The Grass is Half-Full:
New Biofuels from Field to Wheel

By

Andrew Moseman

B.J. News-Editorial
University of Nebraska-Lincoln, 2006

SUBMITTED TO THE PROGRAM IN WRITING AND HUMANISTIC STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

MASTER OF SCIENCE IN SCIENCE WRITING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEPTEMBER 2008

Signature of Author: ____________________
Graduate Program in Science Writing
May 16, 2008

Certified by: ____________________
Boyce Rensberger
Director, Knight Science Journalism Fellowships
Thesis Advisor

Accepted by: ____________________
Robert Kanigel
Professor in Science Writing
Director, Graduate Program in Science Writing

The Grass is Half-Full:
New Biofuels from Field to Wheel

By

Andrew Moseman

Submitted to the Program in Writing and Humanistic Studies
on May 16, 2008 in Partial Fulfillment of the
Requirements for the Degree of Master of Science in
Science Writing

ABSTRACT

The current biofuels market in the United States is dominated by ethanol made from corn. But corn ethanol has limitations that will prevent it from displacing a large amount of fossil fuel use in the U.S. To achieve that goal, biofuels will need to come from different sources. Cellulose, one of the main candidates, looks like it could provide a much higher volume of ethanol. The Department of Energy has sponsored new research centers to investigate cellulosic ethanol and improve the technology necessary to produce it. Even so, questions remain about the true potential of biofuels in the future alternative energy market.

Thesis Supervisor: Boyce Rensberger
Title: Director, Knight Science Journalism Fellowships

E Energy Adams – the E stands for ethanol – sits almost out of view on a gloomy December morning. Only Highway 41 is easily traversable on a snowy morning, and off that a separate spur of pavement leads into the heart of the complex, a few miles outside the village of Adams.

It rises up like a fortress over this otherwise lonely stretch of prairie. Trucks pull into the loading area with their haul of corn, 18 million bushels of it annually. Another building houses great pyramids of milled corn about the consistency of sand, the leftovers of the ethanol-making process.

The main building is a jungle gym for biochemistry buffs. Color-coded pipes of various circumference travel parallel, connecting colossal indoor storage tanks. Workers climb metal stairs to the second story rafters and ladders to the third, where windows permit a peek into the mishmash of corn and chemicals. The whole building smells like a brewery. So does a visitor after spending a few hours inside. Silos hold stockpiles of corn at the front end of the process; giant vats over by the train track that bounds E Energy Adams's east end contain the finished product, pure 200-proof ethanol, ready to ship out in tanker cars.

Kevin Meyer, the plant manager of E Energy Adams, says the southeast Nebraska ethanol factory opened in the autumn of 2007. "We made the first gallon on Halloween," he says. "That's hard to forget."

It's certainly hard for an ethanol veteran like Meyer, who worked for a decade in an older plant in Aurora, Nebraska, before becoming the overseer in Adams. Giving a tour of his new baby, he rattles off the facts and figures by rote – E Energy Adams produces 50 million gallons of ethanol in a year, a product that requires about 57,000 bushels of corn every day. The mashed-up corn in the slurry blender should register a 5.8 pH; the hydro-heater should cook the mixture of steam, corn slurry and enzymes up to 225 degrees. The plant produces about 2.66 gallons of ethanol per bushel of corn. He and the lab technician, Jackie Andersen, joke about someday breaking the magic number of three gallons per bushel. Someday.

Adams is a picture typical of biofuel production facilities in mid-America, towering biotech plants in and around the small farming towns of the Great Plains, turning corn from the fields into ethanol for car engines. In 2006, America's corn-based ethanol plants brewed up almost 5 billion gallons the stuff. By contrast, the U.S. burns 5 billion gallons of gasoline in about two weeks. At the industry's present rate of expansion, the United States will produce more than 10 billion gallons per year sometime soon, probably within the next five years. That's nothing to sneeze at. The Adams plant, which began production in October, is small compared to many of the newest factories, which can make twice that amount.

But the biofuels industry has become a lightning rod for political controversy. Many economists loathe ethanol, seeing it as an industry propped up by federal subsidy because it could not stand on its own. It takes away corn that could be used for food, driving up the price of what's left. It requires large energy inputs to make, maybe as much as the ethanol gives back. The corn lobby is thick with members of Congress, so their opponents see corn as pork – wasteful spending on a dubious fuel, but one that Congressional representatives from farm states would dare not oppose.

Those charges have validity. But the heart of the problem with corn ethanol is that it has been ballyhooed far beyond its true potential. As a result, the United States is being lobbied into an energy future that is economically unsustainable, environmentally regressive and yet, it would seem, politically unavoidable.

In 2006, for example, Missouri Gov. Matt Blunt signed a law requiring that all gas sold in his state by 2008 contain 10 percent ethanol. At the signing, he said this: "Missouri corn fields have now become the oil fields of the 21st century." That's a common refrain for corn ethanol advocates. In recent Chevrolet commercials, cars pop out of corn kernels and drive off into a clear blue sky. Stickers declaring, "Ethanol: Clean Air for Iowa" adorn gas pumps across the Hawkeye state.

The trouble is, almost none of the claims is true. Corn ethanol might be giving a spark to small town economies. It might save a little bit of fossil fuels, depending on whom you ask, and therefore make the air a little bit cleaner. But even with increasing yields with the best agricultural technology, it's already clear that farmers cannot grow nearly enough corn to replace Middle Eastern oil fields as the source of America's transportation fuel or make much of a dent in carbon emissions. In fact, the numbers are nowhere close to that. According to agricultural economists, corn ethanol will max out somewhere around 15 billion gallons per year. But according to the federal government's Energy Information Administration, American drivers used about 142 billion gallons of gasoline annually. So if the goal of making biofuels is to cut down fossil fuel use and combat global warming, researchers must find and develop new ways to make them.

Nearly all of today's fuel ethanol in the U.S. comes from cornstarch, but it need not. Anything that can be broken down into simple sugar – glucose – can be fermented, the age-old beer-making process, and distilled into pure ethanol, another ancient practice.

What are the contenders to replace corn? Its chief rival for the next-generation biofuel crop is cellulose, the ubiquitous organic compound that forms the cell walls in plants of all species. It accounts for one-third of the dry weight of all vegetable matter. With numbers like that, ethanol from cellulose has the potential to blow well past the limits on how much ethanol the United States could make from corn.

On January 31, 2006, cellulosic ethanol got its moment on the red carpet. In his sixth State of the Union Address, President George W. Bush announced his Advanced Energy Initiative. After the former Texas oilman famously denounced the country's oil addiction and promised to raise the budget for research on hybrid and hydrogen car designs, he said: "We'll also fund additional research in cutting-edge methods of producing ethanol, not just from corn, but from wood chips and stalks, or switchgrass. Our goal is to make this new kind of ethanol practical and competitive within six years."

Six years wasn't a deadline chosen at random, or because it would become another president's problem. By the year in question, 2012, the U.S. government wants the country to produce 12 to 15 billion gallons of ethanol, close to that high-water mark for corn-based ethanol. But the Advanced Energy Initiative of Bush's speech quadrupled the 15 billion gallon target for 2012 to 60 billion gallons by 2030. Meeting the government's broader goals will takes something more than corn ethanol.

It could take a decade or more to unlock an efficient and economical way to make cellulosic ethanol, and longer for even less developed alternatives, according to Raymond Orbach, the undersecretary for science at the Department of Energy. Having experience in these matters, Orbach says the White House likes to give what he calls "stretch goals." It's like the old *Star Trek* series. Captain Kirk liked to push – he might ask the engineer, Mr. Scott, how fast he could reasonably fix something, and then ask him to do it in 15 minutes less. Stretch goals, Orbach says, are best-case scenarios – how much biofuel could the United States produce if everything went according to plan – and 60 billion gallons by 2030 is one of those.

Building on 15 years of dabbling in various new ways to use biomass for fuel, and now spurred by an ambitious goal for renewable fuel production, the federal government took the first major step into a technologically unexplored wilderness in the summer of 2007. The U.S. Department of Energy provided $375 million to fund three brand new research centers, one each in Tennessee, Wisconsin and California. Each one received a grant of $25 million a year for five years, with numerous universities and private firms providing scores of scientists. Each tackles a fragment of one huge puzzle – how to make new kinds of biofuel, to make them economically, and to make a lot of them, enough to surpass corn ethanol's limited promise. The funding isn't much as these things go, but it's a start.

Orbach knows it's going to be difficult. He gets excited about the possibility of cellulosic ethanol. With the excitement and advances in biotech research, new biofuels seem closer than ever to realization. But he's realistic. He knows the cellulose molecule is not keen to be broken apart, having evolved precisely to give plants, including trees, stiffness and to resist degradation. But for seeking out a major new source of energy, $375 million isn't a lot. After all, according to the Global Subsidies Institute, the federal government provides between $5.5 billion and $7.3 billion in subsidies for biofuels in 2006, mostly to corn ethanol. "There are big ifs," Orbach says with a note of exasperation. But "now that we're in an energy crunch, we're trying to do it on the cheap."

*

The clock is running. Experts argue whether or not the world has already passed "peak oil," the high point of oil production, but in the long run, that's irrelevant. Petroleum is non-renewable, unless you're willing to wait a few million years for the Earth to make some more. John Ranieri, the head of DuPont's own biofuels project, said 99 percent of transportation energy in America comes from oil. Its market volatility is already hitting the economy hard. On January 3, 2008, the crude oil price passed $100 per barrel for the first time, a brand-new panic point. Three months later it was $120. Only six years ago the price was in the $20s, and this March it passed the previous record price from the 1979-80 oil crisis, adjusted for inflation. Before this shock to the system, Ranieri said, research into alternative fuels wasn't a high priority. But, he said at the American Association for the Advancement of Science's annual meeting in February 2008, "When oil tripled, it changed the dynamic."

The political dynamic isn't sunny, either. Americans imported 60 percent of their oil in 2005. Much of it continues to come from countries that cause much of the political consternation in United States, like Iraq, where war persists, Saudi Arabia, home to most of the September 11, 2001 attackers, and Venezuela, whose President, Hugo Chavez, threatened to cut off oil sales to the United States in February over a long-standing dispute with oil giants ExxonMobil and the U.S. government. "We're just too dependent on the wrong kinds of people," former Sen. Fred Thompson said in the January New Hampshire debate for the Republican Presidential candidates.

That's because we're locked into the wrong kinds of technology. Nearly everyone depends on the internal combustion engine for travel, says Lord Ronald Oxbrugh, a geologist in England's Royal Society and a chairman of Royal Dutch Shell, while speaking to scientists at the AAAS meeting in Boston. Oxbrugh said other transportation technologies like cars that run on pure electric and hydrogen power aren't developed enough to make a big mark on the market anytime soon, so the I.C.E. would most likely rule the road for at least another quarter century. For aircraft, he says, nothing is on the horizon.

Eventually, something will have to take the place of petroleum if the jet setting, car driving American way of life is to endure. Consumers need a new fuel to wean the country from its long love affair with polluting hydrocarbons. The Energy Information Administration reported in 2006 that greenhouse gas emissions from transportation had risen to more than 28 percent of the country's total, second only to the industrial sector. And with transportation ruled by typical automobiles, Americans will need a liquid fuel for years to come.

Cellulosic ethanol can come from switchgrass, a grass that stands taller than a person, which is native to much of the Eastern and Central U.S., or wood chips or a number of other sources. Other researchers are looking anywhere they can – even to farming algae for their cellulose or bacteria that make oils which could potentially be converted to biofuels. Biodiesel made from soybeans has already carved out a small niche in the market. Synthetic compounds made from plants, like biobutanol, may be possible down the line.

Those exotic possibilities are a far cry from what as become our iconic biofuel image, a farmer's perfectly lined Iowa cornfield swaying gently in the breeze. It's a charming idea that we could drive our cars on homegrown fuel rather than imported oil, a green vision that sparked all this excitement from biofuel scientists. Ethanol is the leading candidate to be that liquid fuel, because it's already integrated into the fuel supply and engineers know how to use it, according to Tim Donohue, the leader of the a new DOE-funded research center at the University of Wisconsin. And, as Donohue says, "we make ethanol because it's the one thing we know how to make."

*

The word "ethanol," at least in recent times, has called to mind fuel made from corn. But it is just a contraction of ethyl alcohol, which is no stranger to humans. It has inebriated minds and encouraged boisterous behavior since people figured out how to make alcoholic beverages 9,000 to 10,000 years ago, probably by accident. The "ethyl" doesn't appear much in common usage; it is mostly a designation for chemists to keep ethanol separate from the other chemicals in the alcohol family, like toxic methyl alcohol. While ethanol is just one member, it's one with practical uses aside from inspiring country songs and hangovers. It is a valuable antiseptic, which is why so many stock their bathroom drawers with a bottle of foul-smelling rubbing alcohol. (Don't drink it, though – they poison the stuff so stores can sell it without a liquor license.) Ethanol can be a solvent, an antifreeze, or a germicide. It's no coincidence that ethanol has played a major role in human history.

Its use as a fuel dates back at least to the dawn of the American auto industry. A century ago Henry Ford envisioned a country burning American-made ethanol in their

Fords. His first design of the Model T in 1908 ran on ethanol. But back then oil was cheaper, so he dropped the idea.

Ethanol's potential as a fuel lay dormant through most of the 20th century. During both World Wars, when military operations caused gasoline shortages, the U.S. government debated reintroducing some kind of alcohol as a fuel additive. But it didn't happen. It took the oil crisis of the late 1970s, when the OPEC cartel quadrupled the price of oil, to really grow the desire for energy independence in America. In 1978, the government established the National Alcohol Fuel Commission. But it was nowhere close to actually running automobiles on ethanol.

The United States first used fuel ethanol on a major scale as a small percentage additive, which is still its primary purpose today. Burning fossil fuels in an internal combustion engine has always been an inefficient process. A Colorado State University study estimated that ICEs convert only 20 percent of their energy into powering the car. That can be improved by mixing pure gasoline with small amounts of other oxygen-containing chemicals, raising the octane number on that ubiquitous yellow sticker on gas pumps. High-octane fuel burns cleaner and spews fewer hydrocarbons into the air through its exhaust; in high-compression engines it prevents annoying and damaging "knocking."

For a long time ethanol wasn't the fuel additive of choice in most parts of the United States. Methyl tertiary butyl ether, MTBE, came into vogue in 1979, but it traded one environmental bad for another. A gas/MTBE mixture contains more than 20 times more sulfur than a gas/ethanol mixture, and it can seep into groundwater and persist in the environment for decades. The Environmental Protection Agency concluded that it isn't bad enough at low levels to earn the classification "carcinogen," but MTBE's name already had been dragged through the mud. States enacted partial or full bans, including California and New York, which contributed a healthy proportion of the country's MTBE use.

In many places, that opened up a vacuum for ethanol to fill. Many of the first states to move against MTBE were in the Midwest – places like Nebraska, Iowa and South Dakota that already used home-brewed ethanol as their main oxygenating mixer. When bans on MTBE in more populated states opened their markets for ethanol, production accelerated to its current rate. Agricultural economist David Peters of the University of Nebraska-Lincoln said corn ethanol makers would likely surpass 7.5 billion gallons in 2008, halfway to the Advanced Energy Initiative's 15 billion-gallon goal for 2012.

Corn yields will continue to increase as farmers, aided by technology, get better at their job. But the country's and the world's demand for energy will increase as well. So most ethanol experts agree that corn could never displace much more than 10 percent of the gasoline pool. E10, what people used to call "gasohol," is gasoline mixed with 10 percent ethanol. It's an oxygenated fuel, not an alternative fuel. Americans could improve air quality slightly by burning E10, maybe, but 10 percent isn't going to break the country's oil addiction.

Some experts think it could actually be making things worse. Numerous scientists have studied the energy balance of producing corn ethanol to see if it's really saving anything, and even the best results aren't awe-inspiring. In 2002, the U.S. Department of Agriculture reported that corn ethanol yielded 34 percent more energy than it took to produce it. The next year, David Pimentel of Cornell University found the opposite – he concluded that corn ethanol requires about 29 percent more energy to produce than it gives back as a fuel.

Fights about ethanol reach beyond energy, however. Corn ethanol also has riled people dedicated to reducing world hunger. Much of America's prime farmland, its most fertile and nutrient-rich topsoil, underlies the Corn Belt stretching from Eastern Nebraska across a swath of the Midwest to Ohio and Pennsylvania. But every acre of corn diverted to make fuel is an acre that doesn't feed human beings. A lot of corn goes to feed human beings, especially in the United States. It's not just in cans or on ears; cornstarch and corn syrup are major ingredients in a huge variety of processed foods – soft drinks, breakfast cereals, ketchup, even some kinds of bread. Despite record yields in 2007, the price or corn has risen steadily. Hovering near $2 a bushel in the summer of 2006, corn traded above $5 by February 2008.

And given the number of acres needed to meet the U.S. government's goal of displacing 30 percent of fossil fuel use by 2030, there has to be another way, DuPont's Ranieri says. Even if corn ethanol could reach that target, he says it would drive the corn price out of control. The same holds for expanded sugar ethanol production in Brazil, the world's only other viable ethanol industry – it spurs more land use, which might result in less rainforest. "You cannot get to the target using a food crop," Ranieri says.

With such limits on the prospects for corn ethanol, it's no wonder biofuels scientists and advocates turned their attention to the possibility of brewing fuel from cellulose, with its far greater abundance. Just as the need for alternative energy sources is multi-dimensional – involving resource scarcity, carbon reduction and political leverage – so too the enthusiasm for cellulosic ethanol springs from more than one place.

For one thing – the stuff seems to be greener. Over its entire lifespan, from farm to fuel, cellulosic ethanol from switchgrass could cause a 70 to 90 percent reduction in greenhouse gas emissions compared to burning straight gasoline, according to the World Resources Institute. Burning corn ethanol yields a much more modest improvement over gas, according to the same report, a reduction in the 20 to 40 percent range. Corn's need for other energy inputs –fertilizer, transportation, and pesticides – drag it down as a greenhouse gas saver.

The early looks at cellulosic biofuel crops come off much better. Ken Vogel from the University of Nebraska-Lincoln and his team planted switchgrass in fields or marginal land across eastern Nebraska – land too uneven or soil too poor to make it worthwhile for growing a pricier crop. They hired farmers to harvest the grass and bring it in. Even with transportation and processing, Vogel says, ethanol from switchgrass contained more than five times as much energy as the scientists needed to make it.

Besides growing tall, switchgrass also grows thick: A fully developed field of switchgrass is a dense thicket, containing twice as much biomass as a cornfield. Like a weed, switchgrass takes root and thrives in poor soil. It's low maintenance, requiring less energy input than corn, and it's perennial. And once switchgrass is established, the roots stay in the ground and prevent soil erosion.

That why it's the current favorite. But switchgrass is not the only contender to supply cellulose. The compound is everywhere – not just in grasses, but in trees and all other green plants. Environmentally it makes little sense to cut down trees that absorb carbon dioxide just to get at their cellulose to make ethanol. But thankfully, Orbach says, there's plenty of cellulose lying around that nobody's using. It's in the waste wood and pulp at paper mills. It's in the switchgrass farmers grow in fallow fields to prevent soil erosion. While starch inhabits the edible part of the corn, cellulose exists in what's called the stover – leftover stalks and leaves.

That's one key to appeasing some ethanol opposition: making fuel from poplar, switchgrass, or many other alternatives to corn wouldn't take food off someone's dinner plate. If scientists could simply take advantage of the heretofore unused wastes, Orbach predicts, cellulosic ethanol and other newer biofuels could replace "perhaps as much as a third" of fossil fuels used for transportation without taking more land out of food production.

Still, new corn ethanol plants keep sprouting in states like Nebraska, Iowa and Minnesota. They remain a ray of hope for agricultural communities that had been losing jobs, and people, for decades. It's not a huge increase – only 30 local workers operate the E Energy Adams plant. But, "nothing is moving into small-town Nebraska," Peters says, "except ethanol plants." The potential for cellulosic ethanol exudes the same dreamy scenario, but geographically unbound. Organic waste is everywhere. Poplars, touted as a wood crop for cellulose – grow on the West Coast. Switchgrass grows across the Eastern United States, as well on land in Midwestern states with a steep grade or poor soil, causing farmers to abstain from planting corn.

That bounty of potential positives sounds almost too good to be true. But this much is definitely true: cellulosic ethanol is years, and a scientific breakthrough or two, away from commercial production. Yet its backers, and those who dream of a homegrown fuel supply, quiver with anticipation. Cellulose is abundant, renewable, and to many scientists, tantalizing.

*

"Hectic," Tim Donohue says, and then released a sigh. It was only 10 a.m., but he sounded already in need of a breath.

His office sits on the fifth floor of the University of Wisconsin-Madison's microbiology building, not too far from Lake Mendota, which was partially frozen on this mid-January morning. There are two ways up to his office – brand-new elevators that speak in a soft female voice, and long, sleek open staircases illuminated by reflection of the snow through the atrium's expansive windows. Great Lakes Bioenergy, the DOE-funded research center Donohue leads, is the most expensive research project ever housed at the University of Wisconsin. And while its new building has not yet been constructed, Donohue's current quarters reflect the swelling interest in biotechnical research.

A professor of bacteriology, Donohue specializes in photosynthetic bacteria – manipulating microorganisms to produce hydrogen through the physical process of photosynthesis and harnessing that hydrogen's power. It's one of the more exotic of the plethora of alternative energy ideas that took off as the energy crunch worsened. The more familiar ones are nuclear power plants, solar cells on the roof of a house, wind turbines, hydropower produced at a massive dam. The Department of Energy funded Donohue's bacterial research, so his name was in the department's Rolodex. In December 2005, he says, they asked him to come to a Maryland workshop along with about 100 others to act as the Department of Energy's biofuel experts. Government officials wanted to hear straight from the scientists how much work it would take to go from a non-existent industry to one capable of supplying a major share of the American fuel supply, assuming it were possible at all.

He and the other workshoppers at the 2005 Maryland meeting convinced the government they could jump those scientific hurdles – or, at least, that cellulosic ethanol is such an attractive option it was worth a few hundred million dollars and probably more to find out. Donohue's team at Great Lakes Bioenergy includes researchers from Wisconsin, Michigan State University, Illinois State, Iowa State and the University of Florida, plus contributions from some private companies. In three months at the end of 2006 they crafted their proposal – 50 pages of science, with about 25 more to cover the logistics of pulling together so many researchers, projects and dollars. Seventy-five pages for $125 million. "We joked about it, but it was serious," he says. "Every page is worth $2 million. It was a sobering thing."

On January 14, 2008, a day like any other in the past half-year, Donohue was exhausted by 10 a.m. He meets frequently with the other eight current members of the center's management team. Once a week he speaks to groups around the state of Wisconsin about ethanol research. They settled on the location in the center of the campus, Donohue said, but he can't announce it to the public. And besides being a leader, a speaker and a real estate developer, his normal life intrudes – classes to teach, and projects that were funded before this undertaking ever came along. "It still includes talking to my grad students," he laughs.

*

Though biofuels scientists like Donohue's group aren't starting from the beginning, they aren't many steps into the race, says the DOE's Orbach. It's frustrating, he says, that far too little research has aimed at the base of biology – truly understanding simple plant genomics, or the mechanics of how proteins work in plant cells. "To me, that's pretty primeval medicine," he says. "It's virgin territory."

Researchers have been trying to break down cellulose for years, but haven't gotten very far in breeching its defenses. Cellulose isn't that different from starch, which we eat all the time in staple foods like corn and potatoes. They're both polysaccharides – compounds formed from many chained molecules of glucose, the simple sugar that ethanol makers want to get at. The difference depends upon how those glucose molecules bond together.

Starch is a straight line – alpha linkages, as biochemists call them. They're weak, which makes starch worthless as a building material and fantastic as a source of carbohydrates for hungry humans. Cellulose, by contrast, has more elaborate beta linkages: thousands of individual glucose molecules join to curl back and wrap around themselves in a web of chemical bonds, giving cellulose a tough, crystalline structure. "That's why you have wood furniture," says Michael Ladisch of Purdue University, "not starch furniture." Humans can't produce the enzymes in their gut they'd need to digest cellulose, but some other creatures can – cows do, allowing them to graze on grass, and so do insects like termites, which lets them plow through the cellulose in a house's wooden studs.

The biofuel industry isn't the first to seek the commercial possibilities of cellulose. Rayon, the fabric made from cellulose, emerged in France more than a century ago, when it was called "artificial silk." One hundred years ago, in 1908, a Swiss scientist named Jacques E. Brandenberger dreamed up cellophane, the clear waterproof covering. Both of those products take advantage of cellulose's strength. Nowadays, biofuel scientists want to tear cellulose apart.

Scientists know the basic process they need. Cellulose possesses two layers of defense: its own crystalline structure and its ties to lignins and hemicelluloses, the neighboring polymers in plants it clings to for strength. So scientists use a two-step process to break it apart. First they crush the biomass and then blast it with steam or boil it in water, breaking the "lignin seal," as Ladisch calls it – the links to the other polymers. Then they add enzymes to the reaction – proteins that control the speed of chemical reactions. With their help the cellulose breaks apart into sugar, which then can be fermented into alcohol.

Despite this knowledge of the necessary chemistry, as of yet there is no widespread cellulosic ethanol industry. That's because the best-known process is terribly inefficient. Ladisch, who has been working on this for decades, said the manmade enzymes on the market are still too expensive for large-scale production, and don't work that well anyway. Plus, piles of money are at stake, so there isn't a lot of sharing. Iogen, an Ottawa-based biotech company that partners with the Canadian government, is one of the few private firms attempting to make cellulosic ethanol, and a representative absolutely refused to discuss the specifics their process.

The companies and universities that currently produce cellulosic ethanol can produce only small batches despite their huge investment. The BioEnergy Science Center, the DOE-funded group co-led by University of Tennessee agricultural economist

Kelly Tiller, plans to build an actual switchgrass biorefinery in addition to their lab work. With some creative design, she said, the plant will have interchangeable parts, so they can install new technology as soon as they dream it up and build it. But when it powers on for the first time next year, she said, researchers will be able to produce about 5 million gallons of ethanol each year. By contrast, the largest corn ethanol plants can produce 100 million gallons or more. "We kind of know how to process starch into sugar," Donohue says with a bit of nonchalance, "and that's *okay*. But we don't know how to process cellulose into sugars very well – yet."

*

Biological systems are so complex that often scientists find it easier to observe them in the natural world than play with them in the lab. The same holds for breaking down cellulose, Ray Orbach says. "We're looking at termites, the guts of cows, forest floors. We are really doing strange things."

One of the places Great Lakes Bioenergy researchers look to copy nature's tried-and-true methods to break down cellulose is in ants – leafcutter ants, specifically. They live across the tropical regions of Central and South America. Swarms of these red insects carry leaf scraps much larger than themselves into their massive underground nests, chew them into a paste and use that paste to create a pile, a compost heap that can be as big as a grapefruit. But that's just the first step – despite their prowess at sawing off bits of foliage, leafcutter ants are as utterly ineffective at digesting the cellulose in leaves as humans. Fifty to 65 million years ago, however, the ancestors of leafcutter ants found a clever way around this.

That's what captured the attention of University of Wisconsin-Madison biologist Cameron Currie. He was a studying the ants purely as an evolutionary biologist until a casual conversation with Donohue one day. While the researchers who want to break down cellulose are just beginning to understand the process, many animals have been evolving ways to digest the compound for millions of years. If these ants can do it, they might have some hints for human researchers. Suddenly, Currie's found his curiosity about strange insect eating habits become part of a bioenergy research lab.

Leafcutter ants are actually farmers. They grow fungi. Neither the ants nor the fungi could live without this mutualism. The partnership began so long ago that nobody knows for sure just how it started, Currie says, but they've lived in symbiosis ever since.

Leafcutter ants carry the fungi in a special compartment in their mouths. Once they pile up the leaf paste, they spit the fungus onto the greens. The microbes then go to work, breaking down cellulose bonds in the leaves and using that energy to reproduce. For the fungi, the pairing is a fatal attraction – the ants reward them for their effort by devouring them. But these particular fungi can't live outside the ant colony, so they have no choice. Ants bring in fresh bits of leaf, refresh the top of the pile with more food for the fungi and the cycle keeps on churning.

Moreover, Currie says, the ants and fungi have had 50 million years of competition among one another to perfect their systems. "Over that time period," Currie says, "there has been intense competition between nests." Since he doesn't have 50 million years, he wants to steal their playbook.

But it's a tricky puzzle. The leafcutter ants' partnership with their fungi is peculiar enough to human eyes that it's already attracted considerable attention. Researchers, however, haven't been able to isolate how it works because the chemical reaction is more complex than it first appeared. Upon inspection in the lab, the fungus seems to lacks cellulases – the class of enzymes that microorganisms produce to break down cellulose. It's possible the fungi have some help from bacteria, making the whole process a three-part system. Another problem is that the ever-efficient ants pull material off the bottom of their food mound and toss it outside the nest, in what Currie calls trash piles. Some of that refuse is cellulose and lignins, which suggests the chemical breakdown is incomplete.

In addition to watching the methods of leafcutter ants, and another animals like termites and cows that developed cellulose-digesting systems, Currie has partners in Costa Rica who comb the rainforest for new enzymes and chemicals. They call it bioprospecting, the biologist's analogue to panning a river for gold. Those who seek to save the rainforest often invoke the idea that we'd lose natural disease cures no one has discovered yet. If Currie is on the right path, scientists might lose the quickest path to new biofuels as well.

Though Currie and others want to copy nature's time-tested methods, scientists are not limited to the options natural selection provided. In the modern era they can tinker with the genetic foundations of plants and engineer them to develop in ways never seen in the natural world. In high-value crops like corn, scientists have delved deep enough into the genomics that they know how to tinker. They can make pest-resistant corn, or rice that's enriched with extra Vitamin A.

If scientists can interfere with plant genomics to produce other beneficial traits like pest resistance, it's possible that with enough knowledge they could genetically modify switchgrass to develop cellulose with slightly weaker bonds to lignins and hemicelluloses – enough to make the decomposition at the refinery, but not so much that the grass can't stand up in the field. Sandra Austin-Phillips from the University of Wisconsin is trying to engineer plants to produce large amounts of cellulases – the cellulose-degrading enzymes – for researchers to then harvest and use on biofuel crops. Genetic engineers could try to make the plant produce different polymers, like starch, that are easier to break down into sugars, or plant oils that could be used in other fuels, like biodiesel. Unfortunately, Donohue says, they're just at the beginning of developing a full-scale enterprise to tackle these problems. "There aren't really any examples of how to do this," he says. "There is no blueprint. There is no manual."

*

Tiffany Groode's aging metal desk is covered in decade-old bumper stickers for elections long gone, and torn paper and old glue where somebody tried to remove one of them. She shares an office with four or five other graduate students in Building 31, one of the tucked-away rectangles on the MIT campus map. Now a post-doc, Groode was a chemical engineering grad student in Professor John Heywood's lab in the fall of 2007, when the students picked their chemical of choice from a piece of paper passed around. She chose ethanol more or less on a whim, she says, and devoted her thesis and much of a year of her life to ethanol from switchgrass.

She created what's called a life cycle analysis, an economic outline of what it would be like to develop the grass into a major crop for cellulosic ethanol makers to use. That includes where farmers would grow switchgrass, how much they could grow, where people would build refineries to brew ethanol and more. Switchgrass is the odds-on favorite to become the next big biofuel crop, and Groode wanted to know what it would take to scale up from a drop in the bucket today to a multi-billion-gallon industry someday.

A new industry takes a new infrastructure. Take all the steps in corn ethanol production, for instance. As new plants continue to spring up across the Midwest, they can tap immediately into the 11.1 billion bushels of corn that American farmers grow each year, more than 40 percent of the world's total. Once they use the centuries of corn-growing know-how and established technologies to make ethanol, a plant needs to sell it. E Energy Adams ships theirs by rail to a wholesale company called Aventine, which pools it with ethanol from around the region and sells it to fuel stations. They mix it with gas to create the E10 mixture in gas pumps.

For all those reasons, corn ethanol "was the easiest thing you could give people right now," Groode says. "It was an established industry, mature technology, and easily scalable." But for the second wave, those trying to get the cellulosic ethanol industry off the ground, there's a lot more work to do even presuming researchers find an efficient way to break down cellulose.

To make a truly substantial amount of cellulosic ethanol from switchgrass, farmers first would need to start growing vast fields of the crop specifically for that purpose. Then switchgrass ethanol makers will have to build much of their infrastructure from scratch, with hardware and chemical procedures tailored specifically to cellulose.

Every October, MIT hosts an Energy Night at the MIT Museum. This year Groode stands in front of her laminated county-by-county map of the United States. The swaths of green, she explains, represent areas where farmers would be willing to grow switchgrass at the price she calculated it would fetch in her life cycle analysis. A number of counties are totally white; Midwestern farmers, for example, would never sacrifice the high prices they get for corn in order to grow switchgrass. But in many parts of America with less productive soil, a large demand for switchgrass would cause many farmers to plant, she says. Much of the South is colored bright green. Groode said Southern farmers, whose cotton and wheat fetch far less at market than Midwestern corn, would be among the first to jump on board.

In 2008, however, that's all speculative. The only farmers growing switchgrass are those protecting fallow fields from erosion, and a few who have contracts to grow the small amount researchers need for their experiments. While Groode and others predict many farmers would line up to grow switchgrass, they won't take the plunge until ethanol plants stand ready to buy it. At the same time, plants can't afford the mammoth expenditures to create a switchgrass ethanol facility if there's no biomass ready for them from the get-go.

Once potential ethanol makers get the switchgrass in their hands, some of the process will be roughly the same. If researchers can solve the biological problems of breaking down the grass's cellulose into glucose, they're on the downhill slope. Thanks to years of corn ethanol production, and millennia of humans brewing alcohol, people have a pretty good handle on how to go from sugar to liquor. Yeast ferments the simple sugars in grains like barley and wheat into beer. Though they use slightly better technology than Appalachian bootleggers, ethanol makers use the same principles to distill their beer into high-concentration alcohol. Heating the beer evaporates the alcohol, which travels through pipes to a cooling tank where it condenses back into a liquid. At E

Energy Adams, Kevin Meyer says, it emerges as 95 percent pure alcohol, with the remaining five percent – mostly excess moisture, to be removed through subsequent distillation and refinement.

Just as a cellulosic ethanol plant could borrow fermentation and distillation techniques from corn ethanol plants, they could also use the same kind of distribution system that a place like E Energy Adams uses once they've made created the ethanol – shipping out by rail to a wholesaler like Aventine, who turns around and sells it to fuel stations. A whole network like this exists. But it exists in corn country.

That infrastructure is nowhere to be seen in the East and Southeast, Groode says, the areas where switchgrass would most likely take root. Switchgrass growers and cellulosic ethanol makers would be locked in a symbiotic relationship, but the enterprise would require wholesalers, who would need huge vats to store the ethanol. It would require reliable rail lines, which are by far the best way to transport ethanol, but hard to come by in many parts of the United States. It would require more fuel stations equipped to sell gas blended with higher concentrations of ethanol than E10.

"You have to get all the players in at the same time," Groode says.

That's the problem Tiller faces at the Tennessee-based BioScience Energy Center. She leads a partnership between the University of Tennessee, Oak Ridge National Laboratory and Mascoma, a cellulosic ethanol research company in Cambridge, Mass. To figure out how all the parts will fit together, Tiller's Tennessee team decided to set things in motion with a giant real-life experiment – their switchgrass facility. While it will produce about 5 million gallons of ethanol in the first year, that total should be enough to find out what sorts of headaches and conundrums a full-scale switchgrass ethanol industry would have to confront.

Because those problems might change over time, the plant is being designed for flexibility. It will begin equipped with current technology so it can start making ethanol immediately, but Tiller wants to employ new technology as soon as it's ready, which would be a major hassle for a typical plant. "We're trying to build flexibility into the facility," she says, with lots of extra valves, outlets and other features. It just takes a little creative engineering, time, and a big grant. "Money solves a lot of those problems," Tiller says.

The plant, however, occupies only the middle part of the process. Tiller and her colleagues need the raw material, the switchgrass, and they need it grown in the area around Oak Ridge and the university in Eastern Tennessee. Since they aim to create a model for the future switchgrass industry, there's no point in having trucks burning fossil fuels bring the crop from 100 miles away. So the project leaders funded local farmers to grow 8,000 acres of switchgrass, about 12.5 square miles. It's the beginning of a supply chain.

But it's not as easy as writing checks and planting seeds. For cellulosic ethanol to make a sizeable dent in the United States' fossil fuel usage (and for companies producing it to make their profits), the production process must be as efficient as possible.

That means UT's hired farmers are conducting an experiment as well. Tiller can turn up many unanswered questions about switchgrass: What varieties of switchgrass are best? When should you plant it? How deep? What kind of soil? When's the best time to harvest? And how do you figure out the price scale – how much the stuff is worth? Those are just a few, and only on the supply side of the UT experiment. Corn has a price that varies day by day; it has futures markets and many seed lines and generations of accumulated knowledge by farmers who know it inside and out. Switchgrass enters its infancy as a commercial product beset with unknowns.

Still, biofuels scientists are confident they're going to surmount the list of scientific struggles and technical problems of creating a mass quantity of cellulosic ethanol. But even if they're wildly successful, Groode says, her last concern is this: where is all this ethanol going? Most American gas stations carry only E10. It runs fine in normal car engines, though supplying slightly poorer mileage. Only a few carry E85, and not only because the United States currently can't produce that much ethanol. According to the World Resources Institute, it can cost up to $200,000 for an E85 pump. And while ordinary car engines can burn E10 safely, drivers need what's called a flex-fuel engine to burn any of the several higher concentrations of ethanol. There were only about 6 million vehicles equipped with flex-fuel engines in 2006, out of a U.S. fleet of around 100 million vehicles.

Ideally, mass production of switchgrass ethanol would provide more people the chance to burn a gas with higher ethanol content – E20, E30, on up to E85. But if that's the goal, Groode said, many more people will need a flexible-fuel engine. Otherwise, some of that product might have nowhere to go, and ethanol enthusiasts need to figure that out, she says – "I don't think they know what they're going to do with it."

*

It takes many kinds of scientists to do biofuels research. Donohue was a bacteriologist by trade before becoming the leader of the Great Lakes project. Currie is an evolutionary biologist who took a tangent into biofuels because his ants happened to be useful. Phil Robertson is a gardener.

Robertson is a professor of ecosystem science at Michigan State University, and he is the project's dean of sustainability. All three research centers have undertaken a mountain of work with the goal of making new biofuels not just possible, but eventually affordable and widespread, so that one day most Americans would be running the errands or taking road trips on grass-powered cars or wood-powered trucks. It rings of being clean and green, but, cynics note, so did corn ethanol. If the new industry is not an environmental positive, the entire enterprise could be a federally funded waste of time. Crunching numbers and projecting the consequences of a whole new crop for a whole new biofuel industry is a daunting challenge. But Robertson specializes in the astounding complexities of ecosystems.

Counting the many parts of the cellulosic ethanol puzzle – genetically engineering crops, growing the crops, harvesting, transporting, breaking down cellulose, processing it into ethanol and delivering it commercially – there are countless places where things could go wrong. Every step, from "field to wheel," Robertson says, must be just right for biofuels to be an environmental good. If farmers burn too much fossil fuel to harvest the crop or refineries buy from faraway farmers, they increase the energy needed to make biofuels. "We haven't said whether the cost of driving eats up our carbon credits," he says.

Robertson and his team of eight are the overseers, those who keep tabs on all the science projects going on in Great Lakes Bioenergy to see whether they fit the mission. Biofuels need to be useable in our vehicles. But if their production fails to diminish greenhouse gas emissions, or growing a new crop causes erosion or kills off habitat, then we're simply shuffling around environmental negatives.

He isn't just a babysitter, though. He's got his own project – his garden. Robertson planted mini-fields of many leading biofuel candidate crops, 30 by 40 meters, a little bigger than a baseball infield. That's not a perfect simulation of large field, but it allows his team to project the effects that growing biofuel crops could have on the environment. Plants like switchgrass and poplar are better choices than corn or soybeans because they need less energy input, Robertson says, but there's a lot more to the question of "environmental good." Ecosystems are delicately interconnected systems of organisms and nature's raw materials. Pushing on one thing pulls on another; problems are never one-dimensional. Fields of different crops become habitat for different insects, they attract different microorganisms in the soil. And all those factors can cause different chemical compositions of the soil, too.

Take carbon, for one example. Burning cellulosic ethanol releases less carbon dioxide than burning a fossil fuel (though it might increase other greenhouse gas emissions like methane, according to a 2007 study by Mark Jacobson at Stanford University). But a car engine isn't the end of the story. With the world's increasing awareness of global warming has come more conversation about carbon sequestration – if we can't stop creating carbon emissions, then let's stash them somewhere before they get into the atmosphere. One promising place is the soil. "In a natural system," Robertson says, "soil carbon builds up." Under a dense Michigan forest like those near his home, carbon content could rise as high as 3 percent as organic material decomposes into the ground.

Clearing the forest for agriculture breaks that natural system, and that's why some have argued cellulosic ethanol wouldn't be much better for the environment than its corn predecessor. This is because a massive biofuel industry would need a lot of land, potentially new land not currently under cultivation and, quite probably, quietly storing carbon. A Princeton study published in *Science* in February said land-use change for biofuels would cause farmers to plow even more acres for food. The researchers wrote that cellulosic ethanol production could actually increase greenhouse gas emissions by 50 percent – better than corn ethanol, but still a waste of time and an environmental debacle.

The DOE's Orbach wants to avoid land use change altogether, because frankly, there's not enough space and good soil to grow everything. "If we get in competition with food crops," he says, "it doesn't work." But his goal for making cellulosic ethanol without taking over more land leads to a best-case scenario of displacing only 30 percent of U.S. fossil fuels. That's further than corn ethanol could ever go. But to go even further, say, to brew enough biofuel to displace more than half of U.S. fossil fuel use, would require developing a crop like switchgrass and devoting huge swaths of land to grow it, land that currently has another use.

Robertson conceded that Americans would probably have to farm more acres than they do now in order to really make a difference in the researchers' and the government's long-term goals for biofuels – weaning the country off fossil fuels and fighting global warming. But, he contends, it won't have to be a negative as some fear. It just has to be done exactly right.

Turning poor land that currently grows corn and changing it to switchgrass, for instance, would benefit the environment. It takes more tender loving care (and fertilizers and pesticides) to bring corn to bear in bad soil, while comparatively switchgrass isn't so finicky about where it makes it home. As opposed to plowing up the soil and releasing the stored carbon, Robertson says, native grasses like switchgrass could soak in carbon from the ecosystem. And grasses don't leach nitrogen into the soil as badly as corn or soybeans do – a big plus, because nitrogen can contaminate groundwater. That all sounds pretty good, but then we're circling around back to the economic concern about growing corn for ethanol: diverting cropland for more biofuels drives up the cost of grains even more. At that point it could be tempting to say, "All right, then, why not just scrap corn ethanol and use all our corn for food?" Well, according to Peters, the agricultural economist from Nebraska, the power of the corn lobby isn't going to let that happen.

The fact is, Robertson says, there are more ways to do biofuels wrong than right. That explains why respectable researchers get wildly different numbers – the Princeton study says cellulosic ethanol will actually increase greenhouse emissions when it's all said and done, while the World Resources Institute calculated a 70 to 90 percent reduction. Ken Vogel from Nebraska predicts ethanol from switchgrass would contain 5 times more energy than needed to make it. Lee Lynd, a professor and biofuels expert from Dartmouth University, said that could be more like 10 times as much.

Lynd, speaking at the 2007 Nobel conference at Gustavus Adolphus College in Minnesota, says he got those figures through technological optimism, presuming scientists will overcome the challenge of breaking down cellulose with flying colors and mass-produce ethanol with ease – a long way from the present day, but consistent with the confidence of most biofuel scientists. And he presumed smart growing – alternating switchgrass on the same land as costlier cash crops and growing them alongside each other, but in different seasons. He said those kinds of tactics allowed him to get around the land-use change predicament, although that could overthrow a key advantage of switchgrass – its perennial nature.

But here's the keystone of Lynd's case: in saying he believed cellulosic ethanol could someday replace a majority of transportation fossil fuels, he assumed compromise. Yes, he says, researchers can toil in the lab and the field and figure out how to supply billions of gallons of fuel from the earth. But energy won't be as easy as the oil-based lifestyle to which the world's well off have grown accustomed – if you picture a world of people continuing to drive 15 mile-per-gallon vehicles, he, said, biofuels just won't be able to satisfy that relentless thirst for energy. The demand side must give, too. As second-generation biofuels come to bear, he said, cars must become more efficient, and people might just have to drive less. That gets him occasional catcalls from scientists and regular citizens alike, he said, accusing him of being an idealist. But that's fine. "We need no less than redesigning the world, folks," he says at the Nobel conference. "We're going from an energy non-constrained past to an energy-constrained future."

That's a lot to ask, though Americans' willingness to compromise might increase if gas price continue to go up. For most people, there's a long way to go before they reach that kind of desperation – even the $3.50 a gallon or more that most Americans were paying for gas in early 2008 was still half of what many Western Europeans are paying. But the slow pace doesn't bother Robertson, so long as biofuels head in the right direction. "The biggest danger," he says, "is that we end up with a biofuel landscape that doesn't look different from our current landscape."

*

Americans grew up in a world of energy monarchy, especially for transport. That isn't new. As Kevin Phillips wrote in *American Theocracy,* rule by one fuel has been the way for some time. The British rode the industrial power of coal to their globe-spanning 19th century empire. America uses plenty of coal and natural gas, and dabbles in alternatives. But the U.S. rose to its status as the world's most powerful nation on oil, powering its military fleets of planes and ships and its civilian fleets of cars and trucks, now numbering nearly 2.3 per household. But with petroleum slowly on its way out, many experts foresee a future ruled by many sources of energy, not one or even a few.

There are good reasons to doubt that cellulosic ethanol or any other biofuel could ever become the country's major motor fuel, even if the rosiest outlook comes to fruition. Besides the potential pitfall of needing more and more land, ethanol is not a completely renewable resource. There are still heavy energy inputs for such a detailed chemical process. But even if those could be replaced – if we could use totally renewable energy to biofuels – there's a problem: One hundred percent ethanol doesn't work in our internal combustion engines. It doesn't vaporize as well as gasoline, so stations don't sell a concentration higher than E85. In wintertime, when vaporization is worst, gas stations compensate – the E85 pump might actually be dispensing E70 in January.

In addition, consumers who claim reduced mileage when running on ethanol are correct: E85 contains only 68 percent as much energy density as gasoline. As Donohue says, one of the biggest reasons to invest in ethanol is that scientists know the basics about how to make it, and cars can burn a high percentage right now. But its technological link to petroleum casts doubts that cellulosic ethanol could be the fuel of the future. In an already inefficient internal combustion process, ethanol worsens the amount of energy per gallon of fuel.

A revolution in hydrogen power, or a major investment in electric cars, could overturn how we think about the auto industry. But as long as liquid fuels in internal combustion engines power our vehicles, biofuels continue to look like the best viable alternative to burning gasoline. Scientists can't make big batches of cellulosic ethanol today, and it's a fair bet they won't be able to in 2012, when the when this round of the DOE's funding for the new research centers expires. With the federal government so keen on expanding the use of biofuels, it's a good bet they'll re-up the money. That's a good sign for cellulosic ethanol. As E.O. Wilson once wrote, "Science, like art, and as always through history, follows patronage."

In time, a single new way of making energy might rise above the rest – because it's cheaper, or engineers can scale it up to a large enough level to displace a great amount of the energy we're now getting from dirty and dwindling fossil fuels. In the meantime, policymakers are hedging their bets. Fossil fuels will stay in use for decades to come because so much of the world's infrastructure was built with them in mind. But the cost is getting higher and higher, and not just in a monetary sense.

Some economists dream of an environmental double dividend. Governments could tax the creation of pollution or other environmental problems and use that money for cleanup projects. Cleanup projects require workers, so the end result of this cycle could be the best of both worlds – a cleaner Earth and higher employment.

The new wave of biofuel enthusiasts is betting on something of a quadruple or quintuple dividend – cellulosic ethanol will give us cleaner air, jobs in rural areas and developing countries, energy independence, better soil and greater biodiversity. Yet that hope hangs on an experimental fuel, the same moniker you might drop on something Bugs Bunny uses to go to the moon. Years of sweat and patience stand between scientists and policymakers finding out how many of cellulosic ethanol's promises can be reached. "If there's one thing I've learned in my life," Orbach says, it's this: "Don't predict how science will look five years from now."

But if that's the case, he and the other scientists pushing for new biofuels have a lot on the line for an uncertainty. In one sense, the potential negatives of pursuing biofuels are miniscule by comparison: if the alternative is sitting idly by as oil keeps disappearing, we might as well try. But there are other possibilities out there, other ways to power a car or a truck that don't remain linked to the technology of the past – be it internal combustion or distillation – and probably some ways people haven't thought of yet. That's the longer term, or course. But for now, when corn ethanol has promised far more than it can deliver, the next wave of biofuels may force technology lock-in – causing us to pay less attention to technologies with more promising potential because they're farther away than the biofuels we can make now.

*

At the same AAAS meeting in Boston where John Ranieri and Lord Oxbrugh raved about multi-layered potential of biofuels, Joachim von Braun lumbered up to the stage for his chance to comment. A member of the International Food Policy Research Institute in Washington, D.C., von Braun is the picture of a stone-faced German realist. "Discussant," he's called in the program.

It's fine, he said, to dream big about a kinder, gentler and better way to make biofuels. Research might go well, and humanity might reap the benefits in air pollution reduction and rural employment. But remember this about the next generation of biofuels: "It's not about to be born," he says. "It's about to be conceived."

Bibliography

Brown, R.M. Jr. and I.M. Saxena eds. Cellulose : molecular and structural biology : selected articles on the synthesis, structure, and applications of cellulose. Dordrecht: Springer 2007.

"Cellulose." Encyclopædia Britannica. 2008. Encyclopædia Britannica Online. < http://www.britannica.com/eb/article-9022028/cellulose>

"Cellulosic Ethanol: Fuel of the Future?" Science Daily. 1 March 2007. <http://www.sciencedaily.com/releases/2007/02/070218140448.htm>

Child, Britt and Rob Bradley. Plants at the Pump: Biofuels, Climate Change, and Sustainability. World Resources Institute, 3 December 2007.

Davey, Monica. "In Farm Belt, Ethanol Plants Hit Resistance." The New York Times. 13 November 2007. <http://www.nytimes.com/2007/11/13/us/13nimby.html?ei=5087&em=&en=afd88c3e0a5d49e5&ex=1195102800&adxnnl=1&adxnnlx=1209839187-mukplOHvkoS9UqqgSM7ptA>

"Enzyme." Encyclopædia Britannica. 2008. Encyclopædia Britannica Online. <http://www.britannica.com/eb/article-9032739/enzyme>

"Ethanol, schmethanol." The Economist. 27 September 2007. <http://www.economist.com/science/displaystory.cfm?story_id=9861379>

Gardner, Timothy. "Corn is Not the Future of U.S. Ethanol: DOE." Reuters. 28 March 2007. <http://www.aresearchguide.com/12biblio.html#h>

Gibson, Richard. "Some Interesting Oil Industry Statistics." Gibson Consulting. 2007. <http://www.gravmag.com/oil.html>

Jacobson, Mark Z. "Effects of E85 versus Gasoline Vehicles on Cancer and Mortality in the United States." Environmental Science & Technology. 41.11: 2007. <http://pubs.acs.org/cgi-bin/sample.cgi/esthag/2007/41/i11/pdf/es062085v.pdf?isMac=48370>

Koplow, Doug. Biofuels: At What Cost? Government Support for Ethanol and Biodeisel in the United States. Global Subsidies Institute, October 2006.

Krauss, Clifford. "Ethanol's Boom Stalling as Glut Depresses Price." The New York Times. 20 September 2007: <http://www.nytimes.com/2007/09/30/business/30ethanol.html?ei=5087%0A&em=&en=bd695fcc2bcabe84&ex=1191384000&adxnnl=1&adxnnlx=1191261332-fajsC0UDSR96Z/vRTRnmZQ>

"Leaf-Cutter Ant." Bristol Zoo Gardens. < http://www.bristolzoo.org.uk/learning /animals/invertebrates/ant>

Lee, Sunggyu, James G. Speight and Sudarshan K. Loyalka. Handbook of Alternative Fuel Technologies. Boca Raton: CRC, 2006.

Lynd, Lee. "Biofuels: Technology, Challenges and Their Role in a Sustainable World." Video. 2 October 2007. < http://gustavus.edu/events/nobelconference/2007/lynd-lecture.php>

Marshall, Liz and Suzie Greenhalgh. Beyond the RFS: The Environmental and Economic Impacts of Increased Grain Ethanol Production in the U.S. World Resources Institute, September 2006.

Minteer, Shelley, ed. Alcoholic Fuels. Boca Raton: CRC/Taylor & Francis, 2006.

Missouri. Governor's Office. "Gov. Blunt's E-10 Standard Effective with New Year." 31 December 2007. < http://www.gov.mo.gov/cgi-bin/coranto/viewnews. cgi?id=EEAAEukuuupOdDIxVI&style=Default+News+Style&tmpl=newsitem>

Nolan, Bernard T., Kerie J. Hilt and Barbara C. Ruddy. "Probability of Nitrate Contamination of Recently Recharged Ground Waters in the Conterminous United States. Environtmental Science & Technology. 36.10: 2002. <http://water.usgs.gov/nawqa/nutrients/pubs/est_v36_no10/est_v36_no10.pdf>

Pimentel, David. "Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts are Negative." Natural Resources Research. 12.2: 2003. <http://www.springerlink.com/content/n7533126g6363512/fulltext.pdf>

Phillips, Kevin P. American Theocracy: The Peril and Politics of Radical Religion, Oil, and Borrowed Money in the 21st Century. New York: Viking, 2006.

"Polymer." Encyclopædia Britannica. 2008. Encyclopædia Britannica Online. <http://www.britannica.com/eb/article-9060700/polymer>

Revkin, Andrew C. "On the Road Toward One Billion Cars." The New York Times. 10 January 2008. http://dotearth.blogs.nytimes.com/2008/01/10/on-the-road-toward-one-billion-cars/

Searchinger, Timothy et al. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change." Science. 319.5867: 29 February 2008. <http://www.sciencemag.org/cgi/content/abstract/1151861>

"Study: Without More Government Help Ethanol Plants Could Go Bust." Sioux City Journal. 6 September 2007. <http://www.siouxcityjournal.com/articles /2007/09/06/news/nebraska/2b7b012d099543d58625734e001062ef.txt>

Tiller, Kelly. "Biofuel video from the Tennessee Agricultural Experiment Station." The University of Tennessee. 2006. <http://taes.utk.edu/video/transcript.asp?video= 35&tag=Biofuel>

United States. U.S. Department of Agriculture. The Energy Balance of Corn Ethanol: An Update. July 2002.< http://www.usda.gov/oce/reports/energy/aer-814.pdf>

United States. U.S. Department of Energy, Energy Information Administration. Emissions of Greenhouse Gases Report. 28 November 2007. < http://www. eia.doe.gov/oiaf/1605/ggrpt/>

United States. U.S. Environmental Protection Agency. Greenhouse Gas Emissions from the U.S. Transportation Sector, 1990-2003. March 2006. <http://www.epa.gov/otaq/climate/420r06003.pdf>

United States. U.S. Environmental Protection Agency. Methyl Tertiary Butyl Ether. 13 September 2007. <http://www.epa.gov/mtbe/faq.htm>

United States. U.S. House of Representatives. California Gasoline Markets: From MTBE to Ethanol. 2 July 2003. <http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=108_house_hearings&docid=f:89970.pdf>

United States. U.S. House of Representatives. Renewable Energy with a Focus on Cellulosic Ethanol and Biodeisel. 26 August 2006. <http://frwebgate.access.gpo.gov/cgi- bin/getdoc.cgi?dbname= 109_senate_hearings&docid=f:30153.pdf>

Wald, Matthew L. "U.S. Is Creating 3 Centers for Research on Biofuels." The New York Times. 26 June 2007: <http://www.nytimes.com/2007 /06/26/business/26bio.html?_r=1&oref=slogin>

"World Corn Production and Trade." U.S. Grains Council. 2008. <http://www.grains.org/ page.ww?section=Barley%2C+Corn+%26+Sorghum&name=Corn>

Personal Interviews

Currie, Cameron. Phone interview, 26 February 2008.

Donohue, Tim. Phone interview. 4 October 2007. Interview in person in his office at the University of Wisconsin-Madison, 14 January 2008.

Groode, Tiffany. Interviewed in person in her MIT office, 26 October 2007.

Ladisch, Michael. Phone interview, 31 October 2007. Phone interview, 18 February 2008.

Meyer Kevin. Interviewed at E Energy Adams ethanol plant in Adams, Nebraska, 27 December 2007.

Orbach, Ray. Department of Energy conference call, 18 February 2008.

Peters, David. Phone interview, 25 September 2007.

Robertson, Phil. Phone interview, 22 February 2008.

Tiller, Kelly. Phone interview, 4 February 2008.

Vogel, Ken. Phone interview, 23 January 2008.