THE CIRCULAR ECONOMY

The future could be powered by a new economy of sustainability: Large-scale systems reduce waste as they produce better food and biofuel while recycling carbon from the atmosphere.

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INTRODUCTION

A circular economy is functioning all around us, underpinning everything, from the food we eat, to the energy we have available to us, to the quality of our collective lives and the health of our planet. Similar to other economic models, the value derived from the circular economy increases as efficiencies are enhanced and employed on a larger scale.

This circular economy uses a different kind of currency from the other economies we know: It uses carbon. While not particularly plentiful on earth—it ranks 19th in abundance of elements in the earth's crust—carbon is noteworthy because it forms more compounds than all the other elements combined. Because of that tendency, it's in most everything, and is a key building block of life in both plants and animals.

Carbon is a key element of fossil fuels, derived from "fossil" plant and animal matter sequestered in the ground, where it doesn't cause an issue. The problem is, the world needs energy, and hydrocarbons are outstanding energy carriers. They also have outstanding energy density, a key characteristic when thinking about how to power aircraft that need not only to carry cargo, passengers and their own weight, but also the weight of the fuel, efficiently, and over long distances. When we refer to hydrocarbons, we're using a generic term for a chain of carbon atoms bonded to one another, with each carbon also bonded to hydrogen atoms. When hydrocarbons are burned, they release large amounts of energy, and result in carbon dioxide being emitted to the atmosphere. The energy is necessary; it's the source of the carbon that is where the issue arises.

Imagine we have a huge savings account in the bank—that's the carbon in the ground, oil and gas and coal reserves. But the good news is we also have a big wad of cash in our wallet, enough to cover any expense we could think of: that's the carbon in the atmosphere.

The linear economy as manifested in the use of fossil fuels for energy is unidirectional. Fossil fuels, which provide so much energy, have dominated since the Industrial Revolution, and their long-term effects of resource extraction, production, consumption, and disposal are having a cumulative effect: 73 percent of greenhouse gas emissions are tied to this energy sector, according to Our World in Data.

Carbon sequestered in the ground does not pose a problem, but when carbon dioxide is released into the atmosphere, it acts as a greenhouse gas, trapping heat. Along with the carbon, fossil fuels can release other chemicals and particulates that may adversely affect the quality of air and water.

Knowing all of this, the entire premise of using renewable hydrocarbon fuels to reduce greenhouse gas (GHG) emissions is based on using resources that are already engaged in the carbon cycle, rather than adding in more fossil-based carbon.

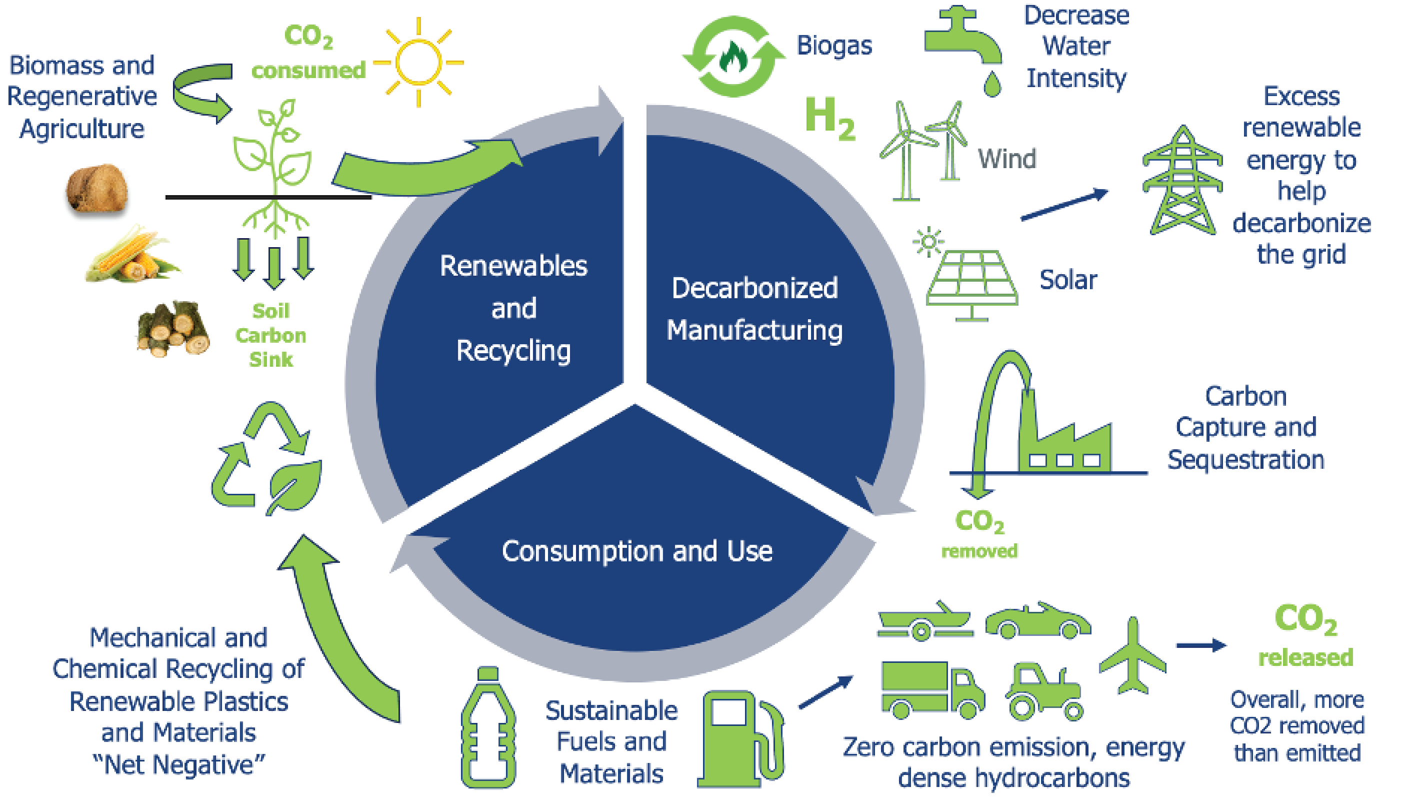
Renewable hydrocarbons are made from biogenic carbon—carbon from living things, specifically plant materials, such as our feedstock. Carbon dioxide in the atmosphere, because it is already part of the carbon cycle, is sustainable as it is recycled.

Think about carbon like it is money and it becomes easier to understand. Imagine we have a huge savings account in the bank—that's the carbon in the ground, oil and gas and coal reserves. But the good news is we also have a big wad of cash in our wallet, enough to cover any expense we could think of—this is the carbon in the atmosphere, ready to use any way we can figure out. Why would we go to the bank to make a huge withdrawal, over and over again, when we can pay in cash from our wallet?

That's exactly what the world has done by using fossil fuels rather than drawing on the carbon already in circulation in the atmosphere. As a result, nature's system for pulling carbon out of the atmosphere can't keep up with our GHG emissions. And actually, we didn't understand how these emissions would affect the climate until scientists started to uncover the impacts and provide future projections for where we are headed if we don't change the way we use carbon today. Too much carbon in the atmosphere causes climate change, pushing the systems that sustain our world's ecology out of balance. Up to this point in our human history, we did not have the technology available to make drop-in hydrocarbon fuels from renewable carbon. Now that's changed with the advent of technologies that companies like us (and a select few others) expect to bring to market.

As an alternative, Gevo has come up with ways to create bio-based renewable fuels that use carbon already in the atmosphere, drawn into plants, specifically No. 2 dent corn as it grows from seed to more than six feet tall across millions of acres. Through use of the Argonne GREET model (The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies) developed and refined by Argonne National Laboratory under the auspices of the U.S. Department of Energy, we have determined that the carbon intensity of our processes can achieve net-zero emissions and even net-negative emissions when we take into account the sequestration of carbon in the soil through the use of sustainable and regenerative agriculture techniques and renewable energy in production processes.

In other words, technology has finally caught up, and Gevo has been on the vanguard of evolving our approach to renewable fuel technology. This means focusing on true sustainability. A big part of that is increasing the efficiency of agriculture to allow us to improve production of high-value nutrition products. Efficiency means cutting out the waste, so we're also developing advanced renewable fuels with enough energy density to power cars, trucks, boats, and airplanes. Our fuels are expected to meet or exceed the standards set



and upheld for petroleum-based fuels (remember, those standards were first written with petroleum-based fuels in mind), and if our fuels meet (or exceed) those standards, they can be freely mixed and blended with those fuels with no impact on performance.

Now we have the technology to reverse the cycle of emitting GHGs by burning fossil fuels. We need to use the carbon already in circulation, in combination with the world's existing systems, to help keep our world fed and its economy thriving, all the while helping our planet to begin to heal itself.

THE CIRCULAR ECONOMY

Part 1: Down on the Farm

The process begins in America's Heartland, where No. 2 dent corn is raised in huge quantities by farmers who have been stewards of the land for generations. These farmers know their plots, and they understand how to get more corn out of each acre, while growing healthy soils rich in carbon and nutrients. Their land is their future. It is their asset to make money. Anyone who thinks a farmer doesn't care about his or her land is simply out to lunch.

As far as the corn goes, people do not eat this corn—it's inedible to humans and is not sold in grocery stores. There's a different kind of corn that can be eaten directly. The variety of corn in our area of the Midwest is grown primarily for its nutritional protein content, which becomes high-value nutrition products. This protein-rich product can be used to feed beef cattle and dairy cows, as well as swine and poultry. All of these animals convert this vegetable protein into forms of protein that contain all of the essential amino acids needed for human nutrition.

Those animals play a critical role in the circular economy as well, both economically and nutritionally. We've all heard about cows and their emissions. Cows need a diet that will meet their nutritional requirements, but the feed program also must achieve goals for growth and cost to the stockman. Dial in the diet and cows suffer less enteric fermentation that results in methane emissions, while also achieving production targets. The high protein content of our product makes it a key additive to virtually any optimized feeding program. The process we use at our production plants

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provides a ready stream of this corn protein, while also leaving a waste stream of carbohydrates that we use to make fuel.

Smart farmers have been using technology as part of an effort to take a holistic approach to improve yield, eliminate waste, and make their operations more efficient, and livestock plays a key role in advancing the cause substantially. Beef cattle, dairy cows, swine, poultry, and other livestock eat feed and produce meat and they also provide other resources, particularly manure that redistributes nutrients when it is used as fertilizer.

The LCA is widely considered to be the best yardstick of true carbon intensity in fuels and chemicals produced to replace fossil fuels, because this metric takes into account the full range of carbon emissions and sequestration from all steps of the process.

Science and technology are key to improving the sustainability and yield of each acre of farmland. Farmers use satellite imagery to target problem areas in fields where insects, drainage problems, and other factors have a negative impact. They program their tractors and harvesters with GPS-controlled precision. Farmers have a deep understanding of the fields they work, and they know the soil is their key resource to make each year a success. That soil is made up of a combination of mineral and organic matter, and farmers don't just take away from the fields when they harvest, they know they must replenish the soil to keep a field producing year after year.

How do they do that? Well for one thing, they use what's known as strip-tilling or zone-tilling, where they set their machinery to only till a four-inch-wide strip of soil, planting the seeds in rows and fertilizing directly in the strip where it can do the most good. This process keeps the soil in place. Even better, the farmers till these strips between the rows of last year's corn, leaving the root structure of the previous year's crop in the field to decay and become organic matter in the soil. The nutrients still contained in the root and stalk of the corn left in the field after harvest get into that soil and stay there, building that healthy soil to help next year's plants grow better, and need less fertilizer to do it. It happens every year.

This is just one aspect of sustainable agriculture, but in truth it's part of the big picture, a more holistic approach that all works together. Farmers plant cover crops, which help slow the flow of greenhouse gases from fallow fields, a natural process. Farmers who pursue biodiversity have better luck with soil health and sequestering more carbon. There are soil amendments that stimulate root growth and are shown to grow the carbon content in the soil around the roots.

Organic matter, by definition, contains carbon, so when it finds its way into the soil, it's the start of the process of locking that carbon back in the ground. As Gevo makes sustainable aviation fuel, it captures carbon in the soil—Argonne National Laboratory is currently reviewing our process to see just how much carbon is sequestered per gallon of sustainable aviation fuel or renewable premium gasoline. Increasing carbon in the soil offsets the impact of fossil fuels, but because that carbon enriches the soil, it also increases feed and food production for a growing global population.

The use of this natural carbon storehouse could allow us to sequester an additional 1 billion to 3 billion tons of carbon annually. That's equivalent to roughly 3.5 billion to 11 billion tons of carbon dioxide emissions. According to the ICAO Carbon Emissions Calculator, a commercial airliner flying from New York to

Los Angeles will burn nearly 74,000 kg of fuel (more than 163,000 pounds) and emit nearly 89,000 kg of carbon dioxide (more than 196,000 pounds), or 98 tons. The EPA shares another measurement and tells us a typical passenger vehicle emits about 4.6 metric tons of carbon dioxide per year. This assumes the average gasoline vehicle on the road today has a fuel economy of about 22.0 miles per gallon and drives around 11,500 miles per year. Every gallon of gasoline burned creates about 8,887 grams of carbon dioxide.

The Fifth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC) estimated a total mitigation potential of 1.6 to 4.6 gigatons CO_2e by 2030 with agriculture and livestock best practices. Researchers at Purdue University tell us that low-till and no-till practices on U.S. cropland today sequester 52 million metric tonnes of carbon, but that those techniques could sequester more than 123 million metric tonnes of carbon each year if used on all U.S. cropland—that's equivalent to two percent of all U.S. CO_2 emissions. Additionally, if cover crops were used to reduce emissions on all U.S. farmland, they could sequester 147 million metric tonnes of carbon.

Combine these techniques with probiotic soil amendments such as those developed by Locus Ag, and greater root development could potentially serve to increase the effect of soil carbon capture to the magnitude of tens of kilograms per gallon of fuel produced.

Part 2: Making the Most of Every Acre

With a circular economy, the feedstock is key. When it's grown sustainably, it provides the spark for the rest of the process. Gevo is developing its Net-Zero plants in areas where the feedstock is ample and sustainable. Gevo buys the corn from area farmers—often it's hauled in by farm tractor—a short trip that further reduces carbon intensity.

We let economics drive the process, and keep the corn grown by our partner farmers in the food chain as a critical product for our business. We make both food and fuel from the same corn. It's like adding a new product line to the same acre of farmland without additional investment in raising the crop. This kind of thinking is a core principle at Gevo.

Our process separates out the parts of the corn for the uses to which they are best suited. We separate out the corn oil, a pure lipid derived from the germ of the corn, and we sell that as a separate product—a direct addition to the food supply.

We use fractionation to separate out the protein and the starch. The protein goes into a high-value nutrition product that supplies nutrition to aquaculture, livestock, and pets. At our Net-Zero 1 plant in Lake Preston, South Dakota, we expect to produce eight pounds of high-value nutritional products for every gallon of liquid hydrocarbon fuel made there. The foodchain is important to us, and we're serious about keeping protein flowing to people—to the tune of 365 million pounds of it each year at each net-zero plant.

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The protein is more valuable than the starch on a weight basis, and by using it as animal feed—something for which whole corn was used in the past—the livestock get a better diet. This feed, when part of an optimized ration, can help result in leaner, healthier animals who produce less gas, such as burps and flatulence, because of their diet. According to "Growth Performance, and Enteric and Manure Greenhouse Gas Emissions from Murrah Calves Fed Diets with Different Forage to Concentrate Ratios" (by Rampoothri, Modini, Malla, Mondal, Pandita, National Center for Biotechnology Infromation, part of the National Institutes of Health, 2018), studies reviewing concentrations of different types of feed can affect the emissions from enteric fermentation. Those cow burps add up—enteric fermentation in animals results in methane and accounts for 28 percent of the agriculture emissions overall in the U.S., according to the EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2006 (2008).

Many people in the world do not get enough protein. A healthy diet is a diverse mix of cereal grains, fruits and vegetables, and protein, and people who don't eat that way can suffer malnutrition. Protein is often considered the most expensive piece of the puzzle, but it has to be the right kind of protein: The complete amino acid profile for animal protein is the one that people need, and, while meat is a great source, dairy and eggs are additional sources of protein with the essential amino acids. These sources can get the right kind of protein to populations who avoid certain types of meat or otherwise are vegetarian.

After the protein and oil are taken out, the leftover carbohydrate—the starch from the corn—also gets used efficiently. Our Net-Zero plants are designed to be fitted out with the equipment to make next-generation fuels. The starch and other cellulosic carbohydrates can be fermented and put through a process to make isobutanol, a four-carbon alcohol that serves as an intermediate building block to create isooctane and sustainable aviation fuel. The plant will also be able to produce ethanol from the same sustainable feedstocks, and Gevo has some exciting applications in its intellectual property portfolio, including renewable diesel fuel and ethanol-to-jet SAF.

A Word About Sustainability

Gevo's process to manufacture isobutanol and ethanol is more energy-efficient than other renewable fuel production methods, but it still has electrical and thermal demands, which potentially could add to the carbon footprint of Gevo products. The smaller the fossil footprint, the better. We want to keep carbon intensity out of our business system as much as we practically can. All of this is a key aspect of the Circular Economy—economizing that currency of carbon to use what's in circulation and not touch what's in the bank.

Farmers who keep livestock as a complement to growing corn have a natural source of inexpensive fertilizer from manure that keeps the nutrients from the corn on the farm, without trucking in synthetic fertilizers.

It doesn't do any good to invest in the research and science of taking the fossil fuels out of isobutanol, isooctane, and aviation fuel if the facility has to draw electricity off the coal-burning electrical grid to run our processes.

To reduce the carbon factor, Gevo has partnered with wind turbine company Zero6 Energy (formerly known as Juhl Energy) to provide renewable electricity through wind power for our plants as we develop them. Whenever possible, we want to ensure the transmission wire from the wind turbines goes directly to our plant, so it meets all the requirements for counting toward sustainability.

We are planning to biogas for thermal energy at our Net-Zero plant. By placing dairy cow manure placed in a digester, we can capture biogas that can add thermal energy.

Net-Zero 1 may be unique. Once the facility is online, we believe it will be the only industrial plant of its size and scale that will not rely on any electricity from the grid. By taking carbon out of every step of the process, Gevo expects to reduce the carbon footprint of every gallon of advanced fuel it produces. It passes the carbon savings along to every consumer as everyone does their part to reduce GHG emissions.

Part 3: Power to the People

The fuels produced by Gevo are expected to go to the market and power the world. Each gallon of next-generation fuel that enters the market replaces a gallon of fossil fuel that would otherwise be burned in a jet, or city bus, or car, or boat, or lawnmower.

Isobutanol is the building block for other fuels that we produce and market, but it's a product in its own right, born of our synthetic biology to create a yeast that manufactures it in our proprietary fermentation methods. Isobutanol is a blendstock oxygenate for gasoline and works well in marine and small engines.

Sustainable Aviation Fuel (SAF): While there are nine different pathways to creating renewable jet fuel, Gevo uses the Alcohol-to-Jet synthesized paraffinic kerosene or ATJ-SPK method to create the necessary 12-carbon chain from its isobutanol, and also has plans to commercialize ethanol-to-jet versions of the pathway.

Isooctane: This gasoline replacement is already in use in auto racing in Europe and for packaged fuels. Gevo uses its isobutanol as a base to create the eight-carbon chain found in the fuel cells of the fastest racecars.

Renewable Gasoline: Gasoline blended from isooctane made

from corn or other renewable feedstocks, and blended with isobutanol or other renewable oxygenate will have low carbon intensity and a reduced carbon footprint. Gevo already makes the components, and as costs fall, this may be the fuel of the future for personal transportation.

Renewable Diesel: Diesel drives much of the freight hauling and human transportation around the world, and to have a renewable replacement would reduce a large part of the world's transportation carbon footprint and attendant GHG emissions. Gevo has developed a way to make biodiesel from isobutanol and fusel alcohols, natural byproducts of the fermentation process.

Ethanol: It's the original fermented fuel blendstock, made from corn and lignocellulosic feedstock. While ethanol is a renewable fuel on its own and is widely used as a blendstock to add a bio-based component to gasoline, it has recently become a key part of Gevo's plan as a building block for other advanced renewable fuels. Gevo has recently completed deals to produce advanced renewable fuels along ethanol-based pathways, including ethanol-to-jet SAF and renewable diesel.

Isobutylene: We have developed fully renewable carbon-based para-xylene, a key ingredient to convert petro-based polyester for fibers and bottles to 100-percent renewable content. The chemicals we produce have the same makeup as the fossil versions, but draw the carbon in their molecules from the atmosphere.

Life-Cycle Assessment

GHG emissions for bio-based hydrocarbon fuels are most commonly evaluated through a life-cycle assessment, which calculates the amount of greenhouse gases that are released per unit of fuel over the entire production process, from the growing of the corn to the process and delivery, to the emissions when they are burned. Emissions reductions are higher for advanced renewable fuels. (Environmental Energy and Study Institute, "Biofuels Vs. Gasoline: The Emissions Gap Is Widening," September 2016). Gevo's product line focuses on decarbonization of the process to give each of its biofuels, chemicals, and co-products the lowest carbon life-cycle assessment (LCA) possible. Sadly, not all LCA models are the same. Some groups choose to use emissions factors and allocation mechanisms that are not fully transparent or scientifically accurate. At Gevo, we have chosen to set the bar as high as possible today by using the best-in-class LCA tool, Argonne National Laboratory's GREET model.

The corn in our area of the Midwest is grown primarily for its protein content, which becomes high-value nutrition products. Animals turn vegetable protein into a complete protein that supplies essential amino acids for human consumption.

Using advanced bio-based fuels releases carbon into the atmosphere. That's a fact of using internal combustion engines to burn hydrocarbon fuels to create power. Remember our carbon-money analogy? With renewable fuels, the carbon that's released into the atmosphere is coming from the carbon-stuffed wallet, not from that bank account of fossil-fuel carbon. And every gallon of Gevo advanced fuel coming from sustainably grown corn sequesters more carbon in the soil, putting it back in the bank.

The carbon dioxide that's released as GHG emissions is gathered up by the cornfields as millions and millions of corn stocks grow from seed to more than six feet tall, storing carbon in stalks and roots, leaves, and most importantly, corn kernels. And they draw more carbon from the atmosphere as new seed is planted each spring and stalks grow to maturity each year. By making energy from the carbohydrate or starch of the corn, that has little nutritional value to the foodchain, we're able to multiply the effectiveness of every acre.

A Word About Tracking Sustainability

While it's great to beat the drum of sustainability, it must be tracked transparently and certified to be an effective way to combat GHG emissions. Distributed Ledger Technology, or DLT, is an immutable tool that allows tracking of data with a product and the transactions associated with the product. Originally developed as an underlying branch of blockchain technology, DLT allows Gevo to attach the key metrics for sustainability to each gallon of fuel, and therefore enable a "sustainability" assurance that has not yet been seen. The data associated with certain key metrics for measuring sustainability are suitable for being digitized through blockchain, and could lead to tokenization of those attributes. Gevo is working with Blocksize Capital to introduce Verity Tracking, which will use DLT to enable Gevo and other companies to sort out what is truly valuable in the end market, assign the correct value to it, and then set up market mechanisms to share value upstream. Eventually, this will help create a system that rewards the value chain for improving sustainability.

Part 4: Food Must Always Come First

At Gevo, we understand the need to keep the food supply whole—food security is just too important. We would never take cropland

away from the critical role that it plays in the health of global population. Instead, we've found a better way.

Protein is critical to the food supply, and meat is cited by studies as the source for 18 percent of the world's protein consumption, and meat consumption grew by 60 percent between 1990 and 2009 (Henchion M., McCarthy M., Resconi V.C., Troy D., "Meat Consumption: Trends and Quality Matters," Meat Sci. November 2014).

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Livestock feeding programs need to be optimized—it will help the rancher achieve production targets on a budget, while making better food as a result. Optimized feeding is the way forward, and our high-value nutrition products help hone the diet. A proper diet reduces methane emissions from livestock. Methane is a greenhouse gas that is widely understood to retain atmospheric heat more effectively than carbon dioxide.

Farmers who keep livestock as a complement to growing corn have a natural source of inexpensive fertilizer from manure that keeps the nutrients from the corn on the farm, without trucking in synthetic fertilizers. Many people cite the contribution to GHG emissions as a reason to stop raising livestock, but nutritionally it's just too important.

This manure is also a source of methane, a greenhouse gas that is more than 25 times as potent as carbon dioxide at trapping heat in the atmosphere, according to the EPA. At Gevo, we saw a triple opportunity: prevent the methane from being released to the atmosphere, while also capturing it for use as a renewable energy source, and still having an effective fertilizer left over. After all, the carbon contained in manure-based methane is sourced from the plants. We established a cluster of digesters in Northwest Iowa and worked with local farmers. We use microorganisms called methanogens as a biocatalyst to break down the manure in the digesters, capturing the resulting methane, while also producing fertilizer that still contains all the nutrients the farm needs, with reduced methane emissions from spreading it on the fields. It's addition by subtraction.

Smart farmers have been using technology as part of an effort to take a holistic approach to improve yield, eliminate waste, and make their operations more efficient, and livestock plays a key role in advancing the cause substantially.

CONCLUSION

The Circular Economy follows the path of carbon atoms that are released from advanced bio-based fuels into the atmosphere. As they are drawn into by the biomass of a cornfield that yields corn to be used in making advanced fuels, these carbon atoms go back through the process and get used again and again. The benefits of taking this carbon from renewable sources keep the fossil carbon in the ground, where it belongs, while sequestering even more carbon in the soil.

The Circular Economy is properly named because it is the economic forces of human existence that drive it. Gevo uses the power of demand to drive the sales of high-value nutrition products and the use of sustainable fuels. The production of isobutanol can be directed to a variety of fuel types, to meet market demand. And farmers who work with Gevo benefit from their farm research to derive best practices that result in improved yield.

The world is facing a huge problem, and it's going to take every idea to begin to reverse the flow of carbon into the atmosphere: sustainable farming and regenerative agriculture, optimized livestock feeding programs, widespread adoption of advanced renewable fuels, large-scale use of renewable energy to power the grid, vehicle electrification, scaling up of biogas and renewable natural gas, clean hydrogen, and the list will continue to grow as efficiencies are discovered.

As economic factors ranging from climate change and food supply needs to population growth add to the equation, sustainability will become even more economically desirable, and more feasible. And Gevo will be on the leading edge.