at it."

That fact led the U.S. National Renewable Energy Laboratory to shut down its 18-year-old algal oil research program in 1996, after it consumed $25 million in research funds. The scientists felt their algal oil would never be competitive with fossil oil and lost thousands of strains of characterized algae after the shutdown. The companies making money on algae today do so by harvesting omega-3 fatty acids, sold as a nutritional supplement at a much higher price than crude oil.

The only company to commercially deliver algal fuel did so by avoiding photosynthesis altogether. South San Francisco–based Solazyme has supplied more than 20,055 gallons of oil to the U.S. Navy—at $424 a gallon. Solazyme grows algae inside the kinds of industrial vats typically used to ferment insulin, force-feeding it sugar instead of sunlight and water. Like other advanced biofuels companies, Solazyme will stay in business by making products that are more expensive than fuel; it sells oil for use in cosmetics and is partnering with Dow Chemical to make specialty chemicals such as insulating fluids.

SYNTHETIC ORGANISMS: GENETICS UNCLEAR

THE ALGAE COMPANIES try to overcome obstacles by changing the microorganism's genetic code with chemicals or radiation, but they have not hit on robust combinations yet. Venter sailed the world for a year on his yacht, *Sorcerer II,* sampling the seas for beneficial strains, with no clear winner. "That's why we're not so sanguine about finding the one magic bug out there to do everything," he says.

Maybe it is time to manufacture that magic bug instead.

Researchers have started by tweaking the genes of microorganisms, notably *Escherichia coli,* the common human gut bacterium that can also cause food poisoning. Jay D. Keasling, who directs the DOE's Joint BioEnergy Institute, has turned *E. coli* into an efficient biological factory that converts sunlight, CO_2 and water into different hydrocarbons, including biodiesel. Conveniently, Keasling altered the bacterium to excrete the oil, so it does not have to be killed for harvest. The oils float to the top of a vat, where they can be drawn off. The bacterium grows three times faster than yeast, is happy at tropical temperatures and is hardy, thanks to a heritage of withstanding the often oxygen-free and poisonous conditions of the human digestive tract.

Here again higher-value hydrocarbons will be the first markets, if any, for these biological factories. Amyris in Emeryville, Calif., has tweaked yeast to ferment sugars into farnesene, which can be sold directly or turned into specialty chemicals such as squalane, an emollient in high-end cosmetics. The company is starting with products that have a higher average selling price and will move toward lower prices, "lower being diesel and fuel products," explains chief financial officer Jeryl L. Hilleman. Amyris just opened its first production facility in Brazil as an adjunct to a sugarcane-fermentation plant.

Even a robustly engineered microorganism may find it hard to produce hydrocarbons at a volume or price that can compete with fossil oil. The long-term solution, Venter argues, "is to make the entire genetic code from scratch and control all the parameters." His company has already created a synthetic bacterium cell that secretes oil, as well as the first organism to live entirely on synthesized genetic code. "We're evaluating thousands of strains and large numbers of genetic changes," he notes.

The approach holds enough promise that fossil-fuel giant ExxonMobil has invested $600 million in Venter's firm. But the hurdles come down to basic biology: even the smallest genomes have hundreds of mysterious genes, and scientists have no clue about their function. Biological architects such as Venter can build a genome, but they do not know which genes are needed to make a synthetic microorganism hardy, cheap to keep alive and able to produce oil in abundance. Venter calls the challenge "bigger" than the one he faced when sequencing the human genome.

Biological architects do not know which genes are needed to make a synthetic microorganism hardy, cheap to keep alive and able to produce oil in abundance.

Even if someone produces the magic bug, its viability will depend on the cost of its food. Right now the cheapest source is Brazilian sugarcane, which is what Amyris, LS9 in South San Francisco and others are using, even though it is still too expensive as the starting point for an advanced biofuel. As with algae, infections and other biological mishaps can shut down production vats, a problem that could be even more acute with specialized microbes, ill suited to survival without help from humans. And inevitably, microbes are slower to make biofuels at volume than chemically processing crude oil.

Amyris's own chief technology officer, Neil Renninger, acknowledges that "we are not going to replace petroleum this way. We are going to augment petroleum. It would be great if we could handle [just] the growth in demand for petroleum." That goal places an emphasis on producing a hydrocarbon molecule that will move through today's pipelines, be manageable in today's refineries and burn in today's engines.

FOOL'S ERRAND?

RENNINGER'S POINT of view concurs with that of other experts who argue that our expectations should be lowered. All the energy in crops grown today—along with plants consumed by livestock and trees harvested for pulp, paper and other wood products—comes to roughly 180 exajoules, or about 20 percent of world energy consumption. Increasing that considerably in the near future may not be feasible and would have significant social and ecological consequences. "The goal should be to produce something like the world's supply of airplane fuel," Princeton's Searchinger says.

Breakthroughs remain possible, and the scientific quest for a better biofuel continues, but investors and politicians might be wise not to stake much money or policy on a high-risk bet. As an option, nations could electrify transportation to reduce fossil-fuel use. Until they do, corn and sugarcane will provide the bulk of any alternative to oil, further straining a global agricultural system already struggling to provide food, feed and fiber for seven billion people plus livestock—and counting.

"We can all live with different kinds of transportation," says ecologist G. David Tilman of the University of Minnesota. "We can't live without food." SA

David Biello *is an associate editor for Scientific American Online.*

MORE TO EXPLORE

Biomass as Feedstock for a Bioenergy and Bioproducts Industry. Oak Ridge National Laboratory, April 2005. www.esd.ornl.gov/eess/final_billionton_vision_report2.pdf

Growing Pains: The Possibilities and Problems of Biofuels. Christian Aid, August 2009. www.christianaid.org.uk/images/biofuels-report-09.pdf

The State of Food and Agriculture 2010–2011. Food and Agriculture Organization. www.fao.org/publications/sofa/en

Biofuels and the Environment: The First Triennial Report to Congress. EPA, January 2011. http://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryID=217443

SCIENTIFIC AMERICAN ONLINE

For an assessment of biofuels from man-made waste, see ScientificAmerican.com/aug2011/biello