REVIEWED COMMENTARY: FACTORY-GROWN WOOD, THE FUTURE OF FORESTRY?

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Abstract. Recent developments in factory-grown foods suggest that factory-grown wood (FGW) may be on the horizon. In fact, recent work at Massachusetts Institute of Technology introduces tunable plant-based materials, an early indicator of what may evolve into a new source of raw material for forest sector companies, and others. Industry and academia would be wise to monitor developments in this field as they may present significant opportunities and/or adjustments for both. We explore the state-of-the-art in this budding area of science and contemplate implications of successfully growing wood or other lignocellulosic materials in factories. Given a changing climate and focus on carbon emissions, the pressure to drastically reduce CO_2 production will continue climb. Could reduction of their footprint via FGW be an important part of this equation for forest sector companies, going beyond the need to "make every tree count"? In other words, might FGW present an environmental and climate protection breakthrough? Or might it simply trade forest-based environmental impacts for others? What other consequences does FGW promise for companies? And what might it mean for wood science programs, critical suppliers of research and development and skilled employees for the industry? We explore each of these questions and contemplate potential actions and outcomes.

Keywords: Factory-grown wood, disruptive technologies, forest sector, plant-based materials.

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INTRODUCTION

In the development of disruptive technologies, science fiction has been the dreamscape in which modern conveniences were born—whether predicted or manifested into the minds of contemporary innovators. As early as 1911, Hugo Gernsback predicted video calling, allowing Alice 212B423 to call Ralph 124C 41+ for aid from 4000 miles away (Gernsback 1925). In 2017, Hugo and Nebula Award winning N. K. Jemisin brought us Syl Anagist, a technologically advanced civilization in which buildings are "walls of patterned cellulose," and bygone, inorganic brick and concrete structures superannuated, almost feared for their lack of self-healing properties (Jemisin 2017). Paradigm shifts in human thinking on natural resource consumption, backed by recent scientific advancements, encourages exploration of the burgeoning field of biotechnology once relegated to the feedstock of science fiction.

Recent work on cultured plant materials (Beckwith et al 2021) triggered a forestry futurist to speculate about a distant reality in which wood is produced in factories rather than grown in forests (Bengston 2021). Recent developments in the related world of cellular agriculture for food production indicate that this vision may not be so far removed. Factory-grown meat is receiving significant injections of capital (Fassler 2021) as proponents claim a windfall in animal welfare (eg elimination of feedlots/chicken houses) and positive climate impacts (eg less deforestation, lower methane emissions) and a segment of the market is ready to pay for such products (Kantor and Kantor 2021). Despite skepticism by some (Fassler 2021), factory-grown meat operations are allegedly scaling up to grow meat products which could soon be purchased in the local grocery store (eg Future Meat 2022). Cost-effective scale-up of cultured food indicates possibilities for the emergence of other cultured commodities, like wood products. The ongoing push to promote a forest-based bioeconomy is poised to increase the demand for wood-based goods (Ceccherini et al 2020). Meanwhile, companies face demands to reduce their footprint and "make every tree count." Lab- or factory-grown wood (FGW), produced by using cells to grow wood products and materials without growing whole trees, could provide an answer—by reducing reliance on trees as a source of forest products and enabling growth of only what is needed, where it's needed, when it's needed.

The following perspective piece first characterizes the state-of-the art with respect to FGW and lab-grown cellulosics. Based on current development status, the provided discussion speculates on the implications that a FGW industry could ultimately have on the forest sector, examining issues around new products, environmental impacts, and business/marketing practices. Final thoughts consider how such a transition could affect the academy, particularly wood science programs.

LAB-GROWN CELLULOSICS

For the purposes of this discussion, FGW is considered to be a cellulosic material that has been selectively grown in a controlled environment (eg laboratory, factory) using biological processes and exhibiting chemical, microstructural, and mechanical similarities to natural wood. The following text explores the state-of-the art of FGW technologies in addition to adjacent advancements in FGW Alternatives (FGWAs) that can be used as replacements for natural wood in some applications and may possess some but not all of the chemical, microstructural, and mechanical properties of natural wood.

Factory-Grown Wood (FGW)

The promise of FGW is only just emerging and recent work provides a first window into how the nascent technology may develop (Beckwith et al 2021). Making strategic use of plant cell culture, tissue-like plant materials (with properties akin to natural wood) can be selectively grown in defined shapes to produce materials that do not require the cultivation and processing of whole plants. Historically, cultured plant cells have not been widely considered as a means of materials production, although plant cell culture has been in practice for over a century (Hussain et al 2012) and now constitutes a sizable and growing industry (Srivas and Sumant 2021). Commonly, plant cell culture is used as an intermediate process step in bolstering plant populations. This culture technique, referred to as micropropagation, can enhance desirable traits in a population through clonal replication, and expand populations of species that are slow to reproduce, endangered, or otherwise, difficult to propagate (Isikawa 1984). More recently, plant cells have been employed as "green factories" to pump out secondary metabolites with applications in food, cosmetic, and pharmaceutical industries (Ochoa-Villarreal et al 2016). Molecular farming techniques are particularly useful in cases where the natural biological source is endangered or produces the desired compound in low quantities and the molecule is too complex to be generated through chemical synthesis (eg Paclitaxel, an anticancer drug initially unsustainably sourced from the Yew tree [Sanchez-Muñoz et al 2019]). Protalix Biotherapeutics, Dow Agrosciences, Phyton Biotech, and Greenovation Biopharmaceuticals are just a handful of players exploring the plant culture pharmaceutical space. Protalix was the first company to achieve FDA approval for a plant cell-expressed biotherapeutic and has demonstrated systems for large-scale cultivation of plant cells and their by-products (Tekoah et al 2015). Given the potential of plant cell cultures to facilitate the concentrated production of desirable plant products in accessible formats and with improved yields, using culture systems to generate improved materials seems a logical progression of the existing plant culture industry. Work by Beckwith et al presents the first published demonstration of grown-to-order plant materials using techniques that allow for control over chemical, microstructural, and mechanical properties, as well as material form (Beckwith et al 2021, 2022). Because of the limited existing knowledge in materials production by way of plant cell culture, we consider this nascent approach as a jumping off point for the following discussions.

Current progress toward FGW production leverages established techniques for generating, maintaining and scaling plant cell cultures (Mustafa et al 2011), directing cell development (Fukuda and Komamine 1980; Möller et al 2003; Turner et al 2007), and bioprinting (Seidel et al 2017; Vancauwenberghe et al 2017; Emmermacher et al 2020; Park et al 2020). By the reported methods, plant cells grown within a structured, nutrient-rich culture environment are directed to develop specific cellular identities and attributes, enabling grown materials to exhibit xylem-like characteristics (Beckwith et al 2021). By modifying the culture environment of growing cells, cultivated materials exhibit great dexterity in their emergent chemical, microstructural, and mechanical characteristics (Beckwith et al 2022). Not only do these customizable plant materials have the potential to one day mimic natural wood materials in mechanical, structural, and chemical respects, but tunability afforded by the culture methods could open the door to an entirely new family of plant-based materials (eg with specialized microstructures and spatially controlled properties) or optimized materials and wood constituents with improved accessibility to reduce processing requirements (eg lignin-free wood, or easy-to-isolate tree-derived biopolymers such as cellulose or lignin). The available proof-of-concept demonstrations have been completed in nonwoody plant species to date, but the developed methods are translatable across species and the fundamental biological principles (eg controllable differentiation into vascular cell types) have already been independently established for cultures of woody species (Möller et al 2003).

Realistically, producing a lab-grown wood product that mimics all characteristics of natural wood, will require years of foundational research. In pursuit of such a wood substitute, future efforts will need to be made in: the translation of developed techniques to woody species, genetic engineering to enhance the uniformity and synchronicity of cellular developments, and improvements to the understanding of cell-scaffold interactions so that improved growth control and competitive material properties can be achieved. In the nearer term, however, developments in plant cell culture could deliver alternatives to wood in select applications. For example, consider applications where wood structure and form are noncritical and intense processing is required to isolate desired end products (eg cellulose for pulp). Given such opportunities for feedstock improvement and the growing wave of support for cellular agriculture, FGW and its precursors are technologies to watch.

In practice, successful FGW generation could effectively untether forest products from forest resources. Inputs and infrastructure for an FGW operation would, therefore, look quite different to traditional practice. Although specifics will vary with species, culture format, and desired output, certain inputs will be common to all plant culture operations. To facilitate growth, plant cell cultures (not unlike whole plants) must be supplied with water, oxygen, macroelements, microelements, vitamins, and carbon (Mustafa et al 2011). A carbon source may take the form of carbon dioxide or soluble polymers such as sucrose. The selected carbon source will have implications on the achievable formats of culture and density of production, which can be achieved. For cultures making use of photosynthesis, eg ensuring adequate light penetration is essential to sustained growth, but becomes increasingly difficult to ensure at high cell densities as optical density increases (Yoon et al 2015). On the other hand, for sucrose-supplied cultures, higher density growth may be possible, but environmental implications of the sucrose supply will need to be factored into the ultimate impact equation. In addition to these consumable inputs, supporting technology is required to: ensure sterility of the growth environment, maintain environmental conditions conducive to growth, ensure adequate gas exchange, and replenish nutrients while removing unwanted metabolites (Allan et al 2019). The supporting technology, often taking the form of a bioreactor, essentially replaces higher level functions that occur naturally in whole plants. On a case-by-case basis, it will be necessary to assess whether the benefits attained thanks to selectivity and tunability of cultured plant material growth are sufficient to overcome any inefficiencies that result from this increased role of technology in production.

A critical element of FGW success and market penetration will be process scalability. How to effectively scale modern culture technologies to displace a meaningful portion of the natural wood market (or any high-volume market, eg meat [Humbird 2021]) remains an open question. Existing demonstrations of plant culture at large scales (Tekoah et al 2015; Ochoa-Villarreal et al 2016; Eibl et al 2018), while promising, are still miniscule relative to the volume of many global wood product streams. Thus, advancements in scalable culture technology will be integral to the widespread permeation of FGW and related products. Specific challenges of scaling cultures today include maintaining an aseptic growth environment and homogeneous growth conditions throughout, as system (eg bioreactor) size increases (Humbird 2021). Accomplishing these criteria while minimizing required energy and media waste will be necessary to achieve an environmental and economic edge. Beneficially, the numerous culture formats allowable in culture of plant cells (eg suspension, callus, dispersed gel cultures, and beyond) create opportunities for solutions beyond the standard liquid bioreactor.

Factory-Grown Wood Alternatives (FGWAs)

Wood by-products and wood-derivatives could represent an intermediate checkpoint en route to a plant culture-based FGW. These types of FGWAs, which could serve to replace natural wood in a limited range of applications, may even find origins outside of the plant kingdom. In some circumstances, FGWAs may provide opportunities to improve on wood as a feedstock for certain applications. Bacterial cellulose technologies provide one such example.

Today, the cellulose pulp used to produce paper, textiles, food and drug additives, and specialty cellulose products (eg filters, acetates, and esters) is predominantly obtained from natural wood (Li et al 2018) in a multistage pulping process. Complex, energy-intensive pulping is necessitated by the structure and chemistry of natural wood. However, by modifying the structure and chemistry of the cellulosic feedstock (eg by reducing lignin content), the need for intensive processing could be substantially reduced. Consider one such example: bacterial cellulose. Bacterial cellulose is a high-purity, extracellular product of certain bacterial cell cultures that is naturally lignin-free.

Like plant cell cultures, bacterial cultures are sustained on a nutrient-rich broth. In these conditions, some types of bacteria (eg Gluconacetobacter xylinus) can directly produce extracellular nano-sized cellulose fibers (known as bacterial cellulose) at purities, which reduce needed downstream processing (Betlej et al 2020). Bacterial cellulose is chemically similar to plant cellulose (Blanco Parte et al 2020) but differs in crystallinity and molecular weight (Betlej et al 2020). Nonetheless, bacterial cellulose can serve as a replacement for wood-sourced cellulose in some applications. Bacterial cellulose has already been demonstrated as a partial substitute for wood-derived pulp in paper production and even improved paper strength (Skočaj 2019; Betlej et al 2020; Kalyoncu and Peşman 2020). Culture-derived cellulose has also been used in the production of textiles (Gao et al 2011; Babaeipour et al 2021) and combining bacterial cellulose with other structural agents can even yield materials with the approximate look and strength of natural wood (Symmetry Wood n.d.). The value of FGWAs is 2-fold, they serve to provide a new supply of a traditionally tree-sourced product, but also encourage the development of culture technologies with improved scalability and resource efficiency. With respect to plant cell cultures specifically, a promising entry point for FGWAs is high-value by-products or metabolites (eg Paclitaxel from the Yew tree; Tekoah et al 2015). As successes in these early applications drive improvements in bioreactor design and fundamental biological knowledge, lower-price point materials, such as high-purity pulp, may also become an accessible target.

Products constituting FGWAs, including the given example of bacterial cellulose and beyond, again provide opportunities to separate forest resources from forest products. If done successfully, this transition could represent an impactful shift. In a factory setting, the tight control allowed over production density and product growth could enable huge increases in production volume per unit land area. Industrial production could also mean reduced environmental sensitivity—with production free from variation in climatic conditions, natural disasters, pests, and disease affecting natural plant populations. In addition, because of their environmental apathy, FG products could be produced anywhere in a democratized fashion. As a result, cultivation could be made more efficient and more robust by colocation of facilities and consumers.

These opportunities for improvement over standard practice are presented with cautious optimism. As in the case with FGWs, an overhauling of supply chains and process flows make estimating comparative impacts of the old and new difficult until the science behind FGW and FGWAs progresses further. In all cases, careful analysis is required to understand under what conditions and for which applications the culture systems can provide sufficient benefit over traditional practice.

In summary, research progress toward FGW is underway. Although achieving parity with natural wood will require continued scientific development, production of wood by-products and derivatives presents a near-term steppingstone, which could support ongoing progress toward a true wood replacement. A new production process will make use of a supply chain distinct from traditional forestry activities and rely on different supporting technologies. The specifics of process inputs and technologies will vary with product output and the impacts of these specifics will need to be uniquely evaluated. A key challenge is ensuring an FGWA can improve upon environmental and or social aspects of current practice while presenting a scalable solution delivering at approximately competitive costs.

WHAT'S THE FUTURE?

Growing wood commercially in a lab is likely decades into the future and there is little empirical work on this promising technology. The sections that follow are best described as "educated speculation," by design and necessity. We use words such as "might" and "could" to communicate that future developments are highly uncertain, yet critical for wood scientist to contemplate. Recent developments in lab-grown plant materials are a signal for anyone interested in forests, forestry, and wood products to consider implications of this development, including: 1) what products might result; 2) how might existing industry be impacted; and 3) what might it mean for the academy?

What Products?

In general, FGW has the potential to eliminate many of the inefficiencies in production and preparation of tree products. The current model of utilizing cone-shaped, long-lived plants as raw materials is inherently inefficient. Recovery rates have increased drastically over past decades, but geometry dictates a certain percentage of material that will not meet final product (eg lumber or veneer) requirements. And while modern primary processing facilities convert 99% or more of a delivered log to sellable products, as much as 50% of the end products are lower value by-products such as chips, shavings, bark mulch, or energy (Simmons et al 2021). And, there is considerable biomass left on the forest floor that never makes it to a mill.

There are clear trade-offs in considering potential products that may result from FGW. One might argue that the best opportunities will be situations for truly engineered, high-value products, with high unit costs, significant processing requirements (and significant losses in yield each time it is processed), inadequate performance, limited supply, or significant environmental impact. Components for musical instruments (eg material for fretboards for guitars) would seem to meet all of these categories. On the other hand, pioneering a new technology like FGW by targeting wood for musical instruments might be analogous to striving to be an Olympic sprinter before learning to crawl. Therefore, we propose three examples for FGW that span the range of complexity (that being a relative term here), volume, and value.

Cellulose fibers. Near-term opportunities for FGWA may include specialty products such as those produced from cellulose nanomaterials (CNMs). CNMs are candidates for solving global environmental issues (Mokhena and John 2020) and the market is estimated to consume 35 million metric tons annually when key features of the technology are realized (Shatkin et al 2014). Currently, CNMs are mechanically separated from plant and animal tissues using mechanical filtration followed by chemical or biological treatments, which results in unaligned fibers. The most significant component to CNM macroscale functionality is controlling fiber alignment (Li et al 2021). Another limiting feature in making nanocellulose materials sustainable is developing isolation strategies for high-grade cellulose of specific morphology. FGWA could provide access to high volumes of high-purity cellulose material, in specific alignments, thereby allowing for applications in environmental remediation, energy storage/conversion, packaging, biomedical, sensors, textiles and filters, etc. (Mokhena and John 2020; Wang et al 2020).

Cellulose fibers from wood have been used for well over a century to produce textile fibers as well as paper. For example, in the viscose process, pulp is dissolved into a liquid and then regenerated to form the fabric rayon. The first patent on this process dates to 1893 (Wilkes 2000) and alternative processes have been developed over the years to lessen the environmental impacts of the viscose process. For example, Spinnova, a Finnish firm, promotes its product as ". . . the most sustainable natural fibre in the world" (Spinnova 2021). In simple terms, the process involves mechanically refining pulp to break it down, chemical purification, and then solubilization of cellulose, followed by spinning into longer fibers (Pineda 2020). In this situation, FGWAs might easily substitute for wood-based cellulose.

The development of specialized FGWA for "smart materials" (eg self-healing) is currently a niche market with noteworthy growth potential. Caro-Astorga et al (2021) have already developed a patternable engineered living material based on bacterial cellulose that is self-repairing through regeneration of cellulose in response to damage. In the biomedical field, CNMs are incorporated with hydrogels to improve mechanical properties. Shao et al (2017) demonstrated the healing efficiency of wood-pulp derived cellulose nanocrystal hydrogels networks during cyclic tensile and compressive loading–unloading tests and cleavage. Cellulose nanosheets have been used in the development of compliant, self-adhesive, and flexible skin strain sensors (Lu et al 2020).

And working up the scale to consider larger aggregations of fibers, the wood composites sector converts high-volumes of relatively low-quality materials (eg chips, flakes, and sawdust) into useful products through proper design/engineering and just the right adhesives. Tradition and the genuine utility of many composite products may mean their continuation regardless of raw material. Might it be possible for FGW to be grown as networks of fibers and preformed into direct substitutes for the common end products of particleboard, MDF, and hardboard, ie panels, countertops, cladding, molding, cabinet components, etc.?

Custom architectural components. Natural wood is anisotropic, ie its properties differ depending on the orientation of the anatomical elements (tracheid, fibers, vessels, etc.). Anisotropy in large part dictates the shape of lumber, and this in turn has dictated the form/structure of historic buildings—think lots of rectangles. These days, digital and parametric design, 3D printing, and CNC processing are slowly changing these constraints, allowing creations like the Metropol Parasol in Spain. Consider the possibilities that FGW might enable for architectural components engineered and grown to specific shapes and with precise and consistent structural properties. Long, straight pieces no longer need be a necessity. Nor would designers need to be limited by the variation inherent to different wood species as well as lumber or panel grades.

Tone woods. And now finally, working up the value chain, we may consider tone woods: high-value timber, often from endangered or protected species, frequently poached and unsustainably harvested for their color and acoustic properties (Sheppard 2012; Department of Justice, US Attorney's Office 2015; Gibson and Warren 2016). Therefore, components for musical instruments might seem a good place to start. This end use appears to "tick all the boxes" related to value, limited supply of the current resource, inefficient conversion practices, environmental challenges, etc. However, given the complexity, and well-ingrained traditions of using specific species, even from specific regions, for instruments (Brown 1978; Rymer 2004; Wegst et al 2007), this market is likely in the distant future.

The science that emerges as fiber-based and architectural products are developed could enable growing materials with specific physical, mechanical, and even acoustical properties for musical instruments. Using adulterated wood is not an uncommon practice—Stradivari himself did not rely solely on the properties of maple and ebony, but incorporated borax, zinc, copper, and alum (Su et al 2021). Su et al (2021) have already posited that engineered wood can reintroduce the cellulose rearrangement and hemicellulose fragmentation created by famed Cremonese violin makers of the 1700s. Modern analytical techniques have allowed scientists to identify the properties of prized musical instruments—can these properties be replicated via FGW?

Impacts on Forest Sector Companies

A growing field of research emphasizes "corporate foresight," the ability of firms to perceive possible futures and better prepare their strategies and operations for those eventualities (eg Rohrbeck and Kum 2018). Corporate foresight informed perceptions of the future can complement innovation management, helping to identify the "right" innovation pathways to pursue. Improved innovation management and corporate foresight may be essential ingredients for successful transition of forest sector companies to the circular bioeconomy (Hansen et al 2021), and navigate changes tied to development of FGW. While the largest global forest sector companies may be nurturing corporate foresight capabilities, there is little evidence suggesting that it is common practice (Näyhä 2020). In fact, forest sector companies are often criticized for lacking the innovativeness and forward-thinking necessary to effectively navigate evolving market needs (Hansen 2010; Näyhä 2020). Moving from natural wood to FGW would be more than evolutionary, impacting many aspects of company operations, from strategic decisions to tactical communication. Supply issues would shift significantly with a different set of risks and constraints and there would likely be special considerations for those parts of the industry that currently rely on by-products from primary producers.

Impacts will differ based on whether a company chooses to passively accept a new type of supply or, instead, proactively engages with development of the technology. In the context of bioeconomy transition, considerable emphasis has been given to the need for forest sector companies to collaborate with nonsector firms to develop next-generation products such as wood-based chemicals and textiles (Guerrero and Hansen 2021). In this case, the most innovative firms might collaborate with bioscience companies to develop FGW technology and become suppliers not only of natural wood, but the intellectual property of producing FGW. This brings us to the idea of FGW as a disruptive technology, displacing established products, as plastics did glass among other things, or as a sustaining technology that improves existing product performance.

One must consider the idea of "forest sector company" in the light of this disruptive technology. In its infancy, producing morphologically or chemically specific cellulose and lignin, FGW could generate a novel industry—especially if traditional forest sector companies do not track and participate with interdisciplinary research in bioscience and materials engineering as discussed previously. Could there be an era in which "forest" materials are no longer linked to natural forests?

Environmental performance. In comparison with natural wood, factory-grown materials promise a number of advantages. Forest-free, environmentally protected growth of materials could allow for more robust supply chains and resilience against climate change, pests, diseases, and natural disasters. FGW could enable the localization of production to potentially reduce transport-related emissions. Furthermore, direct growth of plant materials enables control over both material properties and form. As a result, materials could be optimized to reduce processing and increase yields of high-value products in downstream activities. But, despite the potential of FGW to address limitations in existing forest-product industries, these advantages must be weighed against new impacts introduced by a more demanding production process and an accompanying raw material supply. Optimized FGW may reduce energy required in harvest, hauling, and downstream processing, but the growth of the material itself will naturally demand electrical energy, infrastructure, and raw material inputs that forests do not. Thus, to fully understand and address environmental impacts, responsible FGW production will need to consider everything from host grid cleanliness and carbon sourcing to lab-consumable usage and waste management. On the other hand, if FGW is proven to be environmentally advantageous in some applications, the broader implications of devaluing forest resources must also be considered as an unintended consequence. If standing timber is of lesser value, forestlands may experience increased conversion to other uses (Hannah et al 2011). Comprehensive assessments are, therefore, needed to evaluate the magnitude and value of these and other tradeoffs and to determine under which conditions and for which applications FGW can provide net environmental benefits.

Although an understanding of the ultimate environmental impact equation is in the future, early indications are that FGW may be a meaningful opportunity for forest sector firms. Forest sector companies have seen pressure for environmental performance improvements from society and environmental nongovernmental organizations for decades. The issues have been many and global, and have ranged from dioxin in pulping operations to harvesting old growth. Simply put, most members of the general public have a negative gut reaction to trees being cut and often for good reason: illegal logging is the third largest international crime and largest natural resource crime (May 2017) and accounts for an estimated 30% of all logging activities (Nellemann 2012). Based on the pressure from the public and various interest groups, the forest sector has made real changes in both philosophy and operations. Reduced emissions, certified forests, and corporate sustainability reports are examples. The current state of the global environment does not suggest a reprieve for forest sector companies. Instead, all indicators are that redoubled efforts will be necessary to maintain a social license to operate.

Current momentum around a forest-based bioeconomy may dramatically increase demand for wood fiber. Early signs of this are occurring in Europe where there has been a spike in total forest harvest as well as unit harvest sizes (Ceccherini et al 2020). This development leads to concerns over adverse effects on biodiversity, soil erosion, and water regulation. Of course, this is all framed within the context of such global societal challenges as climate change, increasing population, and the declaration by the United Nations of 2020-2030 as a decade of restoration, suggesting the focus on companies and their forest footprint (acres managed) are only likely to increase.

Because of the threat of global warming and climate change, the carbon impacts of forest sector operations are especially relevant. Quantification of these impacts and their true role in nature-based solutions are not without controversy (eg Hudiburg et al 2019; Seddon et al 2021), but, ultimately, the sector will be seeking to further improve its carbon story. Decarbonization, the movement toward net-zero carbon emissions, through growth of renewable fiber and design and use of long-lived products is an inherent advantage for the sector. The decarbonization potential of wood products is increasingly tied to waste reduction, repairability, repurposability, refurbishability, reuse, and recycling. Significant design and technology developments are needed to facilitate the “re’s” abovementioned and FGW may play a meaningful role through improved design-for-purpose.

Fiber geolocation shifts. For most of history, production of natural wood products has had a strong connection to the physical location of forests. Although wood has been traded internationally for centuries, it is only in the recent decades of globalization that a major shift in production has happened, such as China becoming a global center for furniture production despite its relative lack of forests. The sector has long been effective at adapting to new supply realities, to the point that new product development has largely been tied to supply characteristics rather than customer demands (Bull and Ferguson 2006). In the mid-1990s in Oregon, ponderosa pine was in short supply due to severe harvest reductions on Federal land. Secondary manufacturers throughout the state were experimenting with radiata pine from New Zealand, and none were happy with the new raw material. However, fast forward several years and those same operations had adapted effectively to the peculiarities of radiata pine. Similarly, Western US softwood sawmills have quickly adapted to shrinking log diameters by retooling operations.

Relying on natural wood for supply comes with a specific set of risks. Forests, be they natural, planted, or industrial, plantations are susceptible to disease, insects, wildfire, hurricanes, and, overall, climate change. For example, the British Columbia beetle epidemic drastically reduced harvests in that region and ultimately contributed to Canadian companies investing in the US South. West Coast US companies have also made investment shifts to the US South, partially to maintain supply continuity. Factory operations change the nature of logistics and transportation, likely simplifying chain of custody. Systemic challenges in identifying and monitoring suppliers in complex value-webs, are leading companies, across sectors, toward vertical integration (Murcia et al 2021). However, vertical integration may seldom be an economically viable approach in a globalized economy and it maintains many negative social externalities (Panwar 2020).

Instead of a connection to forests, FGW is more likely connected to the dynamics of industrial clusters where competitive advantage derives from the colocation of competing firms that drives increasing productivity, innovation, and stimulates formation of new businesses (Porter 1998). The concentration of similarly oriented firms attracts suppliers, service providers, specialized workers, etc. Just as Silicon Valley fosters high-tech start-ups and operations, FGW might be especially well-suited to a particular location, where water is cheap and accessible and the electricity grid is particularly clean. Alternatively, clustering could hold for research and development aspects of FGW, but actual production could easily be well-suited to small-scale, distributed production for local markets. One can envision franchise factories (growing operations) operated by entrepreneurs, potentially colocated with customers, essentially eliminating channels of distribution.

Competitive advantage. Sustained competitive advantage is achieved when a company possesses resources that are rare, valuable, nonsubstitutable, and inimitable (Barney 1991). This advantage is held over rivals in the marketplace and can be based on tangible and/or intangible resources. The traditional approach to competition in the sector, commodity production with a concentration on price (Näyhä 2020), is becoming, and will become even rarer in the future. Developing a sustained competitive advantage associated with FGW likely fits into two broad scenarios; 1) a company holds exclusive rights to a source of FGW: or 2) a company possesses the intellectual property associated with producing FGW. Either scenario requires collaboration outside of the sector or actively investing in small startups with promising technology (where FGW will likely find its genesis). Intellectual property and accumulated knowledge from these collaborations can be rare, valuable, nonsubstitutable, and inimitable resources. Ultimately, it is a question of whether forest sector company leaders can envision and implement collaboration with, eg bioscience companies to develop future feedstock. The alternative is to sit back, wait, and buy FGW as it becomes available on the open market. This would unlikely provide meaningful contribution to sustained competitive advantage.

Marketing strategy. Fundamentally, marketing strategy consists of choices about the type of product offered, the customer targeted, the location of that customer, and competencies or capabilities that allow the company to effectively compete. Generally, forest sector firms are moving from a focus on commodity products to special and custom-made products (Hansen and Juslin 2018). FGW could contribute to this evolution, where the raw material or a final product can be grown to stringent customer specifications. FGW could open a new set of positive environmental claims that could be used to target customers/regions with a high environmental ethic. Concerns over origin and supply chain infiltration of illegal products could cease to be relevant. The level of supply chain control possible through FGW would facilitate business models mirroring the farm-to-market and Know Your Fisherman approaches. Customization and effective targeting open a host of new branding opportunities. Of course, some of these opportunities could come at the expense of natural-grown wood and could cause confusion in the marketplace regarding what is "good" wood and whether "bad" wood is still better than nonrenewable materials. Overall, FGW could facilitate increased sophistication of marketing strategies and tactics undertaken by the sector.

Implications for the Academy

Decarbonization of the global economy creates many opportunities for wood and wood-like materials as industries look to substitute fossil-based raw materials with renewables. What does this mean for wood scientists? We believe that the field will become ever more interdisciplinary, attracting biologist, chemists, engineers, and others, exploring developments such as FGW in applications across many sectors of the economy. Accordingly, wood scientists must embrace these opportunities through, eg leadership of transdisciplinary teams to drive innovation and commercialization of wood-based products. Societal interest in mass timber buildings has injected significant resources into many wood science programs. FGW presents a similar opportunity for growth and renewal.

As the science changes, curricula must follow. Although much of currently taught foundational wood science knowledge would remain, a new knowledge base around the nature and possibilities of alternative supply would be necessary. Dendrology and forest management courses typical of today's curricula might become plant physiology, cellular biology, and biological systems engineering tomorrow. These developments could ultimately benefit wood-based undergraduate programs through enhanced student interest and enrollment. Today, there is a shortage of highly-skilled employees for traditional forest sector firms. The diversification of industries utilizing wood-based products will enhance demand for specialized employees and wood science graduates will find themselves employed by companies throughout the economy. Often referred to as a "discovery" major, wood-based degree programs must capitalize on the buzz associated with futuristic technologies and the promise of high-tech jobs. A whole new student demographic, one that is highly STEM-focused and destined for laboratory and research and development work should be a target for wood science programs.

SUMMARY

It is reasonable to expect that FGW is on the distant horizon. New techniques for producing traditionally tree-sourced materials such as wood and biopolymers (ie cellulose, lignin) promise optimized plant products with grown-to-order properties and structures. The forest-free production of these materials can facilitate democratization of production and build in resilience to climate change, pests, and natural disasters. Tunability and selective production of desired plant tissues could reduce upstream and downstream processing with plant tissues optimally designed to meet application needs. On the other hand, real-world implications of these new technologies have yet to be fully understood or characterized. The timeline and manifestation of the technology can only be speculated at this time, but implications are highly relevant to forest sector companies and wood science programs; active consideration of emerging innovations in forest technology enable both industry and academia to adapt and remain relevant. This thought-experiment is motivated by nascent scientific advances, the aspirations of industry, and demands of modern society. Just as today's modern conveniences were yesterday's Sci-Fi, today's Sci-Fi will be tomorrow's conveniences. FGW, self-healing architecture, climate change resilient enterprises, and net zero emissions connect the precipice of innovation-led futurology to the pinnacle of science fiction.

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