The Plan to Feed the World by Hacking Photosynthesis

With the world population projected to soar past the 11 billion mark by 2100, we’re going to need to find some creative new ways of putting food on the table. The latest science-powered plan to feed the world? Hacking photosynthesis.

Imagine if we could grow 30 to 60 percent more wheat in a field, using the same amount of space, water, fertilizer, and sunlight. That’s what scientists are now hoping to do, by redesigning the process plants use to turn sunlight into chemical energy. The idea of upgrading photosynthesis isn’t new, but it’s been gaining momentum in step with our ability to manipulate life on a molecular scale. This week, a paper published in the Proceedings of the National Academies of Sciences lays out the scientific roadmap that’ll make it happen.

Here’s why scientists want to improve nature’s solar-powered sugar factory—and how they might actually do it.
Imperfect by Nature

Some 3.4 billion years ago, a puddle of green slime kickstarted a process that would terraform an inhospitable Earth into a planet with oxygen and ecosystems. Ancient cyanobacteria had stumbled onto something incredible: using photons of light to split water, and channeling the resultant burst of energy to turn carbon from the air into sugar.

Today, that process—photosynthesis—is the basis of nearly ever food web and ecosystem on our planet. It’s also been responsible for recycling the atmosphere these last few eons, by drawing down CO2 and releasing oxygen as a waste product. If plants stopped spinning sunlight into sugar tomorrow, every animal on Earth would soon starve and asphyxiate.

With that in mind, here’s an excellent video that illustrates exactly how plants eat light:

It’s certainly one of the most astounding bits of biochemistry that ever evolved, but photosynthesis isn’t perfect. Like anything else in biology, this process was shaped by natural selection—a slow and meandering path of trial and error, addition and subtraction. We don’t see brand new limbs cropping up in the fossil record overnight, and by the same token, biochemistry like this doesn’t rewrite itself easily. To some extent, plants have been stuck with what their slimy ancestors evolved billions of years ago, when the world was a very different place.

“Evolution is incremental. It can only build on what it has by itty bitty steps,” plant biologist Donald Ort and lead author of the new PNAS paper told me over the phone. “And what was adaptive for plants was not necessarily what we want for food and bioenergy production.”

That fact has become increasingly clear to plant scientists over the past decade. In the 1940s, agronomists began boosting crop yields tremendously, using a combination of fertilizers, pesticides, selective breeding, and new management
techniques. For better or worse, the Green Revolution changed our planet, growing the human population by an estimated four billion. But the tricks that allowed farmers to squeeze more calories out of the land for decades are running their course. In many of the world’s most important growing areas, productivity is now on the decline due to drought, climate change, soil erosion, and poor land management.

But just as our conventional yield-boosting tools are hitting their limits, our ability to manipulate genes and proteins has skyrocketed. We can now zero in on specific inefficiencies in the photosynthetic pathway, swap out old parts for new ones, and engineer designer crops that grow faster, bigger, and more efficiently. We can build ourselves better solar machines.

**Tap that Sun**

The first aspect of photosynthesis Ort and his colleagues focus on is solar efficiency. Plants actually aren’t very good at using light. Most only turn a few percent of the photons they absorb into biomass, whereas photovoltaic cells can convert roughly 10 percent of incoming sunlight into fuel. Theoretical studies suggest we can boost the conversion efficiency of sun into sugar up to 12 percent or higher. So, how do we go about doing so?
Inserting different versions of chlorophyll into plants could increase the amount of light they use—and change their color!

Somewhat counterintuitively, one option might be to decrease the number of light-absorbing chlorophyll molecules in a given photosystem. (Chlorophyll is the pigment plants rely on to absorb solar energy, and a bunch of chlorophyll molecules together makes a photosystem, kinda like a solar array). Since plants already absorb more sunlight than they can use, having fewer solar panels won’t slow photosynthesis down. But it would free up resources that can be used for growth.

“Plants have a variety of mechanisms for safely diverting excess absorbed energy, principally as thermal dissipation, but they represent a significant loss inefficiency,” Ort and his colleagues write. “If plants had fewer light-harvesting pigments per photosystem and fewer photosystems in their uppermost leaves, light might be absorbed more judiciously, and a greater proportion of absorbed photons converted to biomass.”

Engineers trying to design more light-efficient algae for biofuel production have seen some success with this strategy, but it hasn’t yet been tested in higher plants. But Ort’s optimistic that we can give it a try.

“There’s a biosynthetic pathway for chlorophyll, which has about eight different enzymes,” Ort told me. “Affecting any one of those enzymes can affect chlorophyll. That’s a fairly easy engineering problem, to go in and make one enzyme work more slowly.”

(As an aside, scientists aren’t totally sure why plants evolved to produce more chlorophyll than they can use, but Ort suspects it has to do with competition. Robbing your neighbor of sunlight, even if you have no use for it, can help you stake out your turf. A perfect example of what may be an adaptive trait for wild plants, but isn’t so great for food production).
Absorption spectra for two of the most common chlorophyll molecules in plants.

Another popular idea is to hack different types of chlorophyll into plants. The chlorophyll-based photosystems that color plants green absorb mostly in the red (620-700 nm) and blue (450-490 nm) parts of the visible spectrum, while ignoring vast swaths of potentially useful light. But certain photosynthetic bacteria carry versions of chlorophyll with different light sensitivities. If we were to express bacteriochlorophyll-b—which is optimized to use near-infrared light up to 1,075 nm—in tandem with the red and blue-loving chlorophylls, we might dramatically increase the plant’s light use efficiency.

“Taking a photosystem from higher plants that operates in visible and coupling with one from bacteria that operates in infrared is a speculative idea,” Ort said. “But that’s how engineers have designed 2-stage solar cells.”
Or perhaps, we could build new, designer chlorophylls that tap any part of the solar spectrum we like. Chemists are already doing that in the lab, so don't be too surprised if you see blue or orange lettuce cropping up at the supermarket soon.

**Carbon Capture**

Solar efficiency is a major aspect of photosynthesis that stands to be optimized. But catching sunlight is really just the first step. The endgame for plants is to convert that solar energy into chemical energy, otherwise known as sugar. But to build sugar, plants need a source of carbon. Fortunately, there’s plenty of that floating around in the air as carbon dioxide.

*Plants grow from the air!*

Plants quite literally grow from the air. To do so, they employ a little CO2-nabbing enzyme called Ribulose,1-5-bisphosphate carboxylase. To save breath, everyone calls it Rubisco.

“Rubisco is most abundant enzyme on Earth, but it’s really not a very good enzyme from the efficiency standpoint,” Ort told me. “When it evolved, there was no oxygen in the atmosphere.”
Once plants began filling the air with oxygen, however, Rubisco discovered it wasn’t actually very good at telling the difference between O2 and CO2.

“About every fourth to fifth catalytic event fixes an oxygen instead of CO2,” Ort said. “And that’s incredibly energetically wasteful.”

When Rubisco messes up and grabs oxygen, it sets off a reaction pathway called photorespiration, which ends up burning energy and creating toxic waste products. To mitigate this problem, so-called C4 plants evolved ways of concentrating CO2 in the parts of the cell where Rubisco operates, making it harder for the enzyme to accidentally grab an O2. Algae and photosynthetic bacteria have developed other CO2-concentrating mechanisms.

“One way to improve the efficiency of Rubisco is to concentrate CO2 around it,” Ort said. “Bacteria do this, the C4 plants do it. But the vast majority [of plants] don’t. One thing we’re wondering is: Can we take CO2 concentrating mechanisms in bacteria and put them into plants?”

A coordinated international effort is already underway to install C4 photosynthesis into rice, and scientists have made significant progress identifying the relevant genes. The team behind this project claims that C4 rice could produce up to 50% more grain with less water and nutrients. Many experts agree giving our veggies a C4 upgrade is a promising direction: “Although significant hurdles remain, success will open the door to dramatically improving the efficiency and yield of many of the world’s most important staple crops,” Ort and his colleagues write.

More speculatively, some have proposed tossing Rubisco out and replacing it with a new carbon fixing pathway, one that’s completely insensitive to oxygen. That’d amount to a much more significant biochemical rewiring job, meaning years of additional research money and time. But in the end, we might build ourselves a corn plant that can soak up carbon many times faster than its ancestors—and that could be a good thing for the future of food and Earth’s climate.
**Smarter Canopies**

While the bioengineers are busy imagining how we can rewire enzymes and photosystems, others are asking how all of this is going to play out in the real world. Remember, natural selection is based on survival of the fittest. In the plant world, a “fit” individual is one that can outcompete its neighbors for light, soil, and water. But for farmers interested in boosting yields, these types of resource hogs are a liability. We’d rather have plants that can cooperate and share real estate.

Because every new idea sounds sexier with a “smart” tacked on, enter the smart canopy: “The smart canopy concept envisions an assemblage of plants that interact cooperatively (rather than competitively) at the canopy level to maximize the potential for light harvesting and biomass production per unit land area,” Ort and colleagues write.
Environmental changes throughout the canopy affect photosynthesis. Relative humidity (RH) tends to increase from top to bottom, the ratio of red to far-infrared (R/FR) light decreases, and CO2 is variable.

How could a crop plant be engineered to optimize the productivity of the land, instead of the individual? For one, breeders could select for certain physical traits that maximize the amount of light penetration and airflow throughout the canopy. Crops that produce more vertically-oriented leaves at the top of the canopy, for instance, will allow more sunlight to shine through to the bottom, improving the overall light availability of the system. Breeders could also select for plants that produce flowers and other non-photosynthetic structures in low-light areas, to avoid wasting the sunniest real estate.

What’s more, in scaling from molecules to fields, biologists need to consider where plants ought to be using their new photosynthesis machinery. For instance, there tends to be more red light available at the top of the canopy, compared with more infrared at the bottom. If we’re thinking about inserting different light-sensitive chlorophylls into plants, we should also be considering how to express these systems in the areas where they’ll actually be useful.

The smart canopy approach—of imagining how our engineering and breeding schemes will play out on the field scale, and eventually, how they’ll translate into higher yields—is going to become more and more important as scientists start test driving some of these ideas outside the lab. We can boost the efficiency of Rubisco and tune chlorophyll light sensitivities all we want, but if the resultant super-crop doesn’t play well with its neighbors, all of our science might be for nothing.

**Plant Hacking: Not a Silver Bullet**

Most of the photosynthesis upgrades being proposed wouldn’t be conceivable without the tremendous molecular biology advances of the past decade. Still, manipulating life in the ways I’ve described here amounts to far more than simply
cutting and pasting genes from one organism into another. It'll involve getting those genes expressed in the right place and under the right conditions, without screwing anything else up in the process. Then scientists will have to determine how these molecular tweaks scale to entire plants and fields. All of this is much easier said than done.

Even if we're able to boost yields immensely by upgrading photosynthesis, this isn't going to be a silver bullet that ends any global food crisis, present or future. It's important to bear in mind that the hunger problem facing our world today is largely a problem of distribution, not supply. As the world population continues to grow, that may change. But any attempts to improve our crops are going to have to be coupled with policies ensuring that those extra calories are being distributed to the people who need them.

And if we don't get population growth under control, all of our efforts to squeeze more calories out of the land won't feed the world.
We’ve also got to face our changing climate. As the Earth warms and regional climactic patterns shift, many of our planet's fertile agricultural lands are drying up, while historically parched regions are becoming wetter. We can upgrade the heck out of photosynthesis, but if we don't have the water to grow our crops, it won't make a drop of difference. Predicting and adapting to changing water resources is critical for our survival as a species.

Eventually, the only long-term survival solution will be for humanity to move beyond Earth. Plants are going to be an essential part of our cosmic migration, and in all likelihood, we’ll have to engineer them even further for off-world living. Upgrading photosynthesis may be a short term step toward continuing to feed humans on planet Earth, but the tools we invent along the way will help us as we venture beyond this pale blue dot.