BIOTECHNOLOGY and BIOENGINEERING

Solar Flux, Water, and Land Impose Limits on Biology

Is it reasonable to think that synthetic biology will find great success in the production of large-scale fuels, chemicals, and plastics? Likely, no. Any good scientist should be wary of trying to prove a negative, yet the challenge of displacing commodity materials is daunting. The limits of what is possible with biology are being stretched daily. Biology, however, is not rate limiting in the context of high volume materials, like fuels, chemicals, and plastics. Biology will always be limited by sunlight, water, nutrients, and available land. These are physical barriers that improvements to biology can never overcome. There will be high value niches where biologically derived materials find application, but they are ill-equipped to compete in commodity markets because of limitations that biology simply cannot address.

Synthetic biology uses the concepts of design or improvement to organisms, using newly developed tools of biology to radically alter life. It is said that anything is possible. New drugs. New foods. New paths to fuels, chemicals, and polymers. Great strides have already been made. Products derived from biotech are transforming agriculture and human health. Glyphosate resistant soy, Bt corn, and drugs like interferon are examples of products brought about from the recombinant DNA technologies that form some of the foundational underpinnings of synthetic biology. No longer content with moving naturally occurring genes from organism to organism, synthetic biology envisions a world where whole organisms are designed incorporating pathways designed by man rather than by nature. Our skepticism about production of high-volume materials doesn't center on whether synthetic biology can realize its lofty goals. We believe that sunlight, water, and available land and the price points of fuels will ultimately limit the ability of biology to supply our energy needs. Furthermore, the scale of operation necessary to produce high-volume materials like fuels, chemicals, and polymers is incompatible with the risk and cost of containment.

Biological fuels were displaced by fossil fuels as society became addicted to replacing human labor with high energy density fuels. The reason is relatively clear: seasonal capture of solar energy simply cannot compete with stored solar energy, in the form of fossil reserves. The biofuels bubble has deflated from the peak in the last decade. This can be clearly seen from the dramatic drop in venture capital funding for biofuels, having peaked in 2008 (McCrone et al., 2012). Claims that biofuels derived from sugars, cellulosics, or algae have not progressed at the pace predicted (Barcott, 2013; Kiefer, 2013). Ultimately, the slow pace of photosynthesis and the small amount of energy falling per unit area combine to make our energy appetite inconsistent with what can be supplied by biology.

Schemes that rely on synthetic biology to convert conventional biomass are likely to fail due to simple energy conversation challenges. Careful analysis indicates it is a stretch to displace 30% of the U.S. petroleum use (U.S. DOE, 2011), which is only about 10% of total U.S. energy consumption (U.S. EIA, 2012). In order for biology to really get to large fractions of our total fuel use, photosynthesis must be improved. Photosynthesis faces a theoretical efficiency limit of approximately 12% (Blankenship et al., 2011), a limit that synthetic biology cannot significantly change. By comparison solar cells routinely convert >15% of light to electricity. Crops rarely exceed 10% of theoretical efficiency under normal growing conditions. Record efficiencies are still less than 4% of the incoming solar energy to fixed carbon under optimum conditions (Walker, 2009; Zhu et al., 2008). Energy provided in the temperate climates is of the order 185 W/m^2 (World Energy Council, 2013), or about 700 MJ/m^2 per year at the theoretical limit of photosynthesis. Wide disparity in plant yields occur because water and nutrients limit growth rates. Availability of sufficient water on land and sufficient nutrients off-shore is far from certain (National Research Council, 2012). Real world experience can never equal the theoretical maximum. Picking a relatively high bar of increasing the primary productivity to 4% of incoming solar energy through re-engineering of photosynthesis would still require slightly more arable land than is available per capita to produce the approximate 250 million BTU per person consumed in the U.S. (Banholzer and Jones, 2013).

Introduction of synthetic organisms face hurdles larger than any that GMO known today. In a world were crops with transgenic traits for enhanced nutrition cannot be grown due to concerns about escape to the wild, propagation of a fully synthetic organism is sure to face hurdles. Cultivation in a closed environment will likely be a requirement. There are no examples of a closed

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photobioreactor operated at large scale from which we can truly determine costs. Experts in algae have widely considered closed photobioreactors too expensive for commodity fuel production (Benemann, 2009). Greenhouses dot the landscape growing tomatoes and flowers, providing data for the cost of an inexpensive structure for large scale, indoor agriculture. It turns out, however, that even the cheapest greenhouse is too expensive to grow fuel, chemicals, or plastics. Imagine the goal is to produce fuel at what it costs today. \$21 per million BTU (U.S. EIA, 2013) using the 700 MJ/m^2-yr provided by photosynthesis operating at theoretical efficiency, provides revenue of about \$14/m^2-yr assuming no other costs. This is an exceeding optimistic analysis since greenhouses today are not biohazard containment systems and since energy would have to be purchased to move CO_2 and water to nourish the plants. Additional costs come from replacement of the 6 mil polyethylene used on the greenhouse every 3 to 5 years. Data indicates an average cost for building a greenhouse is \$64/m^2 (Pena, 2005). Simple payback has its flaws, but is both quick to calculate and well suited for this brief analysis. An unacceptable 4.5 years is required for simple payback using these rosiest of assumptions—direct production of gasoline at theoretical photosynthetic efficiency in a thin-gage plastic greenhouse and with no additional costs. No costs for the land. No energy costs. No labor. The payback time required should photosynthetic efficiency be doubled from current best to approximately 20% of theoretical (~2.5% on incident solar flux) pushes the simple payback to over 20 years still excluding any operating expenses. Even the most inexpensive greenhouse based on only 6 mil polyethylene film still exceeds the capital that can be reasonably spent to make a high volume material like fuel. Tomatoes are a different story. Growers net on the order of \$1500 per million BTU (assumes 0.74 kJ/g and \$0.50/lb) for greenhouse tomatoes at current prices.

The difficulty in displacing commodity materials is becoming evident even to the most ardent supporters of synthetic biology. Craig Venter is a prominent advocate, having created the first organism with a synthetic genome (Gibson et al., 2010). At a recent conference, Dr. Venter offered "Fuels were an early publicly sexy target, but they are the lowest end of the entire field. We were talking at lunch. A glass full of therapeutic antibodies would be worth millions of dollars … or about 50¢ worth of biofuel. If we're going to target one or the other, I think it's clear which direction to go to. Food and chemicals are much further up the economic ladder. With the discovery of all the natural gas, once again the biofuel field is set back tremendously." (Venter, 2013) He has come to the realization that commodities are difficult to displace with biology. Other companies devoted to synthetic biology have also pivoted away from fuels toward higher value materials and away from cellulosic biomass (Bomgardner, 2012; Hayden, 2014).

In closing, past performance is frequently the best indicator of future performance. The track record for biology supplying fuels, chemicals, and polymers is not stellar. Synthetic biology is in its infancy and the claims of what is possible remain largely unsubstantiated. Advances will certainly come but limitations in the energy supply from the sun, limited ability to exploit economies of scale, and cost of processing biological media combine to temper expectations. It is unlikely that synthetic biology will reap great benefits in fuel or commodity materials production.

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