THE CARBON HARVEST

Vast bioenergy plantations could suck up carbon and stave off climate change. They would also radically reshape the planet

By **Julia Rosen**

PHOTO: SEAN BAGSHAW/GETTY IMAGES

A poplar tree farm in Oregon is a fast-growing bioenergy source.

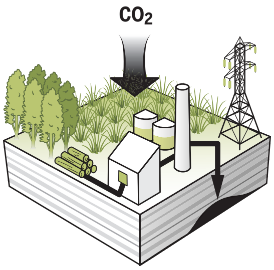
On a sunny day this past October, three dozen people file into a modest, mint-green classroom at Montana State University (MSU) in Bozeman to glimpse a vision of the future. Some are scientists, but most are people with some connection to the land: extension agents who work with farmers, and environmentalists representing organizations such as The Nature Conservancy. They all know that climate change will reshape the region in the coming decades, but that's not what they've come to discuss. They are here to talk about the equally profound impacts of trying to stop it.

Paul Stoy, an ecologist at MSU, paces in front of whiteboards in a powder blue shirt and jeans as he describes how a landscape already dominated by agriculture could be transformed yet again by a different green revolution: vast plantations of crops, sown to sop up carbon dioxide (CO_2) from the sky. "We have this new energy economy that's necessary to avoid dangerous climate

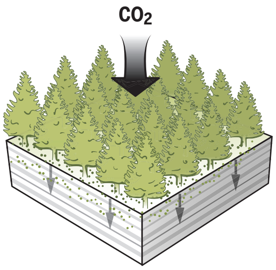
Take it back

Researchers are pursuing a handful of negative emissions technologies (NETs) that would mitigate global warming by pulling carbon dioxide (CO_2) out of the atmosphere. A prominent NET is bioenergy with carbon capture and storage (BECCS), because it combines existing technologies.

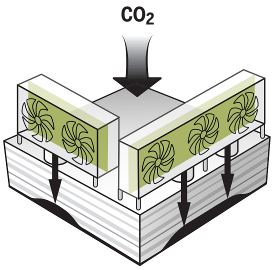
Six ways to pull CO_2 out of the air



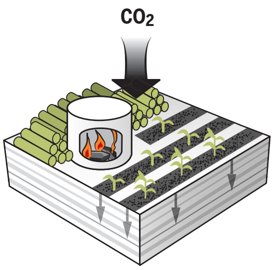
BECCS
Fast-growing plants are harvested and burned to make energy. Exhaust carbon is captured and piped underground.



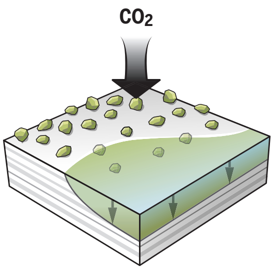
Forestation
Planted trees capture CO_2 as they grow. The carbon remains sequestered as long as forests are not cut down.



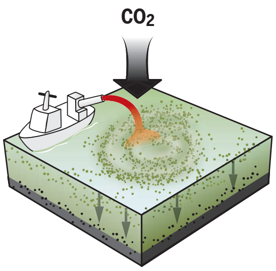
Direct air capture
CO_2 in air selectively "sticks" to chemicals in filters. Filters are reused after releasing pure CO_2, which can be stored underground.



Biochar and soil sequestration
Charring biomass stores carbon in soil by making it resistant to decomposition. Altered tilling practices also enhance CO_2 storage.



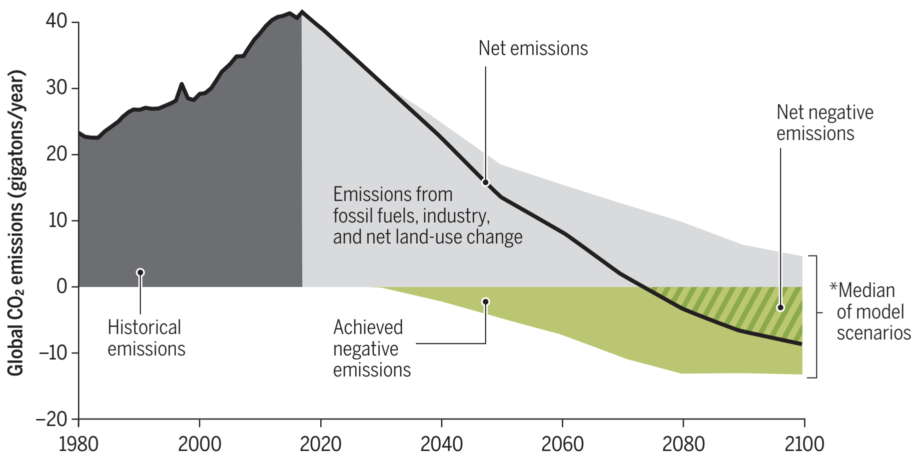
Enhanced weathering
When spread across fields or beaches and wetted, crushed silicate minerals like olivine naturally absorb CO_2.



Ocean fertilization
Injections of nutrients like iron spur phytoplankton blooms, which absorb CO_2. When they die, they take the carbon to the sea floor.

A global unwinding

In order to prevent the world from warming more than 2°C, models count on the fast development of NETs. But many scientists question whether they can be scaled up in time.



*Median values at 10-year time steps of 18 scenarios evaluated by six models using shared socioeconomic pathways assessed in the next report of the Intergovernmental Panel on Climate Change.

change, but how is that going to look on the ground?" he asks.

In 2015, the Paris climate agreement established a goal of limiting global warming to "well below" 2°C. In the most recent report of the Intergovernmental Panel on Climate Change, researchers surveyed possible road maps for reaching that goal and found something unsettling. In most model scenarios, simply cutting emissions isn't enough. To limit warming, humanity also needs negative emissions technologies (NETs) that, by the end of the century, would remove more CO_2 from the atmosphere than humans emit. The technologies would buy time for society to rein in carbon emissions, says Naomi Vaughan, a climate change scientist at the University of East Anglia in Norwich, U.K. "They allow you to emit more CO_2 and take it back at a later date."

Whether that's doable is another question. Some NETs amount to giant air-purifying machines, and many remain more fiction than fact. Few operate at commercial scales today, and some researchers fear they offer policymakers a dangerous excuse to drag their feet on climate action in the hopes that future inventions will clean up the mess. "In many ways, we're saying we expect a bit of magic to occur," says Chris Field, a climate scientist at Stanford University in Palo Alto, California, who instead favors drastic emissions reductions. Others say we no longer have a choice—that we have dallied too long to meet the Paris targets solely by tightening our belts. "We probably need aggressive and immediate mitigation, plus some negative emissions," says Pete Smith, a soil scientist and bioenergy expert at the University of Aberdeen in the United Kingdom.

One particular technology has quietly risen to prominence—thanks to global models—and it is the one on tap in Bozeman. The idea is to cultivate fast-growing grasses and trees to suck CO_2 out of the atmosphere and then burn them at power plants to generate energy. But instead of being released back into the atmosphere in the exhaust, the crops' carbon would be captured and pumped underground. The technique is known as bioenergy with carbon capture and storage, or—among climate wonks—simply as BECCS.

Few at the Bozeman meeting have heard of BECCS, and most are suspicious; it sounds like a far-fetched scheme that might disrupt the world as they know it. During a break, Martha Kauffman, a regional director for the World Wildlife Fund in Bozeman, wonders whether BECCS might encroach on lands used to graze cattle. In grasslands like this, she says, "It's the pri-

CREDITS: (GRAPHIC) K. SUTLIFF/SCIENCE; (DATA) GLEN PETERS/CICERO mary way people make a livelihood while keeping habitat."

She's not the only one who's wary. Although BECCS is relatively cheap and theoretically feasible, the sheer scale at which it operates in the models alarms many researchers. In some future scenarios, BECCS would remove up to a trillion tons of CO_2 from the air by the end of the century—about half of what humans have emitted since the start of the Industrial Revolution—and it would supply a third of the globe's energy needs. Such a feat would require growing bioenergy crops over an area at least as large as India and possibly as big as Australia—half as much land as humans already farm. "It is easy to say, 'Hey, globally, how about we just do this, guys?'" Stoy says to the room. "But what is actually going to happen?"

Stoy and a team of researchers hope to provide answers gleaned from the Upper Missouri River Basin, which includes parts of Montana, Wyoming, and the Dakotas. They have just launched a $6 million effort to study the impacts of BECCS on such things as local food production, water use, and biodiversity. In other words, what happens when you pluck BECCS from the idealized realm of global carbon accounting and plop it into a real place, with patchwork lands, messy politics, and interconnected ecological, physical, and economic systems? "Nobody's evaluated what these assumptions mean at the regional scale," says Ben Poulter, a carbon cycle modeler at NASA's Goddard Space Flight Center in Greenbelt, Maryland, and a leader of the project. "It's really important that we try to figure that out."

After all, the future of climate policy—and possibly the planet—hangs on the answer.

IN EARLY FALL, Montana's Gallatin Valley is a study in gold. Flame-leafed cottonwoods burn like candles along the narrow country lanes, and the hills wear a mantle of thick, honey-colored grass. Dale Flikkema, a third-generation farmer, almost blends into the landscape. With sandy hair and a sun-bronzed face, he surveys his field on the outskirts of Bozeman. Beneath the yellow canola stubble at his feet, stray seeds have sprouted into tiny sprigs of green. "These spilled from my combine," he says, kneeling to inspect them. Today, this food-grade canola—which can also be used to make biodiesel—is the closest thing to a bioenergy crop being grown in Montana. But under the models' BECCS scenarios, farmers like Flikkema would see big changes.

As BECCS is usually conceived, bioenergy crops would be grown on unused agricultural land. In the Upper Missouri River Basin, that could mean conscripting fields set aside as part of the U.S. Department of Agriculture's Conservation Reserve Program (CRP), which pays farmers to leave fields fallow for environmental benefits. Given the right incentives, farmers could pull these lands back into production—something that has already happened in the region as demand for corn and soy have grown. "Farmers are no different than anyone else. We are profit-driven," Flikkema says.

Here in Montana, farmers' bioenergy crop options are limited for now. Only a few adventurous growers like Flikkema are experimenting with canola and other oilseeds. As the climate warms, however, the entire region is projected to become more hospitable to plants such as switchgrass, a towering grass called *Miscanthus*, and vigorous poplar trees. These "second-generation" bioenergy crops are often seen as the future of bioenergy because, as perennials, they are far better at storing carbon in the soil and in their biomass than traditional fuel crops like corn and canola. They can also grow on marginal lands with less fertilizer and water, making it less likely they will compete with food production.

A bioenergy field trial in Wisconsin is evaluating how switchgrass, *Miscanthus*, corn stover, poplar trees, and native prairie grasses stack up against each other.

Once harvested, these crops would get ferried by truck or train to power plants and other industrial facilities where, along with waste from food crops and timber harvests, they would be burned for heat or electricity, or converted to ethanol and other liquid biofuels. The CO_2 given off by either process would be siphoned off and compressed into a fluid. That concentrated CO_2 would be piped away and pumped underground into porous rock formations, which abound in the Upper Missouri River Basin. Because of its long history of oil and gas production, the area is perforated with wells. Lee Spangler, an MSU chemist involved with the project, is studying whether any of the 11,000 wells near the Colstrip Power Plant in eastern Montana, for instance, would be good conduits for injecting carbon underground. The final result? Carbon is transferred from the atmosphere back to the geologic reservoirs from which it came.

BECCS isn't the only route to negative emissions. But alternative approaches, like capturing CO_2 directly from the air using chemical reactions or absorbing it with ground-up minerals added to soils, are just beginning to see their first real-world tests (see graphic, p. 734). These techniques could one day surpass BECCS, but for now, they cost more, Vaughan says. "BECCS will pay for itself to some extent because it generates energy."

BECCS isn't a total technological reach, either; its two components—bioenergy and CCS—are already happening to some degree today. Power plants around the world are burning biomass for energy, either alone or together with fossil fuels. CCS has been slow to take off, but dozens of projects are underway, including numerous pilots in the Great Plains, many of which pump CO_2 from fossil fuel power plants into dwindling wells to drive out residual oil. One of the longest-running operations is in the North Sea, where the Norwegian oil company Statoil has been separating CO_2 from natural gas and sequestering it underground for more than 2 decades.

To put the brakes on climate change, however, these tools would have to be deployed on an entirely unproven scale.

AS FLIKKEMA DRIVES BACK from his canola field, his blue pickup rumbles across a narrow irrigation canal. "Our lifeblood," he

A farmer harvests a poplar plantation in Germany. Wood chips can be burned to produce energy at power plants, where emissions can be captured.

remarks. Water is a scarce commodity in Montana, and irrigated crops are by far the biggest consumer of it, although lately, there is growing demand from the oil and gas industry. Poulter says BECCS could divert precious water that would otherwise support crops or native ecosystems. "Water already defines land use in the West and is bound to be an issue," Poulter says. According to one global assessment, using switchgrass to sequester 3.7 billion tons of CO_2 would use almost as much water as is in Lake Michigan, and many scenarios require that much carbon or more to be removed each year. (The same study concluded that BECCS would eat up the equivalent of a quarter of the world's annual nitrogen fertilizer production, too.)

Critics are also concerned about BECCS's big footprint. "It worries me that the landscape already has to produce food, and now we will rely on it to produce energy, too," says Meghann Jarchow, an ecologist at the University of South Dakota in Vermillion. The prairies of the Upper Missouri River Basin are home to iconic species such as the prairie dog and provide critical habitat for many grassland birds, but they are losing ground to food production and, increasingly, to bioenergy crops. BECCS could make the problem worse.

Some BECCS advocates disagree, saying that if it were done right, it could be a boon for the environment. Today, much of the abandoned farmland where second-generation bioenergy crops could grow is degraded and dominated by invasive plants, says Phil Robertson, an ecologist at Michigan State University's W. K. Kellogg Biological Station in Hickory Corners. "Generally, it doesn't have high conservation value," he says. But field studies in the Midwest suggest that planting native switchgrass, with a few other plant species thrown in for good measure, could actually help restore the grassland ecosystems that once covered the middle of the continent. With smart policies in place, Robertson envisions a world in which farmers could turn the profits from bioenergy harvests back into restoring more land. "I think it could underwrite conservation," he says.

Worldwide, there is no shortage of farmland that's been abandoned because of low productivity or fickle markets. A conservative estimate by Field and his colleagues suggests an area at least the size of India is available globally, and others suggest there is several times that—plenty to support a robust BECCS industry. But more farmland may also be needed to feed a global population that could peak between 8 billion and 12 billion people sometime this century. Most model scenarios make a big assumption: that rising agricultural productivity and vegetable-based diets will limit the need for new farmland. But the real world, where demand is growing for meat and dairy products that require lots of land, could be a different story.

Researchers like Vaughan worry that without strong regulations, surging demand for bioenergy could displace food crops—causing prices to rise—or push farmers into uncultivated lands. Past experiments with biofuels also brought new land into cultivation, which not only threatened biodiversity, but also undermined some of

PHOTO: AGENCJA FOTOGRAFICZNA CARO/ALAMY STOCK PHOTO

the climate benefits of bioenergy in the first place. That's because cutting down trees to make new farmland, for example, releases far more carbon into the atmosphere than bioenergy crops can sequester. "That can wipe out any future benefit for years to come," Robertson says. Even planting crops on abandoned fields, like CRP land, can create a sizable carbon debt if soil is tilled, which releases CO_2.

Then there are the economics. Getting farmers to grow specialized crops will require proper incentives. "The markets will have to come for guys to change," Flikkema says. Farmers here didn't start growing soy until a local elevator started buying it, he says. To establish BECCS in the Upper Missouri River Basin and worldwide, governments will have to set a price on carbon—through something like a tax or a cap-and-trade program—and use the proceeds to incentivize individual farmers to grow bioenergy crops on their land.

These headwinds lead many researchers to conclude that the amount of BECCS in models is unrealistic. "Nobody is actually saying it's coherent," says David Keith, an engineer and climate policy expert at Harvard University who wrote some of the early papers on BECCS. Keith, who has since helped launch a direct air capture company, says the modelers seized on BECCS because it was one of the few ways to simulate negative emissions—and negative emissions were one of the few ways to try to keep warming below 2°C.

Modelers stress that scenarios are not projections of the future, and shouldn't be treated as such. "They're what-if pathways," says Katherine Calvin of the Pacific Northwest National Laboratory in College Park, Maryland. But Keith says that hasn't stopped BECCS from attracting undue attention. The result, he says, is a perilous mismatch between models and reality that presents a "moral hazard" by committing future generations to technological solutions that may not work in the end.

It's an accusation that has often been lobbed at Keith's main area of study: geoengineering Earth's climate to counteract warming by, for instance, injecting particles into the sky to reflect sunlight. Keith is miffed that many policymakers see geoengineering as a "completely crazy, risky, way-out-there thing we shouldn't talk about" while remaining sanguine about massive reliance on negative emissions. "If moral hazard is sweeping the problem under the rug, and pushing more of it to future generations, and making it look like you are meeting the targets when you are not," he says, "that is for sure what's happening with BECCS now."

A pilot project in Ketzin, Germany, is monitoring the long-term storage of carbon in a porous layer of sandstone hundreds of meters underground.

PHOTO: NESTOR BACHMANN/DPA/PICTURE-ALLIANCE/NEWSCOM

BY THE END OF THE DAYLONG MEETING in Bozeman, Stoy and Poulter have made progress on their first goal: spreading the word about this arcane acronym, BECCS. But most of the work, and the loftier questions, lie ahead. Stoy raised one earlier that day: "How can we not just run roughshod over the entire northern Great Plains?" Or, by extension, the world?

To that end, the team will use detailed physical models to construct a handful of scenarios for the region. At one end of the spectrum is a world that goes long on BECCS, with farmers using CRP land, and maybe even existing cropland or virgin prairie, for bioenergy. At the other end is a future that sacrifices some amount of carbon storage for the benefit of conservation, food production, and other local values. In this future, there would be only a small amount of BECCS. Instead, most carbon would be stored by protecting forests, adopting no-till farming practices, and taking other climate-friendly approaches to land stewardship. A recent study found that such actions, carried out on a global scale, could provide a cheap and easy way to accomplish a third of the CO_2 mitigation needed in the next decade to be on track to meet the Paris goals.

The team doesn't know which of its scenarios will come to pass. But it does know that, as atmospheric CO_2 continues to rise and the world warms apace, time is running out for countries to decide whether to count on negative emissions. If we are going to rely on technologies like BECCS in the future, we need to start ramping them up now, says Sabine Fuss, an economist at the Mercator Research Institute on Global Commons and Climate Change in Berlin. "It's a little bit dangerous if it's conceived as something that you just switch on." So far, only one commercial plant is doing anything close to BECCS—a bioethanol refinery in Decatur, Illinois, that each year sequesters 1 million tons of CO_2 released from fermenting corn.

The researchers repeatedly try to impress this upon the audience in Bozeman—that despite its many risks and drawbacks, they should take BECCS seriously. Some amount of BECCS, or some other carbon-eating technology, is probably coming. "Even though it's very fantastical at this point to think it could happen," Poulter says, "it's one of only a few remaining options we have to deal with this problem."

BECCS would bring sweeping changes to the region, but then again, so will climate change. Indeed, among all the options the team will consider in its study, there is one it won't include: allowing the Upper Missouri River Basin to stay the same. ■

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Science

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