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Upward Farms Technical White Paper

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May, 2021

Summary: Upward Farms has overcome the economic barriers to scaling indoor vertical farms by innovating at the intersection of hardware, software, and ecosystem engineering. The Company focuses on mastering the management of biodiverse ecologies, which is the key to its existing competitive advantage and to its future potential. Quantitative field studies have conclusively demonstrated that diverse ecosystems are more productive and stable than monocultures, and that a key driver of these advantages is an appropriately complex microbiome. This complexity is eschewed by other vertical farms, in which inefficient crop monocultures are stabilized only through costly energy and chemical subsidies. In contrast, Upward Farms constructs resilient systems that utilize the complexity in biodiversity. The biological engine powering Upward Farms is integrated aquaculture, in which plants, fish, and, most importantly, diverse bacteria, together comprise a complex and self-regulating ecosystem. Upward Farms leverages automation, monitoring, and control systems to precisely quantify and predictively control the functional biodiversity of these complex farm environments to maximize production and stability. The innovation that results from embracing this complexity will become more important and valuable over time as ecosystem engineering becomes integral to increasing productivity across the economy.

Introduction

Upward Farms is an indoor agriculture company that has developed an extraordinarily efficient biomanufacturing system based on ecosystem engineering. Broadly writ, Upward Farms is a systems engineering company, where the system is composed of hardware, software, and wetware – i.e., sensors and automation, monitoring and control algorithms, and biology. The biological engine that makes this system possible is integrated aquaculture, in which plants, fish, and, most importantly, bacteria, comprise an ecosystem and exist in self-regulating nutrient loops. The combination of ecosystem engineering and mechanical engineering, coupled to automation and machine learning, yields an extremely productive manufacturing system, and one that benefits from rapidly falling costs across the constituent technologies. Taken together, Upward Farms operates at the nexus of the three techno-economic trends shaping 21st century industrial capacity: software, automation, and the engineering of biological systems.

There is impressive complexity in this vision, to be sure, but tools exist to manage this complexity. These tools were initially developed for the automotive, aviation, and consumer electronics industries, and they have already been adapted for use in biological engineering and manufacturing. In applying these tools to the entire problem of bioproduction, rather than to individual aspects, the Company is positioned to outcompete all comers.

Utilizing biodiversity, rather than minimizing it, is the Company's most important innovation. Quantitative field studies have conclusively demonstrated that complex ecosystems are more productive and stable than monocultures. By embracing ecological complexity, and learning to engineer it, Upward Farms benefits from these natural processes in its indoor farms.

Aggregating these insights, it becomes clear that, far more than simply managing buildings to grow greens and fish, Upward Farms is a high technology company that will drive innovation at the intersection of hardware, software, and ecosystem engineering. The Company will produce not just food, but also intellectual property and proprietary practical knowledge with broad value. In what follows, I illustrate how all these pieces come together by using examples and analogies from other mature industries as well as emerging technologies developed and demonstrated by Bioeconomy Capital portfolio companies.

Over the longer term, we (Bioeconomy Capital) see an opportunity to make ecosystems engineering the basis of a general purpose bio-manufacturing foundry – a factory capable of renewably producing biological outputs (including drugs, chemicals, and materials) beyond the current goal of food. We see Upward Farms as critical infrastructure for the 21st century.

The Bioeconomy Capital Perspective: Why Now?

Farming can be viewed as the manufacturing of food, whether at smallholder or corporate scales, and the future of sustainable farming can be found in the history of modern manufacturing. Consider the automobile industry, which at its origin had the critical insight that assembly lines organized by division of labor were profoundly more efficient than individual craftspeople. The assembly lines themselves were straightforward, but they had to be supplied with all manner of raw materials: iron ore from Minnesota, rubber sap from southeast Asia, coal from the Appalachians, etc. This required a highly organized supply chain and a logistics unit that brought raw material inputs to the plant in the right quantity at the right time. This operational complexity was managed using paper ledgers and the brains of human managers.

Over time, the operational demands of vertical integration (i.e., internal specialization and the need to be best-in-class at every activity) became constraints on growth and innovation. To escape these limitations, auto manufacturers focused instead on their core competency, which was the design of cars and their production via the assembly line system. Companies such as Toyota mastered just-in-time manufacturing, which stitched together hundreds of parts and subsystems built elsewhere. These operations required more sophisticated logistics management, with parts from dozens of manufacturers all arriving at a plant, being received into inventory, and placed in the assembly line in windows of four hours or less. New tools, such as mini-computers and scheduling software, were applied to manage the increased complexity.

While supply chains have become more complex, innovation has continued on the assembly line itself. Increasingly capable automation (robots and other equipment running manufacturing-specific algorithms) have replaced humans where advantageous, resulting in higher throughput and fewer errors. It is not necessary, nor even desirable at present, to replace 100% of human labor because humans remain more adaptable and dexterous than robots. But where they remain, humans are being made more effective with technology. In particular, augmented reality devices provide digital guides for moving and placing parts, allowing humans to work alongside robots, thereby increasing safety, reducing errors, and improving overall yield and efficiency. Just as with logistics, the assembly process is becoming a story of continuous improvement in managing complexity with software.

That same progression can be seen in the design and assembly of airplanes and consumer electronics. The electronics industry, in particular, has become a clear example of managing global raw material flows and the precise assembly of circuit boards and semiconductors while also managing the functions of the billions of transistors that make up each of the many chips inside, say, a smartphone or tablet. Software has replaced ledgers and brains as the means to manage complexity throughout the modern economy, with the cutting edge relying on machine learning algorithms and high-dimensional statistical analysis. Upward Farms is deploying these same tools of complexity management to develop scalable, commercializable processes for biological manufacturing in the form of indoor agriculture.

The opportunity to transfer knowledge from mature manufacturing sectors to bear on indoor agriculture is only just opening up. Multiple scientific and technical threads spanning hardware, software, and wetware had to advance sufficiently to be integrated into this multidisciplinary effort. For example, LED lighting has experienced exponential decreases in cost and increases in performance, which only recently reached levels suitable for use in large scale indoor farms.[1]

Similarly, while analytical techniques such as multi-factorial Design Of Experiments (DOE) have been around for decades, accelerated computation has enabled the application of machine learning to process management and optimization. And it is only with the recent emergence of copious quantities of high quality data, generated by the proliferation of low cost sensors, that DOE can be applied to quantitatively understand high-dimensional systems such as the interface of biological and physical environments in an indoor farm.

Finally, the quantitative demonstration that ecosystem productivity depends explicitly on biodiversity was first published only in 2007.[2] Upward Farms is explicitly building this biodiversity amplifier into its integrated operations. Weaving together all these newly developed threads enables the tapestry that is Upward Farms. Below, I briefly address how we see Upward Farms managing complexity in hardware and software, followed by an extensive discussion of the Company's greatest competitive advantage, the embrace of complexity and of ecosystem engineering.

Hardware

The Upward Farms team does not have to be expert in all aspects of engineering and manufacturing. The Company largely uses off-the-shelf components for mechanical engineering, which are utilized in proprietary processes, that can therefore be deployed more quickly in building new facilities (hereafter "Farms") than those of competitors that use fully custom-built hardware. Innovation is still required to adapt and integrate these technologies, as demonstrated by the Company's intellectual property on the basic Farm infrastructure and components thereof. Further improvements in automation, measurement, and mechanical and electrical systems will continue independently of applications at Upward Farms, reducing both cost and technical risk to the Company as it grows. To be sure, such generally available improvements will benefit anyone with sufficient cash to purchase the latest hardware. However, a durable competitive advantage will result from the integration of these secular technology trends with software and wetware; to our knowledge, only Upward Farms is implementing this integration.

Software and Data Analysis

Upward Farms can be thought of as leading the race to develop what we have come to call "software-defined agriculture". In other words, the Company is embedding the management of farming, ecosystem health, and material-handling processes in algorithms. Existing software tools are more than adequate to handle the general level of logistical and physical complexity that will be present in the Farms even when scaled to millions of cumulative square feet. And, like hardware, those software tools will continue improving independently of Upward Farms because any improvements are economically valuable across many industries, again reducing cost and risk faced by the Company.

1 "Haitz's law", *Nature Photonics*, **1**, page 23, (2007). For a graphical representation, see "Haitz's law": https://en.wikipedia.org/wiki/Haitz%27s_law. See also "Growing higher**:** New ways to make vertical farming stack up", *The Economist*, 31 August, 2019.

2 "Biodiversity and ecosystem multifunctionality", Andy Hector & Robert Bagchi, *Nature,* **448**, pp.188–190, (2007).

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There are, however, novel applications of machine learning and data analytics that the Company can use to optimize operations across all its Farms. We do not see this novelty as risk, and on the contrary see it as a competitive advantage, because we have already seen similar complexity engineering efforts bear fruit at other startups.

Here I point to the accomplishments of Synthace, which is pursuing the ambitious goal of developing a soup-to-nuts bioengineering and biomanufacturing software environment.[3] The software platform, called Antha, has been successfully used to manage complex experimental systems with more than 30 degrees of freedom, spanning environmental conditions, instrument settings, metabolic measurements, and genetic variants. This is a demonstration that systems of approximately the same physical and biological complexity as a Farm can be understood and optimized using appropriate tools.

Anything that can be measured or manipulated can be treated as a degree of freedom, or factor, in a statistical model of a complex system. Integration with multi-factorial DOE enables identification of the most important determinants of yield or cost. It also enables discovery of combinations of factors that cannot be identified by other methods. In a study for one client, Synthace demonstrated the discovery of a previously unknown interaction of three factors (one environmental, one genetic, and one instrument setting) that, when tuned appropriately, more than doubled the yield of a process. This is an example of systems engineering applied to manage complexity in a process that had previously eluded understanding.

While Upward Farms is implementing its systems engineering approach with a different goal, we believe the Company is clearly benefiting from applying the same technology to indoor farming. The software systems that run the Company's Farms fuse 1) measurement, monitoring, and automation systems used in datacenters and cloud infrastructure, with 2) production planning systems from advanced manufacturing, and 3) computational R&D platforms for continuous learning and improvement.

Creating software that runs Farms is like any other modern software engineering project. There is a language to encode the production processes. The processes themselves run under a version control system, like Git for software, so that multiple versions of the code (i.e., forks) can be tested simultaneously and branches discarded if they do not work as well as the main line code. "Compiling" the code and executing it on Farm infrastructure results in large quantities of data that, when analyzed, yields new insights that are included in the next generation of algorithms.

At Upward Farms additional software tools will help manage high complexity experiments with multi-factorial DOE in order to 1) collect, organize, and store the resulting data in a way that makes it a perpetually accumulating resource for data mining; 2) control auditable versions and histories of manufacturing algorithms; and 3) ultimately transfer the highly efficient production processes to the Farm manufacturing floor quickly and accurately.

Fortunately, as with the market for hardware, Upward Farms does not have to be an expert in each component of this infrastructure; this suite of tools already exists as a package developed by Riffyn.[4] Riffyn's customers, such as Novozymes and BASF, have seen a halving of the product development and deployment cycle thanks to the use of advanced software. Similarly, and unlike Ford developing the Model T, Upward Farms has access to

3 Synthace is a Bioeconomy Fund 1 portfolio company.
4 Riffyn is a Bioeconomy Fund 1 portfolio company.

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far more powerful tools than pencil and paper. Integrating these tools into the Company's operations will enable it to manage complexity in its indoor Farms.

Biology

I view the embrace of complexity as the Company's most important asset. Competitors attempt to eliminate complexity and to control the oversimplified biology of monoculture farms through brute force application of energy and chemicals, thereby encumbering themselves with operational complexity and excess cost. In contrast, Upward Farms constructs resilient systems that *utilize* the complexity in biodiversity. Diverse ecosystems are more productive than monocultures and are inherently capable of autonomous regulation. Systematically describing and improving the mechanisms of that autonomy comprises yet another component of the Company's competitive advantage.

Ecosystem engineering is a core competency at Upward Farms, and it constitutes a differentiating technical approach. A diverse microbiome 1) provides autonomous regulation of pathogens, and 2) facilitates nutrient regulation and transfer to crop root systems, just as in healthy outdoor ecosystems. The interaction of the complex microbiome with crop plants is the primary reason why Upward Farms has a fundamentally more efficient system than its competitors. Indeed, the Company has found that a carefully curated microbiome autonomously manages nutrient levels in its horticulture stages, eliminating a costly control step present in monoculture indoor farms.[5] This achievement, which is driven by managing biodiversity, demonstrates the critical benefits of including sufficient complexity both in the system itself <u>and</u> in the description of the system. That description forms the basis of a comprehensive engineering model of the Farm ecosystem.

Above I provided historical examples of the importance of managing complexity in modern engineering and manufacturing, and I cited already successful examples of bringing those tools to bear on biological systems. Building appropriately complex digital models is a key piece of this capability. Yet modern engineering works not simply because physical complexity can be described in a digital form and simulated. Accurate simulations must be informed and constrained by adequately precise measurement of the real-world characteristics of all the components in a system as well as how they interact. As described below, without precision in measurement and control, even industries that have led the way in demonstrating predictive simulation and design can see massive engineering failures.

Before diving further into the relevant technical details, I will to take a step back and address the viewpoint that complexity is a risk and that biological systems are inherently hard to engineer because they are unpredictable.

Consider, for a moment, a giant sequoia. Unless disturbed, each of these trees displays entirely predictable behaviors for more than three thousand years, at length scales extending from their subcellular biochemistry to their nearly one hundred meter height. The ecosystem in which these trees live, including animals, microbes, and other plants, is similarly predictable, even while individual organisms in that ecosystem live and die on shorter timescales than an individual tree. Even the humble soil bacteria surrounding the roots of a sequoia display entirely predictable behaviors from hour to hour, from generation to generation, and over eons, albeit subject to evolution via natural selection on timescales less than the lifetime of a tree. And yet despite these changes, the tree, and its surrounding ecosystem, remain a stable system over millennia.

5 Personal Communication, Jason Green.

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Biology is entirely predictable. The perception that biological systems are too complex to be understood or engineered is derived, very simply, from low precision measurement. In other words, historically, biological systems have not been well understood because humans have not quantitatively characterized these systems with adequate precision.

Even today, the results of many molecular biology experiments are often qualitative. It is only relatively recently that truly quantitative tools have been developed and applied to understand the fine details of biological systems at the molecular level, with one consequence being that only relatively recently could engineers understand enough about biology to engage in predictive design.[6] That lack of quantitative precision has been a significant barrier to engineering any biological system, whether at the level of genes or of ecosystems.

As an analogy, imagine for a moment how you would feel if you learned that the airplane you are about to board was assembled from parts machined with 10% tolerances. Rather than measuring one meter across, what if the main cabin door were instead only guaranteed to be between 90 and 110 centimeters. Would you take your seat? Would that plane be safe to fly? Of course, this doesn't happen in real life, and manufacturing tolerances on critical parts are far smaller than 1% – except that Boeing accidentally did this experiment when it outsourced initial manufacturing of 787 components, thereby losing control of precision in its supply chain. Boeing subsequently discovered that it could not even assemble the first airframe to completion, let alone test the airplane, because the sub-sections would not fit together.[7] Manufacturing and testing were successfully completed only after reestablishing control of the supply chain restored adequate precision throughout the complex process.

Just as imprecise measurement and control hamstrung the aviation industry, so has it hamstrung biological engineering. Fortunately, just as precision can enable predictive design of the behavior of the millions of parts in an airplane, so too can it enable predictive design and control of biological systems. We see across the companies in our portfolio that achieving 1% measurement precision, whether of environmental factors such as temperature, processing rates of enzymes, or expression levels of genes, enables predictive design of complex biological systems.

What does this have to do with Upward Farms? A terrestrial or aquatic ecosystem left to its own devices displays predictable species composition and succession over time. Island ecosystems, in particular, are excellent examples of quantitatively predictable complex systems, particularly if they are sufficiently isolated by distance from other landmasses. The circumscribed and quantifiable nature of these ecosystems is the foundation of an entire field of mathematical ecology known as island biogeography.[8] The relevance here is that, while complex, the Farms are, like islands, circumscribed physically by the building's walls and are eminently quantifiable in all aspects of their operation. In other words, the theoretical and mathematical groundwork for quantitatively modeling indoor farms as "island" ecosystems was first laid more than fifty years ago. With the addition of the relatively new capability to precisely quantify and control the environment, metabolic flows, and species composition in Farms – thanks to low cost environmental sensing, genetic sequencing and other "omics", and the computing power needed to process this data – the Company is able to implement an engineering approach that delivers economically advantageous operations.

6 *Biology is Technology: The Promise, Peril, and New Business of Engineering Life*, Robert Carlson, Harvard University Press, 2010.
7 "Boeing finds 787 pieces aren't quite a perfect fit", Dominic Gates, *The Seattle Times*, 12 June, 2007
8 *The Theory of Island Biogeography*, Robert H. MacArthur & Edward O. Wilson, Princeton University Press, 1967.

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With precision established as the tool to enable predictive understanding and behavior, I now return to the keystone that differentiates the capability of Upward Farms: the embrace of systems engineering to manage complex and biodiverse ecosystems as a manufacturing platform.

Across a wide variety of taxa and ecosystems, biomass production increases with biodiversity – measured as the number of species – and biodiversity has at least as strong an effect on productivity as does local climate and nutrient availability.[9] These functional relationships have been observed across multiple terrestrial and aquatic environments, giving support to the hypothesis that they also hold true in Farms.[10] Moreover, functional diversity among species has a larger positive influence on productivity and on temporal stability than does the number of species.[11] That is, ecosystems in which niches are filled out by species that accomplish specific functions are more productive than systems assembled simply to have a large number of species. Finally, many of these experiments have utilized meticulously constructed ecosystems to test the importance of species and functional diversity on productivity, making the results at least as relevant to indoor Farms as to open ecosystems.[12] These results are of particular relevance to the diversity of the Farm microbiome.

In grassland soil modification experiments, microbiome diversity has been demonstrated to improve plant diversity and biomass productivity 6X over sterile soils, while also suppressing plant diseases.[13] The beneficial effect was more pronounced when microbes known to cohabitate with particular grasses were included. These phenomena, while not yet fully explained mechanistically, are attributed to the complex web of metabolic interactions among microbes and between microbes and plant roots. Again, functional diversity is crucial for productivity and stability. This is consistent with the Company's experience that cultivating a healthy, crop-specific microbiome both improves the general health of crops and virtually eliminates crop loss due to pathogen outbreaks.[14] Moreover, these results validate the Company's focus on understanding and cultivating the microbiome best suited to maximizing Farm performance. The microbiome recipe, and methods used to curate it, constitute further intellectual property differentiating Upward Farms from would-be competitors.

Together these results indicate that the Company's integrated systems engineering approach, which incorporates 1) monitoring and control of the physical environment coupled to 2) careful curation of the species comprising Farm ecosystems – that is, ecosystem engineering – is exactly the right way to maximize the economic output of each Farm and to outcompete rivals relying on cultivation of monocultures. Moreover, every strength described above, from species selection, to metabolic monitoring, to community microbiology, will improve as the Company builds and operates additional Farms and learns more. Finally, because the engineering knowledge and ecosystem composition comprise innovations that enable the farm system to function, the combination constitutes protectable intellectual property.

Systems Engineering

Upward Farms already holds advantageous positions in each of the three separate pillars of software, hardware, and wetware. But it is the combination of these elements in an integrated system that truly differentiates the

9 "Biodiversity effects in the wild are common and as strong as key drivers of productivity", J. Duffy, *et al.*, *Nature*, **549**, pp261–264, (2017).
10 "Biodiversity and ecosystem functioning in naturally assembled communities", Fons van der Plas, *Biological Reviews*, **94**(4)**,** pp.1220-1245, August 2019
11 ibid.
12 "The results of biodiversity–ecosystem functioning experiments are realistic", M. Jochum, *et al.*, *Nature Ecology & Evolution*, **4**, pp.1485–1494, (2020).
13 "Soil microbes drive the classic plant diversity–productivity pattern", S. Schnitzer, et al., *Ecology*, **92**(2)**,** pp.296-303, February 2011
14 Personal Communication, Jason Green.

Company from the pack. The combination of 1) a controllable environment, 2) precise measurement of environmental and physiological parameters, and 3) automation and controls, together enables the application of tried-and-true principles from mature manufacturing disciplines – such as automobiles, airplanes, and cell phones – to ecosystem management and engineering.

This is analogous to NASA's embrace of the use of a skycrane for the last two Mars landings, rather than relying on the older, visually familiar, technology of balancing the lander on top of a rocket. Imagine for a moment the task of holding a pen steady in a vertical position while grasping it from above, versus balancing the pen on a fingertip; it is obvious that holding it from above is simpler and more stable. The stability of the overall landing system is the reason for choosing the skycrane. Nevertheless, building the skycrane required a significant investment in managing complexity in order to produce a system that is, ultimately, fundamentally more stable and easier to operate than the older technology. Embracing that complexity is a risk mitigation and management strategy for NASA. Similarly, Upward Farms has invested time and money in R&D on the front end to properly engineer a more complex system that requires less active control because it is intrinsically more stable and more reproducible. Farms can therefore be more readily deployed at scale in a more profitable manner. Moreover, the overall advantages for the Company and its investors should increase over time because the systems engineering expertise will grow with the scale of the business due to the network effects of learning and sharing process information between Farms.

What comes next?

Upward Farms is just beginning to unlock the full potential of its platform. Beyond the fundamental advantages that embracing biodiversity has over monocultures, to our knowledge the Company is currently the only organization commercializing the active engineering of complex ecosystems for indoor food production. Consequently, Upward Farms has a lead in developing proprietary working knowledge and intellectual property, relegating hopeful competitors to the role of perpetual followers. The founding team has a history of innovation, and, so long as the Company continues to learn and invest, their lead is likely to be maintained, if not extended.

How biodiverse and complex will the Farms be five or ten years from now, and how many crops will they produce? The ultimate answer, of course, depends upon developing new growing methods and upon the fundamental economics of production. There will always be the challenge of balancing the level of biological complexity, in the form of more diverse plant and animal crops, with necessary investment in software and hardware. The practical complexity of any given Farm will be determined largely by commercial concerns. And the scope of those commercial concerns will inevitably expand over time.

The Company's collection of intellectual property and practical knowledge will have applications far outside the Farms. In the medium term, the Company's insights into commercializing ecology will be valuable to an agriculture sector struggling with collapsing soil fertility while adapting to a changing climate. Over the longer term, investors interested in expanding human life beyond the surface of Earth will understand the need to take biology along. Any realistic attempt at long-term human habitation on the Moon, or Mars, or in free floating habitats, will require exactly the sort of ecological systems engineering expertise that is being developed by Upward Farms, giving the Company an opportunity to truly live up to its name. This is a grand vision, to be sure, which the reader should ascribe to the author and not necessarily to Upward Farms.

There is an additional vision that I hope is one day realized, but that Upward Farms currently has no plans to pursue. Beyond contributing to the environmental management of closed ecosystems here on Earth and

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wherever humans may voyage, I return to the description of the Farms as electrically-powered, software-defined, potentially carbon-neutral, biological manufacturing systems. These systems could produce more than food.

Central to the Bioeconomy Capital investment hypothesis for indoor agriculture is that, at some point in the future, these systems will contain organisms that are engineered to produce, for example, drugs or materials. These farms may look very different from those currently in operation and on the drawing board, and they may be environmentally circumscribed so as to contain the engineered organisms. Yet the core technology of systems engineering will still require managing complex ecologies. This vision is driven by the economic reality that many biological products made today, such as drugs, or that we would like to manufacture but cannot yet, such as cells and tissues for regenerative medicine, are produced in monocultures. These manufacturing systems are fragile, fail often, and are therefore expensive. By applying ecosystem engineering, we may overcome this economic barrier and realize the goal of a universal, biological, manufacturing platform. Upward Farms is taking the first steps toward making that vision a reality.

About the Author

Dr. Rob Carlson is a co-founder and a Managing Director at Bioeconomy Capital, which invests in early stage technology companies. Carlson is an entrepreneur, author, and scientist broadly interested in the future of biology as a human technology. He is the namesake of “Carlson Curves” (Life 2.0, *The Economist*, 31 Aug, 2006), which describe exponential improvements in cost and productivity in biotechnology, and is the originator of the first estimates of global biotechnology revenues (“Estimating the biotech sector's contribution to the US economy”, Robert Carlson, *Nature Biotechnology*, 34, 247–255, March, 2016; for updates, see the Bioeconomy Dashboard: http://www.bioeconomycapital.com/bioeconomy-dashboard/). Carlson is the author of the book *Biology is Technology: The Promise, Peril, and New Business of Engineering Life*, published in 2010 by Harvard University Press; it received the PROSE award for the Best Engineering and Technology Book of 2010 and was named to the Best Books of 2010 lists by writers at both *The Economist* and *Foreign Policy*. Carlson is an Affiliate Professor in the Allen School of Computer Science & Engineering at the University of Washington. He earned a doctorate in Physics from Princeton University in 1997.