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Carinata is a crop that produces an energy-rich oil and can help to sequester carbon.

The biofuel course correction

Refineries that convert biomass to energy are expanding. Attention must be paid to how feedstock crops change soil carbon. **By Peter Fairley**

Russia's invasion of Ukraine is squeezing global oil supplies and inflation is jacking up prices at the pumps. Although petrol prices have started to fall in recent months, the situation has delivered a powerful reminder of the world's dependence on fossil fuels.

It also means biofuels are having a moment. The corn-ethanol industry boasts that blending its product into petrol is saving consumers money and creating jobs in the farming communities that supply its distilleries.

Refiners producing renewable diesel fuels for long-distance lorries are expanding as fast as they can. Some are building biorefineries designed to process palm, soya and canola oils, whereas others are adding vegetable oils and animal fat to their petroleum feedstocks. Petrochemical producer Phillips 66 is investing US$850 million in its refinery in Rodeo, California, to convert it to exclusively process bio-feedstocks. And, according to market analysts, US refinery expansions that have been announced could boost the demand from biofuel manufacturers for soya bean oil beyond the country's total supply. If filling fuel tanks with these plant-derived liquids reduces carbon emissions by decreasing the demand for fossil fuels, it would help to tackle the climatic shifts that threaten humanity and biodiversity.

In principle, the sustainability of biofuels seems obvious. Carbon cycles in and out of the atmosphere as biofuel crops grow and vehicles burn the fuel they produce. But claims by industry that biofuels deliver greener transport have been battered by a relentless flow of reports. Indeed, the first-generation biofuels that are the market leaders seem to be little better for the climate than fossil fuels. A 2022 assessment[1] of the US Renewable Fuel Standard found that the programme – which requires that transportation fuel contain a minimum volume of renewable fuel, and which drives nearly half of global biofuel production – has probably increased greenhouse-gas emissions. That counter-intuitive outcome is a result of farm operations involving diesel-fuelled tractors and fertilizers made from natural gas. The fertilizers release nitrogen oxide, a greenhouse gas that is nearly 300 times more potent than carbon dioxide. Even farm soils can release stored carbon that is essential to their resilience and fertility.

Worse still, the increase in demand for biofuel crops has extended farming onto marginal lands, damaged biodiversity and increased water use and contamination, as well as pushed up the price of agricultural commodities and thereby exacerbated food insecurity. The authors of the 2022 assessment conclude that only "profound advances" in practice and policy will make the US programme sustainable.

Agronomists, crop geneticists and carbon emission life-cycle scientists agree. To make agriculture smarter, farmers need to pay close attention to what crops work best where, and how those crops are grown. Embracing regenerative farming methods, such as reduced tilling of the soil, can retain carbon and nutrients. So, too, can planting an emerging set of winter oilseeds that can be grown seasonally between food-crop rotations. This would generate revenues that could pay for a soil-saving practice called cover cropping that few farmers have embraced so far.

"We cover crop less than 2% of our land. If you go to 40–50%, you're meeting this huge global demand for low-carbon feedstocks," says Glenn Johnston, referring to the process of growing a crop to protect and improve the soil – a crop that, in this case, can also be used to make biofuel. Johnston leads regulatory and sustainability programmes for agribusiness firm Nuseed at its research centre near Sacramento, California.

Despite this promise, the new era of biofuels still poses environmental concerns. Researchers argue that regulation needs to be much improved to ensure that the industry arcs towards sustainability. Tracking carbon is a complex process full of pitfalls. Get it wrong and biorefineries could end up as one more environmental panacea that bites the dust.

Digging deeper

A decade ago, a transition to better biofuels seemed imminent. A new generation of commercial-scale biorefineries was coming online in the United States, Brazil and Europe. They were designed to make ethanol from fibrous cellulose-rich feedstocks such as agricultural leftovers, grasses or fast-growing trees that generally thrive on marginal farmlands and require less intensive cultivation than corn or soya beans. By now, these cellulosic biofuels made from sustainable feedstocks were supposed to be gushing into the fuels market, trimming transport emissions – the fastest-growing source of CO_2 worldwide.

Alas, the flow of cellulosic fuel is barely a trickle. Processing equipment proved hard to operate, petrol prices fell and governments eased mandates designed to force the pricier cellulosic fuels into the market. "Ultimately all of those facilities struggled. Most are either producing at very low levels today or not producing at all," says John Field, who studies the climate mitigation potential of bioenergy systems at Oak Ridge National Laboratory in Tennessee.

What didn't stop were the generous incentives pushing food-based biofuels, and their shortcomings. Europe's renewable energy directive drove logging and slash burning of tropical rainforests in Brazil, Indonesia and elsewhere to make way for soya bean and oil palm plantations, displacing Indigenous communities and wildlife and releasing the rainforests' massive carbon stocks. And the carbon does not only come from the trees; even more can be released from soil as it heats up and dries. Indeed, soil holds roughly three-quarters of the organic carbon in Earth's biosphere.

Newer programmes that tie biofuel incentives to their carbon intensity, such as California's low-carbon fuel standard, still fail to prevent unintended consequences that can come from a change in land use, says Ben Lilliston, director of rural strategies and climate change at the Institute for Agriculture and Trade Policy in Minneapolis, Minnesota. Demand for feedstocks can release carbon that is stored in forests and farm soils in ways that regulators struggle to factor in. For instance, in the past five years or so, US biorefineries have bought a growing share of US soya bean harvests. This can indirectly bump up carbon releases because soya bean producers elsewhere scale up to meet US soya demands.

The resulting carbon debt might never be repaid. According to a 2020 study[2], once land-use impacts are taken into consideration, the carbon intensity of palm oil-derived biofuels is triple that of petroleum fuels.

Farming to supply biorefineries also imposes an opportunity cost because, in many cases, restoring the same land to forest or native grasses would offer greater net carbon reduction. "The typical analysis of biofuels in effect ignores this cost – it treats land as free, from a climate perspective," says Tim Searchinger, the technical director of the food programme at Princeton University's Center for Policy Research on Energy and the Environment in New Jersey.

The land-use and life-cycle studies required to fully account for a biofuel's carbon footprint or saving are complex and expensive – and can yield inconvenient results for biofuels producers. Furthermore, finding reliable data isn't easy. Soil carbon, for example, varies greatly across short distances. And variability over time means it can take up to a decade before sampling detects important changes in soil carbon. "It's time-consuming and costly to do it right," says Rebecca Rowe, who studies soil carbon at the Centre for Ecology and Hydrology in Lancaster, UK.

That makes assessing biofuel sustainability "daunting" according to Pedro Piris-Cabezas, director for sustainable international transport based in London at the Environmental Defense Fund. "It quickly becomes crazy," he says. But Piris-Cabezas thinks that tools and methods exist to reliably cut through the complexity, and these will show that some biofuels do reduce carbon emissions without degrading ecosystems and communities. Piris-Cabezas has written a handbook (see go.nature.com/3s6hco2) on tracking methods that can ensure that alternatives to aviation fossil fuels have "high integrity".

"We will always be balancing impacts against the needs of society."

Piris-Cabezas is less confident, however, that such rigorous analysis will show that biofuels can be produced sustainably at large scale. And he is pessimistic about their economic viability, thanks to an emerging challenge from another class of alternative fuels: electrofuels, produced through renewable electricity and hydrogen. Piris-Cabezas predicts that in the next decade, the cost to avoid a tonne of CO_2 emissions through the use of electrofuels will fall to about \$70. Cutting a tonne of carbon using current biofuels costs \$300–\$400, he says, and that cost is likely to rise.

The ultimate dilemma regarding biofuel is intensified competition for finite land. The World Resources Institute, a sustainability think tank in Washington DC, projects a 56% gap between food calories produced in 2010 and those needed in 2050 (see go.nature.com/3tknoy3). At the same time, most mitigation pathways that limit global warming in keeping with the Paris climate agreement require an outright reduction in agricultural land use. Expansion of biofuel production will, therefore, inevitably drive up food prices and worsen food insecurity, says Janet Ranganathan, who studies environmental accounting and technology and oversees research at the World Resources Institute. She doubts that future advances can secure more than a niche role for biofuels: "The prospects for improvement are limited unless the need for dedicated land to grow them is eliminated."

Cover for carbon

In spite of powerful headwinds, researchers continue working to improve biofuels' sustainability. "Short of returning land to a completely wild state, we will always be balancing impacts against the needs of society," says Rowe, whose work is helping the UK government to implement plans to expand the planting of bioenergy crops from close to nothing to about 3% of the UK's land area by 2050.

And Field's research suggests that biofuels still have the potential to be more than a necessary evil. In a 2020 paper[3] he and his colleagues showed through simulation that, under certain conditions, cellulosic ethanol can rival or exceed the climate benefits of ecosystem restoration. The best results occurred for the case of land use transitioning from food crops or pasture to the cultivation of switchgrass (*Panicum virgatum*), a popular feedstock for cellulosic biofuel. In those cases, Field and his co-authors estimated that the carbon mitigation potential was comparable to that for reforestation. If crop yields and bioprocessing technologies can be improved, and if CO_2 from biorefineries can be permanently sequestered deep underground, the researchers predict that supplying cellulosic feedstocks could ultimately store up to four times more carbon than does reforestation. "It's aspirational, but these are areas where there's a lot of research and development attention right now," says Field.

Companies are already developing CO_2 pipelines in North Dakota and Illinois, and they're in line for enhanced tax breaks under the US Inflation Reduction Act that was passed in August. Of course, these companies also face significant pushback, including from farmers whose land might be in the pipelines' path.

For the UK bioenergy crop scale-up, Rowe says *Miscanthus* (a crop akin to switchgrass) and other perennial feedstocks are the preferred option. The UK government expects that these crops will help to cut emissions from biorefineries by the 2030s – especially when coupled with deep sequestration. The key, says Rowe, is to use the lessons learnt from biofuels development to work out the most

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The petroleum company Phillips 66's oil refinery in Rodeo, California.

sustainable places to cultivate. That generally means avoiding high-carbon soils such as peatlands, biodiversity hotspots and high-value agricultural croplands.

The best candidates for sustainability are the cover crops in development that seem to be a good response to arguments against dedicating land to biofuels. Soil in fallow fields tends to compact, and is susceptible to erosion by wind and rain. A cover crop puts roots down to secure the soil and its nutrients, and creates channels that help water to sink in rather than drain off. Farmers might be convinced to plant oilseed cover crops because the crop can pay for itself by producing oils that can be supplied to biorefineries.

Nuseed's crop carinata – adapted from *Brassica carinata*, a towering cousin of rapeseed (*Brassica napus*) – produces an energy-rich, inedible oil. And it packs a punch: Johnston says carinata excels at storing carbon in soil and contains about 2.5 times more oil than soya beans, the dominant crop for renewable diesel. Most importantly, he says, carinata does not compete with food supplies or cause climate-harming land-use changes. The latter advantage means that although land-use effects alone add an extra 4–26 grams of CO_2 emissions per megajoule of energy delivered from soya-based fuels, according to Field, carinata cuts 9–13 grams of emissions per megajoule from fuels. "Land-use change goes from being a highly uncertain but potentially large liability to having a small-but-positive effect," says Field, who is part of a consortium partnered with Nuseed on carinata research and development.

A 2022 report[4] by Field and his colleagues shows that carinata could support a major biofuels industry in the southeastern United States. Simulating application of carinata every third year across southern Georgia, southern Alabama and northern Florida – a few percent of US cropland – they project annual harvests exceeding 2 million tonnes. That's enough seed to make about one billion litres of aviation fuel.

The push for rigorous rules

Nuseed started commercial planting in Argentina in 2019 and is sending enough oilseed to the French biofuels producer Saipol this year for the company to generate millions of litres of renewable fuel. Nuseed plans to expand to the southeastern United States by the end of this year and to Brazil by 2024. It intends to scale up fast thereafter, aided by a ten-year supply and market-development deal with energy giant BP, and to be supporting billions of litres of fuel production per year by 2030.

For carinata to occupy a larger role in the biofuels scene smarter policies are needed, says Johnston. Government programmes for biofuels, he says, lack the breadth and specificity to recognize and reward the crop's benefits.

Lilliston concurs, in that refineries selling soya-derived fuels to California pay no penalty for soil carbon depletion caused by industrial farming practices, he says. California and other jurisdictions are planning more sophisticated carbon accounting, but not fast enough for oilseed cover crop developers.

What's racing forwards instead are poorly regulated markets for offsetting carbon – financial instruments that threaten to give regenerative agriculture a bad name. Offsets pegged to soil carbon, created by brokers as well as some agricultural giants, pay farmers to adopt carbon-friendly practices. Corporations purchase most of the offsets to claim progress towards emission reduction pledges such as 'net-zero by 2050'.

These offset markets, however, often ignore the pitfalls associated with carbon accounting, and lack the rigour required for accurate soil carbon measurement. Many offset markets stipulate that soil sampling needs to go to a depth of only 30 centimetres, despite research showing that reliable accounting requires sampling across a crop's full root zone, which could extend down to one metre or more. Some markets also allow contracts requiring farmers to maintain climate-positive practices for as little as five years, after which it might not be clear whether carbon stores have risen or fallen, let alone by how much.

One big concern is that the benefits of soil carbon offsets, including those associated with cover crop biofuel feedstocks, could turn out to be illusory and thereby undermine the integrity of net-zero targets. These offsets could also encourage lobbying for weaker government rules as regulators catch up. "People buying up cheap soil carbon offsets with questionable accounting methodologies have a vested interest in making sure that tomorrow's regulations don't dissolve their offsets' value," says Ranganathan.

Indeed, these markets might also help to perpetuate the extractive culture that dominates agriculture today. Farmers depend on agribusiness giants and fossil-fuel providers for products such as fuel, fertilizer and seed, and they struggle to make ends meet because those big firms capture most of agriculture's economic value. The balance could tilt even further if farmers are also relying on those corporations' offset programmes to recoup the value of regenerative crop production.

Advocates for farming communities are instead calling for a complete overhaul of the agricultural ecosystem that gives more back to these communities – a system that, as Lilliston puts it, "circulates both natural and economic resources to create a more sustainable and resilient system".

But a ground-up revamp for agriculture is a big ask. If the sustainability of biofuels depends on such fundamental changes, one has to wonder whether another next-generation biofuels failure isn't the more likely outcome.

Peter Fairley is a science and environmental journalist who splits his time between Victoria, British Columbia and San Francisco, California.

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2. Xu, H., Lee, U. & Wang, M. *Renew. Sust. Energ. Rev*. **134**, 110144 (2020).
3. Field, J. L. *et al*. *Proc. Natl Acad. Sci. USA* **117**, 21968–21977 (2020).
4. Field, J. L. *et al*. *Front. Energy Res*. **10**, 837883 (2022).