**Microalgae Biofuels: Myths and Risks**

**Biofuelwatch Report, by Rachel Smolker**

**Introduction:**

Microalgae play a key role in the regulation of earth systems. Their voracious appetite for CO2 is thought to have played a significant role in drawing down atmospheric CO2 levels in a previous spike around 50 million years ago. Microalgae allowed all higher life forms to evolve during the earth’s history, by creating an atmosphere rich in oxygen. They still provide about half of the oxygen in our atmosphere. Microalgae also form the base of the marine and freshwater food chains, and play a key role in nutrient cycling. They are found in marine and aquatic ecosystems, but also play a vital, if poorly understood, role in every single terrestrial ecosystem, including in soils.[[1]](#footnote-1)

TEXT BOX: WHAT ARE MICROALGAE?

Microalgae are incredibly diverse, adaptable and ubiquitous. They are also the repository of unrealistic hopes and ambitions for a “green and sustainable” biofuel alternative. In turn this has spurred a rapid and risky headlong advancement of algae biotechnology research and development, including both more "traditional" genetic engineering and new “synthetic biology” techniques. The aim of these efforts is to engineer microalgae to produce biofuels, chemicals, pharmaceuticals, neutraceuticals, plastics, lubricants, and much more, all part of the new “bioeconomy” that is presented as a clean green alternative to the fossil fueled economy; a supposed solution to climate change. Enthusiasts claim microalgae derived biofuels and other compounds can provide “carbon negative” fuels and "recycling" of CO2 from polluting industries.[[2]](#footnote-2) Some advocate using microalgae to “engineer” our climate by fertilizing ocean waters with iron to stimulate microalgae blooms.

Ancient microalgae were largely responsible for the deposits that make up fossil coal and oil deposits, the extraction and burning of which are the major cause of the climate crisis. Now, we are turning to living microalgae as a “green alternative”. In the process, the evolved biology and genetics of microalgae have come under siege by the biotechnology industry, eager to harness them away from natural ecosystems and into commercial and industrial applications.

This report looks at the hype about microalgae biofuels - how, even after hundreds of millions, if not trillions of dollars invested, woefully few cars, trucks or airplanes have been fueled. Meanwhile, the microalgae biofuel hype has been a dangerous distraction that introduces serious, but under-recognized new risks to our health and environment. A slew of new consumer “bioproducts” derived from genetically engineered/synthetic microalgae are already being marketed, with little regulatory oversight, and little evaluation of the potential risks. Meanwhile, the ongoing hype that a truly “green” and “sustainable” biofuel breakthrough lies just over the horizon perpetuates the myth that we can maintain our familiar (or even expanding) levels of fuel and resource consumption even in a climate changing world.

**History and methods of cultivation:**

Research and development of algal biofuels has been an ongoing effort since as far back as the mid-20th century. Cultivation of some microalgae for food, such as spirulina has an even longer history. Methods for cultivation depend first of all on whether the species is autotrophic (meaning they produce their own food via photosynthesis and therefore require light exposure), or heterotrophic (meaning they must be provided with sugars from biomass feedstocks, i.e. sugarcane for example, in order to grow. Some are capable of photosynthesis but will grow more efficiently when provided with sugars

Most research on microalgae biofuels involves photosynthetic microalgae, which produce lipids that can in turn be converted to fuels and chemicals. Macroalgae, or “seaweeds” are the focus of some research for bioenergy, primarily as a biomass feedstock for anaerobic digesters, so far with limited success.

Cultivation of microalgae is generally done either in open ponds, called "raceways" or in closed photobioreactors (PBRs) or in some cases, hybrid systems. Open pond **r**aceways allow the water to circulate via some form of paddlewheel. Ponds must be kept shallow to allow light penetration (hence require more land area) and the water must be circulated via pumps with some source of CO2 addition ("sparge"). Open pond cultivation systems are vulnerable to contamination (bacteria, parasites, other strains of microalgae etc.). They are also vulnerable to the fluctuations associated with weather and environment, including water evaporation. Furthermore, there is no expectation that microalgae cultivated in open ponds are “contained” use, making it necessary to obtain regulatory approval for open pond cultivation if genetically engineered microalgae are used.

Photobioreactors (PBRs) are closed units, and can take a variety of forms: tubular, flat plate, columns etc. They may require less land area, but are more expensive, require more materials, maintenance and cleaning as well as presenting greater challenges to mixing and circulation. They do provide greater control and isolation from the external environment. PBRs, even though they may only consist of thin plastic tubing, are considered “contained use”, making the regulatory process for cultivation of genetically engineered microalgae less challenging.

Research on microalgae biofuels has been strongly supported in the United States, and in Europe, (the primary focus of this report) but also has significant support in China, Taiwan, India, South Korea, Japan, Canada, Mexico and Brazil. For a global review see the recent International Energy Agency report.[[3]](#footnote-3)

In the United States, between 1978 and 1996, the government funded the “Aquatic Species Program”. Both algal-derived hydrogen and algal biodiesel production were investigated along with methods for cultivation and prospecting assessments of nearly 3000 different species for their suitability to cultivation and manipulation. Ultimately the Aquatic Species Program was shut down, concluding that the costs of production and other barriers offered little promise for success. The economics of commercial production require industrial scale monocultures with very high yields, conditions which, it turns out, are not generally favored by microalgae – and hence not easily achieved.

Starting during the oil price spike in the mid-2000s, venture capitalists and some oil companies began investing substantially into algal biofuel start-up companies. With growing awareness about climate change, and the perceived need to develop (especially) liquid biofuels as an alternative to imported petroleum, the dream of microalgae biofuels was revived. Funding supports have continued, and even expanded since. The US Department of Energy (DOE) maintains a microalgae program as part of the Bioenergy Technologies Office. A National Algal Biofuels Technology Roadmap was first published in 2010. In addition to the DOE, funding for microalgae biofuel research has come from the Department of Defense, National Science Foundation, US Department of Agriculture, DARPA and the US Airforce, as well as state and private sources. The American Recovery and Reinvestment Act of 2009 provided a massive cash infusion - $97 million - for microalgae “integrated biorefinery” demonstration projects (including to the startup companies, Solazyme, Sapphire and Algenol).

Four public-private partnership research consortia were established, including the National Alliance for Advanced Biofuels and Bioproducts (NAABB), the Sustainable Algal Biofuels Consortium, the Consortium for Algal Biofuels Commercialization (CAB Comm) and the Cornell Consortium. Each of these included academic institutions, national laboratories, and private companies.

The Microalgae Testbed Public-Private Partnership (led by Arizona State University), and the Regional Algal Feedstock Testbed, (University of Arizona), were funded, along with a series of projects aimed to improve yields and pilot new technologies, as well as ongoing funding for research granted to the national laboratories. Most recently: in December 2016, a funding opportunity announcement for up to $8 million was announced (Productivity Enhanced Microalgae and Tool-Kits”). That followed an earlier $15 million, granted in June of 2016.

Meanwhile there has also been a proliferation of industry associations that promote microalgae biofuels and bioproducts and lobby for supports has taken place. These include the Microalgae Biomass Organization, and the National Microalgae Association, among others. There are seemingly infinite publications, peer reviewed and otherwise, regular conferences and events, all dedicated to research and development of microalgae biofuels and bioproducts.

According to some estimates, in the USA, over 2.5 billion in taxpayer dollars have been spent on research and development of microalgae biofuels over a period spanning 70 years. Recipients of this ongoing torrent of funds include (but are not limited to) academic institutions including Cornell University (housing the Cornell Consortium), University of California, San Diego (housing the California Center for Microalgae Biotechnology), University of Texas (Center for Electromagnetics), Arizona State University, University of Arizona, (housing the Arizona Center for Microalgae Technology and Innovation), New Mexico State University, California Polytechnic, Colorado School of Mines and Scripps Oceanographic. Major funding for microalgae work also has gone into the national laboratories, including; Argonne, Lawrence Berkeley, Lawrence Livermore, Los Alamos, National Renewable Energy Laboratory, Sandia, Pacific Northwest, Oak Ridge. Industry startups have also received funding as collaborators with research institutions, including Cellana, Sapphire, Algenol, Solazyme and others.

In sum, many have made life-long careers, with lucrative grant supports for academics and national laboratories, never ending calls for more research and little accountability or transparency regarding the amount of spending and the delivery of outcomes – commercial production of algae biofuels - from those grants. A scathing analysis of the state of affairs from the National Microalgae Association (whose focus is on commercialization), states: “*The consensus is that the US DOE Microalgae program,, because of its’ leadership, is incapable of commercialization and deployment, but have kept their jobs by touting the latest and greatest microalgae technology and need for additional research rather than admit their failures and misplaced grant awards*”. [[4]](#footnote-4)

In the UK, for example, Carbon Trust in partnership with UK government, launched an “Algal Biofuels Challenge”. Funding for algae biofuel research and development has been forthcoming under the EU Commission Seventh Framework. The EU Renewable Energy Directive includes emissions accounting schemes that provide incentives for algae biofuels by increasing their value towards meeting targets. A European Microalgae Biomass Association promotes the industry, and a “European Roadmap for a Microalgae Based Industry”, was developed. A recent conference opened with overviews from ongoing major projects from across Europe: Pufa-Chain, BISIGODOS, D-Factory, InteSusAl, All GAS, BIOFAT, MIRACLES, SPLASH, FUEL4ME, MicroalgaeBioGas, PhotoFuel and others. The primary challenge identified in the outcome was to “make microalgae biomass cheap”. Microalgae biofuels were relegated to a longer term (10 year) goal, while other products and services (animal feed, nutraceuticals, inks and dyes, and wastewater treatment) were identified as nearer term goals.[[5]](#footnote-5)

**Doubts about the reality of commercial algae biofuels?**

As far back as 2012, the US National Research Council’s review of “Sustainable Microalgae Biofuels Development” concluded “*that the scale-up of algal biofuel production sufficient to meet at least 5 percent of U.S. demand for transportation fuels would place unsustainable demands on energy, water, and nutrients with current technologies and knowledge*.” The report might have been hailed as clear indication that microalgae biofuels would be unlikely to become reality. Shortly thereafter, in 2014, the National Alliance for Advanced Biofuels and Bioproducts (NAABB) consortium published a report which appears designed specifically to dispel the pessimism. They reported several “advances and breakthroughs” and stated: “we envision algal biofuels to be a viable competitor in the liquid transportation fuels market after a few more key improvements”.[[6]](#footnote-6)

Meanwhile the European “Energy Algae” (Enalgae) project, running from 2011-2015 sought to explore the potential for both micro and macroalgae as energy sources. The project piloted various approaches to cultivation, developed standards for best practice, and set the groundwork for the “Microalgae Information Network”, but ultimately concluded: “*One of the major ideas enthusiastically considered 5 years ago was the potential role of microalgae in energy generation. With the barrel cost of oil almost halving, and revised estimates for the realistic potential for algal biofuels coming from the Enalgae project, it now looks highly unlikely that microalgae can contribute significantly to Europe’s need for sustainable energy*.”[[7]](#footnote-7)

The 2017 International Energy Agency (IEA) report provides mixed messages: ”*Significant opportunities exist to take advantage of the high photosynthetic efficiency of microalgae, both macroalgae and microalgae, for bioenergy/biofuels production*.” Followed by: “*Microalgae-based production to produce bioenergy products like liquid or gaseous fuels as primary products is not foreseen to be economically viable in the near to intermediate term*.”[[8]](#footnote-8)

Economic viability depends not only on bringing down the costs of production, but also on the price of oil. Recent low oil prices have made it especially challenging to compete.

Still the overblown promises of “new breakthroughs on the horizon” continues, as does the funding. Even after so many years of investment of time and energy and so much public money spent with so little to show by way of results, the US Department of Energy website still claims that microalgae will “*ultimately be capable of producing billions of gallons per year of renewable diesel, gasoline, and jet fuels.”* Some day! Ongoing support for the “promise of microalgae biofuels” also is bolstered by virtue of the fact that it is playing out against a backdrop of advancing supports and policies for traditional (“first generation”) biofuels including ethanol from corn or sugarcane, or biodiesel from soy or palm oil. As the negative impacts of those fuel processes have become increasingly clear -including food price spikes, land grabs, and failure to reduce greenhouse gas emissions or deliver “energy independence” - public opinion towards those biofuels has soured. Microalgae biofuels, in this context, have arisen as the next bright alternative, a “savior” technology holding great promise, with the important breakthrough lying just beyond the horizon, along with cellulosic and other “advanced” biofuels.

The dream of microalgae biofuels is kept alive through the perpetuation of key myths which are persistently and flagrantly repeated by industry and the media, even though they have little basis in fact. These myths include 1) Microalgae can produce biofuels with “nothing but sunlight, water and CO2” 2) Microalgae are phenomenally productive and can produce massive amounts of fuel using very little land. 3) Microalgae fuels are climate friendly, a clean green alternative to fossil fuels, and can be used to sequester or “recycle” carbon or provide “carbon negative” fuels. 4) Commercially viable microalgae biofuels are “just around the corner.”

How do these myths hold up to scrutiny? Let’s evaluate each in turn.

**MYTH #1: Microalgae can produce biofuels with “nothing but sunlight, water and CO2.”.** An article announcing the acquisition of $40 million in private equity finance by microalgae biofuel startup, Joule, was titled “Fuel From Thin Air”.[[9]](#footnote-9) Joule never produced commercial scale microalgae biofuels, and has since merged with Red Rock Biofuels (a very unpromising wood “gasification” biofuel project in Oregon) both held by Flagship Ventures.[[10]](#footnote-10) Algenol, another microalgae fuel startup featured on their website “harnessing the sun to fuel the world” with a simple childlike graphic of the sun, Co2 and water (“there’s plenty of it”) converted via a scribbled arrow pointing to “ethanol, biomass and oxygen”. The website has since been changed but still conveys the same basic message: “Algenol uses its patented microalgae technology platform for the production of biofuels using proprietary microalgae, sunlight, carbon dioxide and saltwater, all on non-arable land.” [[11]](#footnote-11)

Simple, appealing and clean as these claims sound, there are ***many*** things besides sunlight, water and CO2 required to produce microalgae biofuels. And, as it turns out, even providing adequate sunlight, water and CO2, as well as processing microalgae into fuel, is challenging and energy intensive.

**Nutrients:** Microalgae growth is regulated by available nutrient quantity and quality (nitrogen, phosphorus, potassium, iron, sulphur and various micronutrients). Optimizing access to these nutrients is key to productivity. The production of synthetic nitrogen fertilizers is energy intensive and costly, and results in significant greenhouse gas emissions. Meanwhile, availability of phosphorus is increasingly limited, even as demand for producing agricultural crops for food is rapidly expanding. According to the National Research Council, "*the estimated requirement for nitrogen and phosphorus needed to produce that amount of algal biofuels (5% transport fuel) ranges from 6 million to 15 million metric tons of nitrogen and from 1 mil to 2 mil metric tons of phosphorus if the nutrients are not recycled of included and used in coproducts. Those estimated requirements represent 44-107 percent of total nitrogen use and 20-51 percent of total phosphorus use in the US*.“ [[12]](#footnote-12)

It is widely acknowledged that large scale cultivation of microalgae cannot be sustainable unless methods for acquiring and recycling of nutrients are established. Attempts to circumvent this problem include colocation of microalgae ponds adjacent to nutrient rich wastewater streams, or using seawater (for marine species), and finding ways to recycle nutrients from algae biomass residuals after processing. Wastewater treatment using consortia of algae has been proven effective for removing nutrients from wastewater streams.[[13]](#footnote-13) However, this process is not necessarily compatible with biofuel production, which requires monocultures, and more controlled conditions to maximize and control growth without succumbing from exposure to other contaminants that are common in wastewaters.

**Water:** Cultivation of microalgae on large scale requires massive quantities of water. Water quality is also key to success as microalgae are highly sensitive to salinity, pH and contaminants. The sheer volume of water required is problematic: according to the National Research Council: “*at least 123 billion liters of water would be needed to produce 39 billion liters of algal biofuels (5 percent of US transport fuels)*". To produce 1 liter of microalgae derived biodiesel is estimated to require more than 3000 liters of water. Furthermore, water is especially limited in precisely those regions where sunlight and temperature is most suited for microalgae cultivation such as non arable lands, which tend to be deserts. In open ponds evaporation of water is significant, and even where saltwater is used, salinity increases as water evaporates and hence freshwater must be added periodically. Photobioreactors do not entail as much evaporation, but the reactors must be periodically flushed and cleaned. Marine microalgae species might be cultivated using seawater, but introduction of competitors, predators and pests can be problematic and location of facilities is thus limited to coastlines.

**Light: (see below, re productivity)**

**Energy:** Successful microalgae cultivation requires energy inputs, (which are key in turn to greenhouse gas emissions and costs). These include energy embodied in materials (especially high for PBRs), running circulation pumps, providing and regulating light and temperature etc., separating the microalgae from the water, drying and extracting oils, conversion to fuels, as well as energy used in manufacture and delivery of nutrients and management of the residual biomass, and production of coproducts. Anaerobic digestion of residual algal biomass to produce biogas that can be used to power processes is generally assumed as essential, given the energetic demands for cultivation of microalgae.[[14]](#footnote-14)

Lifecycle assessments for microalgae biofuels which measure the energy (or emissions) outputs relative to energy (or emissions) inputs -vary widely. These are very tightly linked to productivity. Estimates of productivity in the literature vary by a factor of 60.[[15]](#footnote-15) This is in part due to extrapolation from laboratory research to commercial production conditions, which is not at all straightforward and leads to wildly misleading outcomes for projected yields and for lifecycle assessments.[[16]](#footnote-16) In a laboratory setting, it is far easier to optimize conditions for microalgae growth and hence to optimize yields relative to inputs, yet those conditions cannot be duplicated in large scale commercial cultivation.

Lifecycle analyses from actual production systems have not generally been favorable, indicating that algal biofuels produced using photobioreactors require more energy inputs than the fuel produced delivers (energy return on energy investment = <1).[[17]](#footnote-17) Murphy et al report that energy demands for water management for microalgae cultivation alone are found to be around seven times greater than energy provided from the fuels produced.[[18]](#footnote-18). Clarens et al reported that microalgae biodiesel lifecycle assessments are poorer than switchgrass, canola or corn processes, largely due to fertilizer and CO2 input requirements.[[19]](#footnote-19) Dassey et al analyzed the lifecycle for a system operating in Louisiana and reported that energy inputs exceeded outputs by 53% under even ideal circumstances. Grierson et al. analyzed a system that would entail using the residuals biomass for biochar production. Nonetheless, they reported that fertilizer demands and energy demands at various steps in the process undermine gains from the whole endeavour.[[20]](#footnote-20) Lifecycle analyses are notoriously tricky, with outcomes highly dependent on assumptions, values assigned and processes included. [[21]](#footnote-21) Not surprisingly, when industry performs their own lifecycle assessments, highly unrealistic promising outcomes are the result (and should not be taken seriously).

**CO2:** Providing adequate quantities of CO2 to support maximal microalgae growth rates, adds an additional challenge. While CO2 in the atmosphere is a lead cause of global warming, it is mixed with other atmospheric gases in very diluted form (about .04%), not enough to provide what is required to support industrial scale microalgae growth. Industrial cultivation requires input of either concentrated CO2 gas, or soluble inorganic carbonates (sodium bicarbonate, for example), which is costly.[[22]](#footnote-22) Further, as microalgae undergo photosynthesis, the pH of surrounding water increases, a process that in turn alters chemical availability of CO2 and adversely affects microalgae growth. Achieving both adequate CO2 supply (in concentrated form) and controlling pH is a difficult balancing act for successful cultivation. Hooking up algae cultivation to the smokestacks of large industrial power plants or cement manufacturing facilities that emit CO2 is a focus of research. However, there are numerous very substantial hurdles that may prove insurmountable – discussed further below.

**MYTH # 2: Microalgae are phenomenally productive and can produce massive amounts of fuel using very little land.** Biofuels Digest Magazine projected that “Microalgae will provide over a billion gallons of biofuels by 2014”. The Microalgae Biomass Organization anticipated “tens of millions” of gallons of microalgae biofuels by 2016. Greentech media in 2010 projected that over 6 billion gallons per year of microalgae biofuels would be in production by 2022.[[23]](#footnote-23) In 2009 Sapphire Energy claimed: “*By 2011, Sapphire Energy will be producing 1 million gallons of diesel and jet fuel per year, double its initial estimates. By 2018, the number, increases to more than 100 million gallons annually; and by 2025, the company will be producing up to 1 billion gallons of fuel per year. This means Sapphire alone will be supplying enough fuel to meet approximately 3 percent of the country’s 36 billion gallon renewable fuel standard*.”

This litany of enthusiastic projections has been proven wildly overoptimistic. Productivity is key to virtually all aspects of making microalgae cultivation viable, and along with cultivation technology, determines the amount of land area required. Misrepresentations and claims of outlandishly high productivity have been ongoing part of the hype, and key to attracting investment. However, there are fundamental barriers to productivity.

Unlike agricultural crops, we do not have hundreds or even thousands of years of experience with large scale microalgae cultivation to draw on. Like agricultural crops, microalgae do not naturally grow in vast monocultures, but rather in multi-species interactive assemblages.

Pests and predators: Monocultures are more vulnerable to contamination by pests, predators and competitors. In the case of microalgae cultivation, these may be introduced via water, air or animal vectors and are especially problematic in open pond raceways where a large portion of the microalgae may be lost.[[24]](#footnote-24)

Light exposure: Microalgae have very efficient and broad spectrum light harvesting capabilities, a trait evolved for life in aquatic environments where light penetration is often limited. However, under crowded conditions of mass cultivation, upper layers of microalgae effectively harvest incoming light, shading and thereby limiting growth in cells further below (shading). Meanwhile, if exposed to ***too much*** light, cells are damaged and produce reactive oxygen species that yet further hinder growth. Achieving the right exposure to maximize productivity has proven challenging (for review see Sforza et al 2012).[[25]](#footnote-25)

Trading off growth versus lipid production: Most microalgae species, given access to sufficient nutrients, will grow and reproduce prolifically, converting assimilated carbon into proteins. When stressed, and especially when nutrients become limited, they switch gear, directing carbon into production of carbohydrates and lipids for energy storage. For biofuel production, the goal is to produce lipids, but not at expense of the ongoing growth of the culture. This very fundamental trade-off between growth and lipid production remains one of the most significant roadblocks to commercial production, and much research has focused on understanding and overcoming it. [[26]](#footnote-26)

Even more fundamental than all of the above, are limitations imposed by the biochemistry of photosynthesis itself. A 2015 review concluded that "at present, photosynthetic microbial biofuels are not viable in energy terms due to intrinsic inefficiencies in photosynthesis."[[27]](#footnote-27) Flynn et al (2017) illustrate that the performance of the enzyme, RuBisCo, which is central to photosynthesis, is the factor that ultimately defines the limits of productivity.[[28]](#footnote-28) This is a key reality check for any claims about productivity, among other reasons, because, as the authors conclude: “*In a commercial microalgal setting, the assumption of implausible specific growth rates leads to implausible business projections*.”

One of the main “advantages” claimed for microalgae biofuels is the capacity to produce very large amounts of fuel on relatively small land area – hence avoiding competition with food production or biodiversity. That claim is clearly not applicable to cultivation of heterotrophic microalgae since they must be provided with feedstocks produced from land-based monoculture crops. Solazyme is an example of a company that uses heterotrophic microalgae which are supplied with sugarcane, rather than producing their own sugars via photosynthesis. Sugarcane cultivation is a major driver of deforestation and land degradation, as well as being an industry notorious for violent displacement of people from their lands, and slave labor conditions.

Even cultivation of photosynthetic microalgae requires large areas of land. To understand why, begin with the fundamental limitations of RuBisCo and photosynthesis, which imply that there is a limit to the amount of carbon that can be absorbed by microalgae in a cultivation facility, per unit of area, per day – that rate is about 5 grams of C per square meter, per day.[[29]](#footnote-29) Therefore, to provide enough area for algae cultivation to absorb a significant portion of (for example) the hundreds of thousands of tons of carbon emitted by a large industrial facility, would require astronomical land area for algae ponds, located directly adjacent to the facility.

**Myth #3: Microalgae fuels are climate friendly, a clean green alternative to fossil fuels, and can be used to sequester or recycle carbon or provide “carbon negative” fuels.**

This myth rests in part on the believability of the prior myths. Making fuels from nothing but sunshine, water and the pollutant, CO2 sounds climate friendly indeed, but as we have already shown, there is much more to the equation including emissions from production of nutrients, materials and energy. Yet, given increasing pressure to reduce greenhouse gas emissions, combined with simultaneously increasing demand for fuels, the concepts of “recycling CO2”, also referred to as CCU (carbon capture and utilization) has risen into the lexicon, along with “carbon negative emissions”.

The Algae Biomass Organization (ABO) promotes microalgae “Carbon Capture and Utilization” (CCU), a designation they won under the Obama Administration Clean Power Plan (now largely eliminated under Trump). ABO state: "*a new crop of microalgae technologies can flip this approach [the “hammer” of regulations] on its head by converting CO2 into valuable commodities for trillion dollar industries, thus turning a problem – the high cost of compliance – into an opportunity – an ongoing revenue stream. Beneficial utilization of CO2 is the only option to turn the market forces and economics of waste CO2 into a ROI-driven, growth industry that will turn a huge problem into an economic opportunity. In doing so, we can achieve a rare trifecta – the reduction of emissions, the creation of jobs and economic development across the country, and a contribution to our food and energy security.*”[[30]](#footnote-30)

How is it possible not to be enthused by such hype? Hooking up algae cultivation to industrial power plants, to provide CO2 has been attempted with little success An example of a company working in this realm is Pond Biofuels, who established an “Algal Carbon Conversion Pilot Project” in partnership with the National Research Council of Canada and Canadian Natural Resources Limited. The $USD 19 million project, aims to use microalgae to capture CO2 emissions from the Primrose South tar sands oil refinery in Bonnyville, Alberta. The microalgae will supposedly then be used to produce biofuels, livestock feed and fertilizer.[[31]](#footnote-31) Pond Biofuels refers to potential for capture from various heavy industries, including coal, steel, refining and cement. They also have a pilot project in place to capture emissions from St Mary’s cement kiln.[[32]](#footnote-32) Similarly, the Tata Steel manufacturing facility in Port Talbot (UK) has partnered with the UK EnAlgae program to test use of flu gases for algae cultivation.[[33]](#footnote-33) A comprehensive review of pilot projects around the world is available here:[[34]](#footnote-34)

But growing algae on flu gases is fraught with problems. For one thing, there is much more than CO2 emerging from those smokestacks, including a variety of toxins that can inhibit growth or are lethal to microalgae. Species that can tolerate the industrial flu gas environment are not necessarily those that are generally of commercial interest. Furthermore, as discussed above the limits of photosynthesis dictate the amount of carbon that can be absorbed per day. For a facility that is dumping hundreds of thousands of tons of carbon from a smoke stack, providing enough area for algae cultivation to absorb even just a portion of the output would require a vast area of land – directly adjacent to the facility.[[35]](#footnote-35)

Taking the concept of microalgae carbon capture a step further, enthusiasts now refer to producing “carbon negative” fuels. Here the idea is that more carbon is sequestered during microalgae (or plant) growth - or otherwise captured during production and combustion of the fuel - than is emitted into the atmosphere when the fuel is used. Thus, the net impact would be that CO2 is not only being reused, but actually is removed from the atmosphere by use of the fuel. This notion, while highly appealing as it would enable perpetual use of large amounts of fuel, is fanciful at best, completely sidesteps reality and defies the basic laws of physics at worst.

An example of a company touting “carbon negative fuels” is Microalgae Systems, who stated on their website: *“The fuel we need for the future we want is a fuel that lowers atmospheric CO2 levels with every gallon consumed, and fits within today’s existing infrastructure… Microalgae Systems’ partnership with* [***Global Thermostat***](http://www.globalthermostat.com/) *enables us to produce truly carbon negative fuels — feed our microalgae pure CO2, sequestered directly from the air using Global Thermostat’s revolutionary technology, to produce biochar, diesel and jet fuels that actually emit less CO2 when burned than is fixed in growing the microalgae.*”[[36]](#footnote-36)

Taking the algae carbon fix logic yet even a step further, there are those who consider algae as potentially useful for “climate geoengineering” – i.e. readjusting the concentration of greenhouse gases in the atmosphere on a global scale by means of algae cultivation.

ALGAE FOR CLIMATE GEOENGINEERING TEXT BOX

How climate friendly microalgae biofuels are, depends upon many factors – but lifecycle assessments are not favorable. Hooking up microalgae production to polluting power plants and industries could be viewed as “cleaning up” those facilities. On the other hand, it could also be viewed as perpetuating and greenwashing dirty processes that should be halted altogether. Ultimately, the proof is in the pudding, and so far these approaches have only been piloted. Like many technologies, proof of concept in a laboratory does not always translate into real world commercial/industrial scale applications.

**Myth #4: Commercially viable microalgae biofuels are “just around the corner.”** It appears to be taking several decades to get around this corner! Given the fundamental barriers to commercial production of biofuels from microalgae, even after so much investment and effort, it seems clear this claim should be relegated to the dustbin. In an interview with Bloomberg, Craig Venter, CEO of Synthetic Genomics, which is working to create synthetic microbes and microalgae for fuel production and other purposes, stated that microalgae ponds would produce “10 times as much fuel as the ethanol fed by corn fields covering the same amount of space”. (Exxon Mobil invested over 600 million in Synthetic Genomics microalgae biofuels research and development, then stepped back, and has now recently renewed investment.)[[37]](#footnote-37) Rex Tillerson, then CEO of ExxonMobil (and now Donald Trump’s Secretary of State) stated in the same interview that microalgae biofuels were “*at least 25 years away… what we’ve come to understand is that the hurdle is pretty high, and the hurdle seems to come at the basic science level which means it’s even more difficult to solve.*”[[38]](#footnote-38)

**Industry Changing Course:**

Many startup microalgae biofuel companies, after failing to produce commercially viable biofuels for many years, are struggling financially or going bankrupt. Many are turning to production of other products and coproducts such as food additives, animal feeds, flavorings, nutraceuticals and cosmetics as well as CO2 sequestration and water treatment. These can be produced in lower volume, and sell at higher prices, making the economics of microalgae cultivation more viable. Some companies are marketing coproducts, while continuing to pursue viable commercial production of biofuels, for which the market could potentially be vast. In industry parlance, this is a “biorefinery” approach, that makes use of multiple products and coproducts. As Sapphire founder Stephen Mayfield articulates: “*the only way you make money on a pig is if you sell everything but the oink*.” [[39]](#footnote-39)

Products and coproducts that are being marketed include nutraceuticals including Omega-3s, astaxanthin and betacarotenes, polyunsaturated fatty acids DHA and EPA, coenzyme Q10, ACE inhibitor for blood pressure control, various pharmaceuticals including proteins, antimicrobials, antivirals and antifungals and neuroprotective products, cosmetics including anti-cellulite and alguronic acid, hydrocolloids including agar, alginate and carrageenan, biofertilizers, biopolymers and bioplastics, animal and fish feed (especially as replacement for fish meal in aquaculture and livestock.

Examples of companies that set out to produce biofuels, often with massive investment of public funds, and now are either exclusively or primarily selling niche consumer bioproducts:

**Solazyme/Terra Via**, the company started out to produce biofuels, claiming potential to produce vast quantities (see above). Solazyme uses heterotrophic microalgae, *Prototheca moriformis*, raised on sugarcane feedstocks. They also have engineered *Chlorella protothecoides*. They have partnered with Chevron, UP, Honeywell and won a contract to supply the US Navy with microalgae based “drop in” fuels, which they did at the cost of $400/gallon. The company established a joint venture with Bunge in Brazil, and also partnered with Dow and Unilever (oils used in “Lux” soap). Solazyme released “Encapso” a (presumably non GE) microalgae derivedlubricant for use in industrial drilling, including horizontal drilling (fracking) operations. After all the investment, it appears that the main commercial product for Solazyme is their anti-wrinkle “Algenist” cream. They have also introduced, and won FDA approval (Generally Recognized As Safe, or “GRAS”) for a line of specialty foods including high oleic cooking oil and “Algavia” whole microalgae protein and whole microalgae flour, derived from non-GMO microalgae.[[40]](#footnote-40)

**Algenol:** Developed engineered *Synechocystis* species that directly secrete ethanol. The company received between 30 and 55 million dollars in public money along with tens of millions in private investment on the basis of their claim to be able to produce ethanol, gasoline, jet, and diesel fuel, “*for around $1.30 per gallon each using proprietary microalgae, sunlight, carbon dioxide and saltwater at production levels of 8,000 total gallons of liquid fuel per acre per year*." Algenol has since shifted to production of nutraceuticals (Omega oils) and microalgae carbon capture.[[41]](#footnote-41)

**Sapphire Energy:** Based in San Diego, and closely affiliated with UC San Diego, the company set out to produce microalgae biofuels and won supports from DOE and USDA as well as tens of millions in venture capital support. The company accrued a vast and diverse collection of patents, and established partnerships with Monsanto and Phillips 66, as well as Linde and Chinese petroleum giant, Sinopec. Sapphire constructed a 2200 acre microalgae farm in New Mexico along with two other facilities. After selling small volumes of “green crude” (at $26/gallon), Sapphire shifted focus to production of omega-3 oils and animal feed ingredients.Sapphire/UC San Diego announced on May 4, 2017 the results of the first EPA approved open pond test of genetically engineered microalgae *Acutodesmus dimorphus*.[[42]](#footnote-42)

**Aurora Biofuels:** Developed GE *Nanochloropsis* species for open pond cultivation. The company shifted focus from fuel to food production, but went bankrupt and closed down in 2015.

**OriginOil:** changed name to OriginClear and changed focus from fuel production to water treatment.

[**Solix**](http://www.solixalgredients.com/): Started out to produce microalgae biofuels but now produces astaxanthin, DHA, and omega-3 nutraceuticals.

**Synthetic Genomics (SGI):** Works on a wide variety of biotechnology processes and organisms, butwon funding from ExxonMobil to develop microalgae biofuels first in 2009 and recently renewed.[[43]](#footnote-43) In May 2014, SGI announced a partnership with Archer Daniels Midland to produce Omega-3 from (non GMO) microalgae.

**Joule:** Won EPA advanced biofuel pathway approval in 2016 for fuels produced with GE cyanobacteria, (*Synechococcus*).[[44]](#footnote-44) The company claimed they would be producing algae biofuels by 2017, but owner, Flagship Ventures merged Joule with Red Rock Biofuel, and appear poised to wait.

**Cellana: Operating a demonstration scale project in Hawaii to produce** microalgae biofuels. They signed joint agreement with Neste Oil in 2013 for microalgae crude production, using a hybrid PBR/open pond system and non GMO microalgae. Cellana is producing omega oils and animal feed, and recently signed an agreement to collaborate in production of microalgae derived inks.

A number of research initiatives seek to develop microalgae bioplastics, for example “SPLASH” (Sustainable Polymers from Microalgae Sugars and Hydrocarbons), an EU microalgae bioplastics research consortium. Researchers have succeeded in the laboratory to convert microalgae oils into synthetic polyester.[[45]](#footnote-45) Another example is Algix, a biotechnology company based in Mississippi that, according to their website; “operates in a variety of areas, including microalgae remediation, bio-plastics, 3D printing, bio-foams and fish farming.” Cereplast, a startup that worked to market microalgae derived bioplastics, filed for bankruptcy in 2014. The company was bought out by Trellis Earth, who plan to continue work on bioplastics but “*have no plans to continue development of Cereplast’s microalgae plastic at this time. Although the product might have future applications for products like fence posts, Collins said the material’s dark green color, odor and tendency to impart taste limits its marketability*.”

A comprehensive table of microalgae research and commercial operations around the world is available in IEA Task 39, section 11.4.

**Biotechnology to the Rescue?**

Biofuel production may still be the “holy grail” of the microalgae industry, because of the potential massive market that it would serve, but these other microalgae derived bioproducts provide a financial lifeline and are increasingly dominating the agenda for producers. What is common to many is a very heavy dependence upon biotechnology to engineer microalgae for suitability to industrial purposes. The tools available for manipulating genetics have meanwhile greatly advanced. Recent developments include a suite of new approaches sometimes referred to as “synthetic biology”, or “new breeding techniques”. These have arisen with the advent of “omics” capabilities, very rapid screening of genes for function and characteristics as well as laboratory synthesizing of genes and sequences which can then be compiled and inserted into organisms, creating radically altered “synthetic organisms”. The primary orientation of synthetic biology has been to engineer “cell factories” that will secrete chemicals, compounds and molecules with utility for commercial and industrial applications.

Traditional genetic engineering mostly involved the transfer of genes from one organism into another unrelated organism (trangenics), a procedure that was slow and laborious with very limited rates of success. The new approaches provide vastly increased speed with which genes and genomes can be screened, as well as lab synthesized and modified. Some synthetic biology approaches do not involve introduction of foreign genes at all - for example, “directed mutagenesis” which forces mutations on existing genes. One new technique that has gained much attention is “genome editing” using CRISPR/Cas9 (or CRISPR/Cpf1). While only introduced a few years ago, genome editing has since been applied to a wide array of organisms, including microalgae.[[46]](#footnote-46) Genome editing is referred to as “more precise” –providing capability to control very precisely the “editing” of gene sequences, analogous to the use of a word processor for writing. This representation however is misleading. Critics point out that genome editing is only “precise” in the most superficial sense – given many unintended and off-target effects, and a lack of knowledge about the impacts of “precise edits” on the behavior and physiology of the organisms.*[[47]](#footnote-47)* Genetic engineering and synthetic biology are founded on a reductionist view of nature and genetics. The engineering mindset is however poorly reflected in the real biological world, where genes can have multiple effects, depending on the activity of other genes, the organism as a whole, and the environment, all of which change over time. As ecologists, geneticists, and students of nature understand, predictability and control are far more elusive than practitioners of “engineering biology” will acknowledge. Nature in the real world, is messy.

The use of new synthetic biology techniques is increasingly favored due to the uncertainty among biotechnology regulators about ***what and how*** to regulate “edited” or “synthetic” organisms, which has largely resulted in less, rather than more, oversight.

Meanwhile, governments around the globe, and at international fora including the Convention for Biological Diversity are debating how to regulate synthetic biology.[[48]](#footnote-48) A network of civil society groups developed "Principles for Oversight of Synthetic Biology".[[49]](#footnote-49) Industry however, is plowing forward at its own pace, without regard to these processes. Regulatory agencies are in some cases allowing commercialization of products derived from synthetic biology, including synthetic microbes and microalgae with virtually no evaluation whatsoever of their public health and environmental risks.

In the US, microalgae, along with other micro-organisms, are regulated by the EPA, based on the Toxics Substance Control Act (TSCA). Oversight has been minimal at best. The Obama administration called for reform of the regulatory framework for biotechnology overall, prompting the EPA to engage in public consultation and a workshop specifically focused on risk assessments for engineered microalgae.[[50]](#footnote-50) Under the current Trump administration, regulations will most likely be nonexistent. This is troubling given that it is concurrent with a very dramatic escalation in the speed and pace of new applications for commercial deregulation. EPA reported receiving about 5 applications per year for engineered microalgae between 2003-2011. In 2015 they had already received 42 applications by the month of June.[[51]](#footnote-51)

EPA regulations at their best exempted almost all research and development activities - even if ultimately targeted for commercial application. Even pilot and demonstration scale projects are mostly exempted with the exception of projects involving open pond cultivation which does require minimal review (TSCA Experimental Release Application, or TERA). Commercial production requires more reporting and oversight (Microbial Commercial Activity Notice, or MCAN). To date three companies that use engineered microalgae have been reviewed and permitted for commercial use by the EPA: Solazyme, Joule, and Algenol. Meanwhile, the Food and Drug Administration oversees applications for uses as food and feed additives. Solazyme won approvals from the FDA, as "Generally Recognized as Safe" (GRAS), for food products including high oleic oils, protein powder and flour derived from modified microalgae.

In May 2017, results from the first EPA permitted open pond test of engineered microalgae were reported. [[52]](#footnote-52) These tests were performed as part of the “Consortium on Microalgae Biofuel Commercialization” which included the University of California, San Diego, and Sapphire Energy. The microalgae, engineered strains of *Acutodesmus dimorphus* were cultivated in open ponds. Trap ponds at various distances revealed that the engineered microalgae did in fact move out into the environment. The researchers concluded on a positive note, that the engineered traits were maintained in open pond cultivation, and that the engineered microalgae did not outcompete or otherwise interfere with native microalgae in the region. However, the very short time period of the study –just two months – makes conclusions tentative at best.

What are the characteristics that are being engineered in microalgae?

**"Improved" photosynthesis:** Engineering control of photosynthesis to maximize productivity has been a major focus and includes efforts to increase or target light gathering capacity and extend the range of light spectrum that microalgae can utilize. It also has involved efforts to manipulate "Rubisco", the aforementioned enzyme responsible for the ability of photosynthetic plants and microalgae to fix C, from CO2 into energy rich molecules (such as glucose), and hence ultimately responsible for determining productivity.

**Maximize lipid production:** Engineering controls that would enable producers to manipulate that fundamental barrier - the trade-off between growth and lipid production – has been a major focus of biotechnology researchers. The goal is to “overproduce” lipids without killing the microalgae. A 2016 report was hailed as a breakthrough for successfully identifying key genes that control the trade off, and for targeting the role of salinity as a factor controlling the switch from starch to lipid production for *Chlamydomonas* microalgae.[[53]](#footnote-53) How well this generalizes to other microalgae species however, remains to be seen.

**Redirection of metabolic pathways to produce specific kinds of lipids, fuels and chemicals directly:** Manipulating cell biochemistry independent of growth mechanisms, yet again, remains a challenge. It has been possible to genetically engineer microalgae to produce alkanes, ethanol, acetone, ethylene, isoprene, isobutyraldehyde, isobutanol, 2,3 butanediol,1-butanol, 2-methyl-1-butanol, and various fatty acids etc. in controlled laboratory conditions, on small scales.[[54]](#footnote-54) Transitioning production from laboratories to large scale commercial production has not been possible.

**Tolerance to conditions of mass cultivation - Resistance to contamination and predators:** Just as herbicides such as glyphosate are used to control invasive weeds in agricultural crops, chemical controls, including engineering resistance to glyphosate and other herbicides and pesticides, are being investigated for large scale microalgae cultivation.[[55]](#footnote-55) This is alarming as it indicates large scale microalgae cultivation could follow a similar path to that of industrial agriculture: by far most widespread GMO terrestrial crops are those engineered for resistance to glyphosate (roundup). Along with their increase in acreage has been a vast increase in application of glyphosate, now considered a probable carcinogen with multiple health and environmental impacts.[[56]](#footnote-56)

**Hydrogen production:** Some microalgae species naturally produce hydrogen, they can only do so under particular conditions: lack of sulfur availability and cessation of photosynthesis. Hence they cannot grow and produce hydrogen simultaneously. Efforts are underway to engineer "optimal" hydrogen productivity.

Will it ever be possible to engineer microalgae such that they can efficiently and sustainably produce significant quantities of biofuels? This seems unlikely, at least any time in the foreseeable future. As Rex Tillerson noted, the barriers are fundamental. In “Photosynthetic constraints on fuel from microbes”, the authors conclude: “*at present, photosynthetic microbial fuels are not viable in energy terms. This is related to intrinsic inefficiencies in photosynthesis, and thus research has been directed to improving photosynthesis. A brief survey indicates that most suggested modifications would be beneficial only under restricted culture conditions. Controlled growth in bioreactors may then be required but this will incur a significant energy cost. Which, at this point, is much bigger than the engineered efficiency gain*.”[[57]](#footnote-57)

Nonetheless, spending on research and development continues, and meanwhile with the new tools that are available, researchers argue that it is increasingly possible to quickly, inexpensively and profoundly alter genetics. But at what risks to health and the environment?

**Risks and threats:**

What are the risks of genetically engineered/synthetic microalgae? To evaluate these, we have to recognize what we know and also, especially, what we do not know. We know that microalgae are enormously diverse. There are an estimated 800,000 species, of which only perhaps 50,000 have even been described. There are microalgae species that thrive in oceans, freshwater, soils, tree barks, as symbionts with various animals (for example in the fur of sloths!), and many, many other environments. We know next to nothing about most species, and even for familiar species, we know little about their natural history or behavior in nature.

In “Genetically Engineered Microalgae for Biofuels: A Key Role for Ecologists" the authors ask: “*How frequently would GE microalgae escape from cultivation and processing facilities? This could occur through aerosolization (Genitsaris et al. 2011, Sharma and Singh 2011), wildlife vectors (Kristiansen 1996), turbulent weather that damages or destroys these facilities, accidents, human error, or other events. How far would GE microalgae disperse (Kristiansen 1996, Marshall and Chalmers 1997), and how long would they survive (Ehresmann and Hatch 1975)? Could transgenes designed to enhance the growth and fitness of released GE microalgae subsequently spread across metapopulations, species, habitats, and regions, and, if so, at what scales and over what time frames*?" [[58]](#footnote-58)

We do not have the answers to these questions. We do however know that some species can easily become invasive under favorable conditions, and others secrete toxins capable of causing illness and even death in humans and other species. We know also that many ecosystems depend upon a delicate balance of species, including, in some cases, dynamic multi- species aggregations of microalgae. Our lack of knowledge means we cannot really predict or model what would occur with the introduction of non-native, genetically modified or synthetic microalgae into the mix.[[59]](#footnote-59) There are simply too many "unknowns" and "unknown unknowns" to adequately assess the risks. This is disturbing given the pace of research and development. We can however make some assumptions and extrapolations from what we do know about microalgae.

**Release into the wild is inevitable. Microalgae simply cannot be contained, especially in commercial and industrial facilities.** Many researchers **assume** that microalgae under cultivation simply cannot be prevented from escaping containment. Their very small size (single cells) means they can easily escape via minute spills and accidents and be carried out by a variety of vectors - on clothing, in air vents etc. Accidents are inevitable. Some species can remain dormant for long periods. Some also can be transported over long distances, by becoming airborne.[[60]](#footnote-60) It should be considered a “given” that cultivated microalgae, whether native, non-native, GMO or synthetic, will in fact escape into the wild.[[61]](#footnote-61)

In "Cultivated Microalgae Spills: Hard to Predict/Easier to Mitigate", the authors state "*cultivating microalgae on a large scale will inevitably lead to spills into natural ecosystems*... *spills of non native microalgae in aquatic (or terrestrial) ecosystems may have massive ecological repercussions regardless of whether the microalgae are genetically modified*....*it will be very difficult or even impossible to make firm predictions about the risks of non native microalgae based on algal fitness characteristics determined in laboratory experiments or in modeling studies*."[[62]](#footnote-62)

**Many claim that microalgae engineered for industrial uses would not likely survive in the wild. However, microalgae are being engineered in some cases for exactly the traits that could make them out-compete native species.** Those traits include abnormally prolific growth rates which can be achieved in part by outcompeting wild species over access to nutrients, resistance to contamination by wild species which may be achieved for example by engineering microalgae to secrete toxins lethal to invaders. Resistance to the fungi, bacteria and protozoa that normally hold wild populations in check etc.

In a paper entitled “Monster Potential Meets Potential Monster”, Flynn et al. (2013) elaborate via a modeling exercise, that while it is likely possible to engineer microalgae to increase productivity fivefold, doing so would alter the stoichiometry of the microalgae in a manner that would make them unappetizing to the predators that normally are key in keeping microalgae blooms in check. The authors conclude: “*The spread of GM microalgae of the type of configuration we identify would be effectively impossible to halt. As GM factors likely affecting palatability of microalgae is already being conducted in the name of biofuels production, there is a real risk that the genie is already part way out of the bottle. If GM biofuels-optimized microalgae were to destroy fisheries then a main driver for microalgae biofuels research, the argument that such biofuels would not compete with production of biomass for food, may prove to be totally misplaced. Accordingly a strong argument can be made for the regulation of GM microalgae at an international level, because the potential for damage could have global consequences, echoing recent concerns over geoengineering. Whether against arguments for sovereign fuel security, regulation could be enforced is a dilemma that society may soon have to face up to*.”[[63]](#footnote-63)

**Microalgae's high rate of productivity means mistakes spread quickly.** Henley et al. state: “*GM organism that survive in natural ecosystems are potentially unlimited in time or space. Algal populations can grow explosively and episodically through asexual and in many cases sexual reproduction. Indeed, rapid growth is one of the primary advantages of microalgae over plants for biomass production. But it also may represent a larger ecological risk*.” [[64]](#footnote-64)

**Harmful microalgae blooms (HABs)** are a phenomenon where conditions favor proliferation of particular microalgae species that secrete toxins. These toxins can result in massive fish kills, and death to marine birds and mammals as well as illness and even death to humans.[[65]](#footnote-65) Some are neurotoxins, others affect the liver or cause blood poisoning. Studies suggest that exposures to toxins released by some cyanobacteria may be linked to diseases like Alzheimers and Parkinsons disease.[[66]](#footnote-66) The incidence of HAB’s has risen very sharply with pollution and warming of waterways as well as the transport and introduction of various microalgae species in ballast waters among other vectors.[[67]](#footnote-67) In particular, climate change is considered a “catalyst” that is resulting in dramatic increases in HABs and in shifting microalgae population dynamics.[[68]](#footnote-68)

In addition to secreting toxins, microalgae blooms result in hypoxia (depleted oxygen) in waterways, the well-known example being oceanic “dead zones” caused by microalgae blooms supported by influx of nutrients runoff from upstream agriculture. Contamination of drinking water supplies and recreational waterways are often of particular concern along with the economic impacts of microalgae blooms, estimated to range up to over $2 billion annually in the USA.[[69]](#footnote-69) Obviously, mass cultivation of species known to produce toxins would be ill advised, but given our lack of knowledge about many species and their ecology, or the potential impacts of genetically engineered microalgae, a precautionary approach to cultivation of non-native, GE or synthetic microalgae would be advised. Engineering microalgae specifically to secrete toxins (i.e. as a means to deter pathogen contamination in cultivation processes) would seem especially risky!

Palyotoxin (PITX), a compound produced by dinoflagellates and cyanobacteria is an extremely potent neurotoxin, whose mechanism of exposure was reviewed by David Haberman.[[70]](#footnote-70) Exposure, both from consuming contaminated seafood and inhalation or skin contact can cause serious illness, blindness or death. [[71]](#footnote-71) Haberman warned of the serious risks posed by GM microalgae.[[72]](#footnote-72) Presenting at a 2013 International Biodefense and Natural Disaster conference, he referred to genetically modified microalgae as a potential “poor terrorist’s bioweapon” based on the similarity between PITX and the compound “ricin” (recognized in the U.S. as a second priority potential bioweapon). **[[73]](#footnote-73)**

**Horizontal Gene Transfer:** Cyanobacteria are known to frequently engage in horizontal gene transfer, a characteristic that has played a major role in their evolutionary history.**[[74]](#footnote-74)** Horizontal gene transfer refers to transmission of genes not just to direct progeny via sexual reproduction, but to other, even unrelated, individuals, and even potentially to other species. Some species can take up "naked DNA" from their surroundings and import/export DNA using viral or other vectors. Studies indicate HGT between cyanobacteria and their predators (called cyanophages) is so pervasive that it “performs the driving functions in adaptive microevolution”.[[75]](#footnote-75) HGT could result in transmission of DNA into edible aquatic species and ultimately via the food chain, into humans. In sum, the exchange and transfer of genetic material among these organisms is not straightforward and predictable, nor is it well understood.

**Instability of engineered traits:** Engineered traits may not be retained over time due to very high rates of mutation, unstable expression and gene silencing. Researchers maintaining cultures have found that over time the initially identical cultures may no longer be identical after being in storage for some time.[[76]](#footnote-76) In “Genetic Instability in Cyanobacteria” this problem, referred to as “the elephant in the room” is reviewed.[[77]](#footnote-77) Nozzi et al state: “*For continuous production from cyanobacterial strains, culture stability remains a challenge with peak titers occurring after a week in many cases. Loss of production may be due to genetic instability, as carbon diversion creates a selective pressure for spontaneous mutants with an inactive pathway*.”[[78]](#footnote-78)

**More use of toxins:** Monocultures of microalgae have proven vulnerable to invasion from competing wild species, predatory organisms and fungal infections. "Crop protection" is therefore a major focus of research and microalgae are being engineered to be resistant to herbicides (glyphosate and others) and other toxins. [[79]](#footnote-79) Sapphire Energy, for example, has already patented glyphosate resistant microalgae strains.[[80]](#footnote-80) Glyphosate (aka roundup) application in terrestrial agriculture has skyrocketed with widespread adoption of crop varieties engineered for resistance. [[81]](#footnote-81) Meanwhile, glyphosate has been recognized as a "probable carcinogen", along with causing numerous other health and environmental damages including destruction of beneficial soil microbes and the plummeting of monarch butterfly populations. Large scale cultivation of microalgae could result in yet another uptick in the use of such toxins including glyphosate.

Industrial cultivation of microalgae, even if they are not genetically modified, carries serious risks. In “Cultivated microalgae spills: hard to predict, easier to mitigate risks”, the author states; “*Cultivating algae on a large scale will inevitably lead to spills into natural ecosystems. Most risk analyses have dealt only with transgenic algae, without considering the risks of cultivating the corresponding non-transgenic wild type species. This is despite the long-studied ‘paradox of the plankton’, which describes the unsuitability of laboratory experimentation or modeling to predict the outcome of introducing non-native algae into a new ecosystem*.”

**Microalgae are fundamental to ecosystems and to regulation of biogeochemical cycles, hence there is potential for far-reaching and serious harms.** Microalgae form the base of the aquatic food chain, hence the composition of algal communities is a defining feature of ecosystems. Predicting or controlling the impact of introduction of engineered (or non-engineered non-native) microalgae into natural ecosystems is not possible, especially given the lack of knowledge about basic biology and genetics for the majority of species, and changing environmental conditions. In addition to the vast genetic variation among microalgae species and populations, there is also much variation in species composition within ecosystems, which responds over time to shifting conditions, including nutrient availability, temperature, light, presence of predators and pathogens, and water currents - among many other factors.

As the source of much of the oxygen that makes earth habitable for humans and most other species, the presence and population dynamics of microalgae have broad ranging consequences. We face an unpredictable future with escalating pollution, fast paced warming and ocean acidification which is already causing major shifts in microalgae communities and ecosystems and dramatic increase in the incidence of harmful microalgae blooms. We must assume that microalgae will inevitably escape from industrial cultivation systems (not only open ponds, but also photobioreactors, during industrial cultivation). The magnitude of potential negative impacts from introduction of engineered or synthetic microalgae should not be underestimated and should be cause for serious concern and precaution.

**Conclusions:**

Even after decades of effort, microalgae biofuels remain elusive, and it appears that this is due to fundamental barriers that make it difficult to realistically achieve the massively high productivity that would be required to cultivate microalgae at economically viable costs, with positive energy balances, while limiting land, water and nutrient requirements. Instead, producers are turning to high value niche coproducts for which lifecycle assessments and costs are not at issue.

The ongoing focus of research, on genetic engineering/synthetic biology introduces serious health and environmental risks that have been ill considered, and are grossly inadequately regulated. Given their fundamental role in earth systems, it seems particularly unwise to manipulate and engineer microalgae to produce fuels and chemicals for commercial and industrial uses when “containment” in production facilities is essentially impossible.

The risks associated with large scale microalgae cultivation and especially engineered microalgae must be weighed against a realistic assessment of potential benefits. With the long history of failure to produce economically viable microalgae biofuels, it is perhaps time to stop promoting microalgae biofuels as the “savior, just over the horizon if we just keep investing”. The generation of false hopes is a harmful distraction from real solutions. As microalgae producers turn increasingly to producing high-end niche products, the risks are clearly not worthwhile. For example, Solazyme’s “Algenist” anti-wrinkle cream product, “Elevate”, sells at a $USD 96.00 for 2 ounces, affordable by only a handful of wrinkled elites.

Some microalgae derived products and services, perhaps including nutraceuticals (for example Omega oils currently derived from dwindling fish stocks), animal feeds or wastewater treatment, hold potential for broader societal benefits. However, native, non-engineered species should be used, and methods for cultivation must at the very least take serious precautions to minimize release into the surrounding environment. It is time to reassess the ongoing investment of taxpayer dollars (and venture capital) into the risky microalgae biofuel dead-end, and redirect efforts to more promising approaches to transportation in a warming world – approaches that pose less risk to public and environmental health.

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