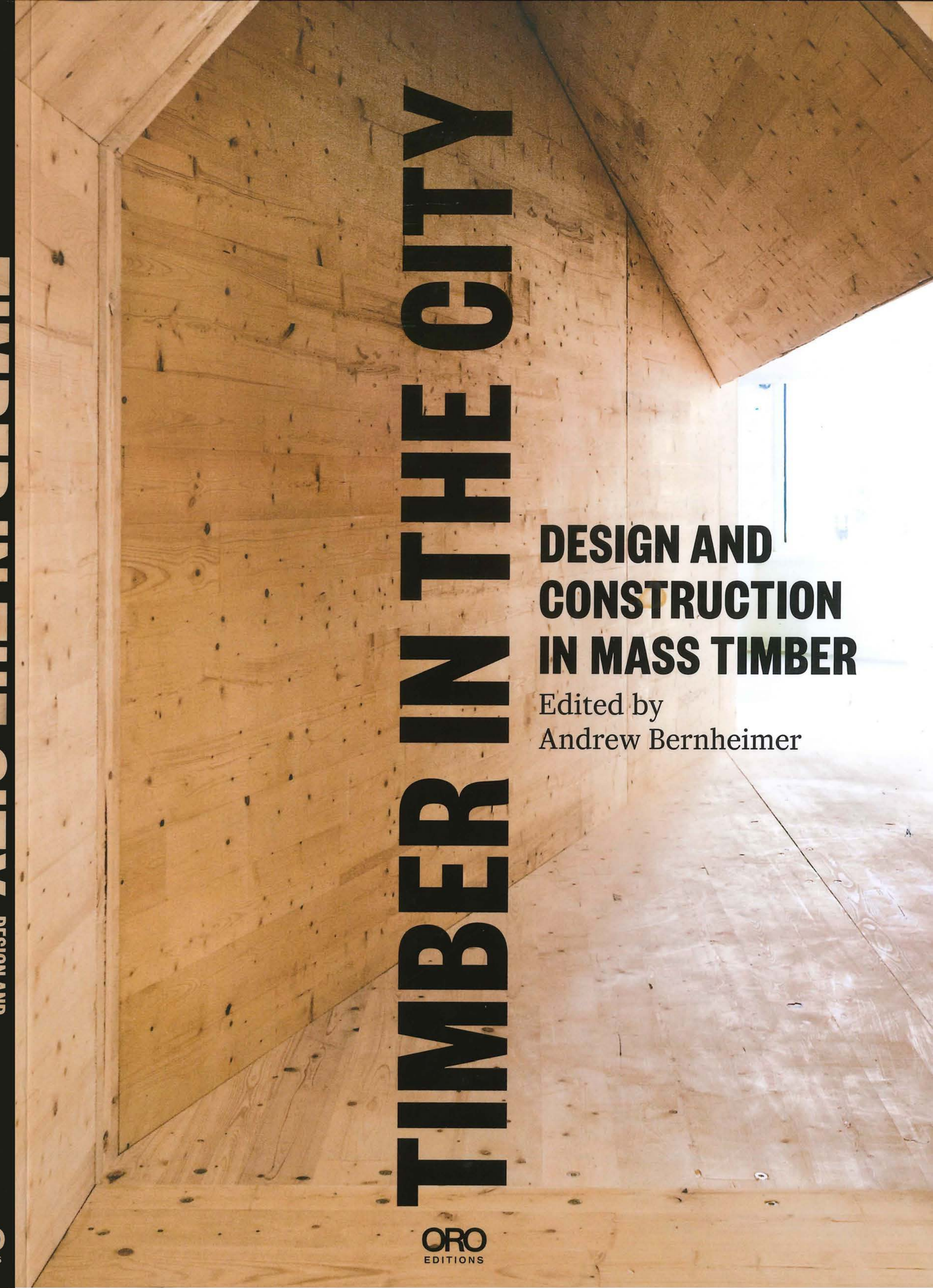
USD$35.00
ISBN 978-1-941806-80-7

TIMBER IN THE CITY
DESIGN AND CONSTRUCTION IN MASS TIMBER
ORO EDITIONS



TIMBER IN THE CITY

DESIGN AND CONSTRUCTION IN MASS TIMBER

Edited by
Andrew Bernheimer

ORO EDITIONS

TIMBER IN THE CITY

DESIGN AND CONSTRUCTION IN MASS TIMBER

Edited by
Andrew Bernheimer
Essays by
Alan Organschi and Andrew Waugh

ORO EDITIONS

ESSAY

Timber City: Architectural Speculations in a Black Market

Alan Organschi

Economics is the science which studies human behaviour as a relationship between ends and scarce means which have alternative uses.
—**Lionel Robbins**, *An Essay on the Nature and Significance of Economic Science*

Without resources there can be no economic activity. I call this the physical conception of economics: all economic activity consists in essence of converting materials in their raw state into finished products using converted energy; this includes the energy for communication, consumption, transport and distribution. In essence the economic process is first and foremost a process of converting resources. But it matters very much—not solely for ecological reasons—what resources we use and how we use them.
—**Hermann Scheer**, "Solar City: Reconnecting *Energy Generation and Use to the Technical and Social Logic of Solar Energy"*

If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm . . . The largest uncertainty in the target arises from possible changes of non-CO_2 forcings. An initial 350 ppm CO_2 target may be achievable by phasing out coal use except where CO_2 is captured and adopting agricultural and forestry practices that sequester carbon. If the present overshoot of this target CO_2 is not brief, there is a possibility of seeding irreversible catastrophic effects.
—**James Hansen et al.**, "Target Atmospheric CO_2: *Where Should Humanity Aim?"*

We're trying to figure out how to make carbon an asset.
—**Klaus Töpfer**, Cities and Climate Change Network *Conference, Potsdam, 2012*

Consider this building material: a complex carbohydrate, synthesized biologically using solar energy and carbon dioxide, with an exceptionally high strength-to-weight ratio. The fibrous substance is formed by the annual introduction of tiny capsules containing a complex but naturally occurring arrangement of nucleic acids to the earth's soils and the regular recharging of that surface with rainwater and sunlight. A single capsule, costing nothing to produce or to distribute, is usually a little less than a centimeter in length and, depending on atmospheric, hydrologic, and soil conditions, can generate more than a metric ton of structural material in a little over 50 years. The supply is potentially infinite, and where extraction is well-managed, the landscapes that are its source will naturally and rapidly regenerate, providing critical environmental services such as well-oxygenated air, filtered potable water, and an array of marketable consumer products, all while protecting diverse biological habitats and sequestering significant amounts of atmospheric carbon. The energies required for its processing are low compared to other common structural materials. Residues left over from the material extraction process can be left as a kind of nutritive feedstock for future production, contributing either to increasingly compressed layers of carbon-rich soil or to a sustainable exchange of aerobic decay and carbon uptake. Similarly, processing waste serves as fuel for the manufacture of building products.

The material is readily available globally, and the landscapes from which it is extracted happen to fall in relative proximity to many major cities, reducing transport energies and emissions. Various forms of its fiber can be used in an array of commercial building products: structural members with a range of capacities and applications, highly insulated and thermally broken wall and roof assemblies, and durable interior surfaces able to regulate swings in interior moisture levels. The material is lightweight and easily worked, making its initial construction, its repair, and its dismantling and re- or upcycling less technologically intensive. The material is applicable to all but a few of the building types and civil infrastructural components common to dense urban aggregations. When applied and detailed properly within a building enclosure, the material is extremely durable, and—most critically at this particular global moment—the carbon absorbed during its synthesis remains embedded in its molecular structure as long as the building is maintained or until its assemblies break down and the material decays or, more catastrophically, burns.

If it weren't so patently obvious that I've just described wood, forests, and photosynthesis, this passage might read like an elevator pitch for a geo-engineering start-up or a book jacket for an eco-utopian novel. Instead I hope to frame a simple argument for a potential (and rapidly realizable) ecological and economic synergy between two landscapes, the forest and the city, as they function symbiotically to absorb and store atmospheric carbon. What I propose is the transformation of our cities from CO_2 source to carbon sink through the development of new urban structural typologies in wood: a timber city.

Our current culture of land use and resource allocation, and the regulatory systems that reinforce it, tends to direct timber away from our cities. Historic concerns about the overuse of wood and the resulting destruction of forests, misgivings and misapprehensions about the properties and vulnerabilities of structural timber, and deeply embedded cultural associations with wood as a provisional service material with a relatively low structural capacity have combined to relegate contemporary use of timber to the commercially profitable but relatively modest structural demands of light-framed, low-rise, low-density applications in the residential building sector. On a continent as timber rich as North America, it is both a conceptual irony and a significant environmental risk that this renewable material, with demonstrably low extraction, processing, and production impacts

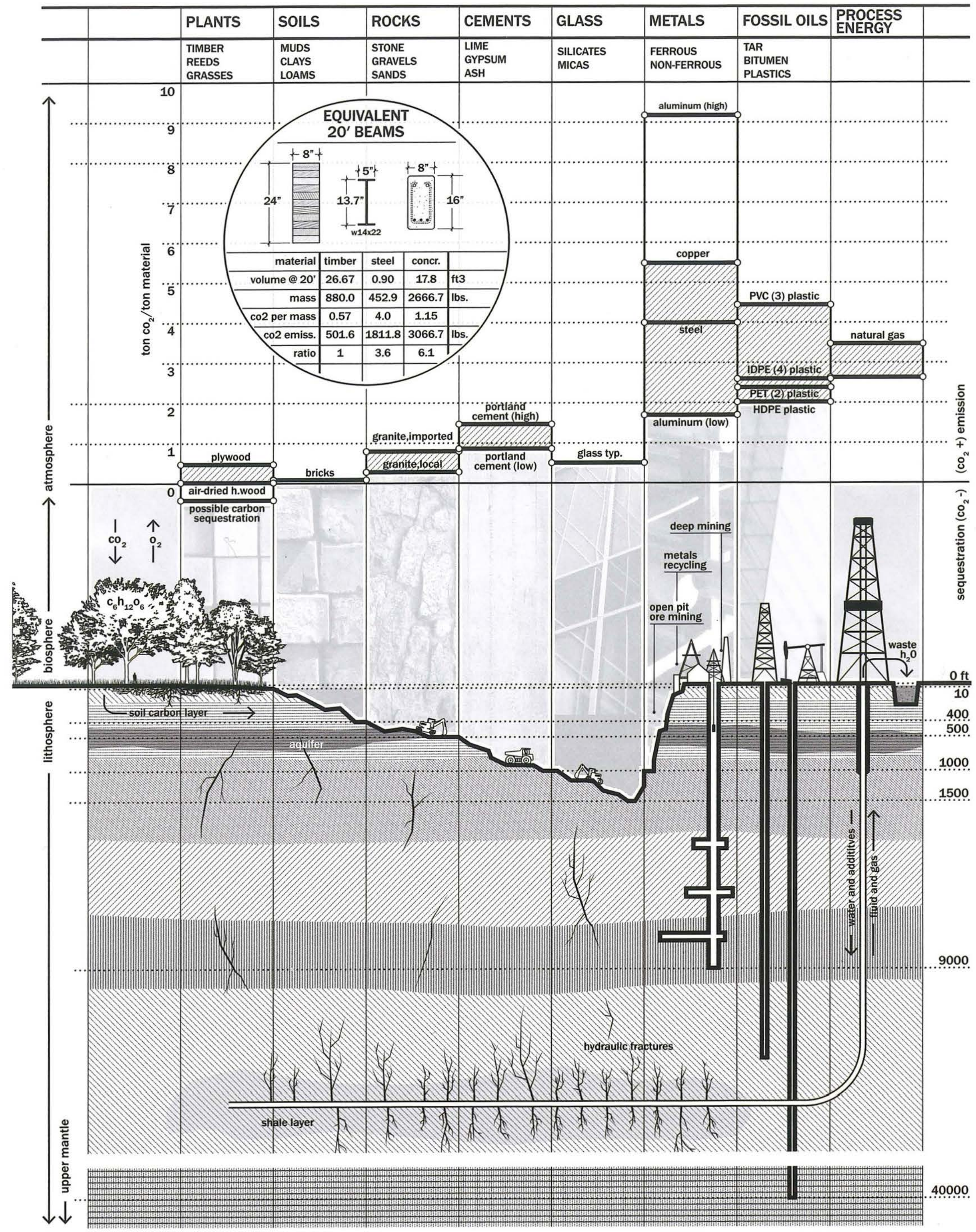
and energy demands, has given rise to the land- and energy-intensive sprawl of suburbia, one of the United States' most durable and pervasive global exports. Meanwhile, the materially demanding building morphologies of our cities, with their relatively efficient use of surface area, space, and infrastructure, are generated from a class of structural materials with a large carbon footprint.

That the very way we go about constructing our built environment, currently a significant source of overall anthropogenic greenhouse gas emissions, might instead be recognized as a means to *offset* them, is a compelling concept, one supported by recent research on building life cycle impacts and forest-carbon management, bolstered by rapid breakthroughs in mass timber engineering and production technology, and made all the more pressing by mounting evidence of rapidly accelerating global climate change. At this particular moment, however, when fossil fuels with high energy densities—coal, oil, and most recently, natural gas—remain abundant and cheap, building-material industries that rely on them will continue to produce high-strength, high-impact products like steel and concrete at relatively low financial cost. Under these circumstances, an economic value proposition about the affordability of mass timber construction is difficult to make. Professional architecture and engineering practice, the commercial building industry, and real estate development culture continue to operate within a strict system of financial analysis, bounded by a relatively short time frame for monetary investment and return. When carbon emissions and their impacts become monetized, however, through various regulatory regimes or economic devices like a carbon tax or cap-and-trade schemes, the boundaries of that cost analysis expand. In an economic system in which emissions reductions are endowed with financial value, the conceptual and material shift of cities from anthropogenic source of greenhouse gas to human-made carbon storage system becomes an appealing proposition. What small city, struggling with budget deficits, wouldn't gladly reap the financial benefits of a sale of carbon credits to an industrial polluter seeking emissions offsets?

This speculation has both temporal and spatial dimensions. The time frame of accelerating climate change, expressed as a projected increase in the atmospheric concentration of carbon dioxide and its greenhouse gas equivalents, has already surpassed thresholds anticipated only a few years ago as being decades away. Analytic predictions that incorporate existing climate forcings, that is, impacts of past human activity with warming potential already in the pipeline, give humankind only a few decades to make dramatic reductions in anthropogenic emissions or seek significant means of offsetting the current emissions rate before reaching a tipping point.[1] Little time separates us, in a scenario of continuing increases in atmospheric CO_2, from "irreversible catastrophic" effects.[2] This means that any effort to reduce our impacts in the building sector, a significant contributor of greenhouse gas, must yield near-immediate results.

The classes of structural material that catalyzed urban construction during the late nineteenth- and twentieth-century expansion of the industrial city and that today continue to be applied as commercial and professional reflex are primarily mineral-based and energy-demanding. The high-reaching, long-spanning, heavy-load-bearing urban artifacts constructed from iron, steel, and concrete (and sheathed in increasingly uninterrupted expanses of aluminum, glass, and plastic composites) were smelted, sintered, and synthesized from raw materials extracted from subsurface geological strata through extensive land-degrading mining. Their processing and production energy demands were satisfied with hydrocarbons drawn from an ever-deeper cross section of the earth's crust with increasingly intensified extraction technologies (fig. 1). Industrial fuel, first gathered from dense plant matter from the biosphere (forests) and then excavated from seams of geologically compacted hydrocarbons in the upper lithosphere (coal), is today drawn from deep reserves through energy- and technology-intensive (and dangerously invasive) extraction (fossil oil and gas). In the more efficient margins of this heavy industry sector, there have been significant improvements in resource productivity through changes in feedstocks and material recycling. Technology upgrades have resulted in energy efficiencies and associated reductions in greenhouse gas emissions.[3] But for the bulk of global cement and steel manufacturers, especially in rapidly developing and urbanizing countries where demands for structural materials capable of higher-density and higher-rise building applications are climbing, the transformation of manufacturing technologies may be too slow in coming. The oxygen furnace and the sintering of Portland cement may linger as means and processes with dangerous impacts.[4]

An immediate spike in building industry emissions may be the unintentional result of the current efforts to reduce our impacts.[5] Our relatively recent efforts to recalibrate and refine building envelopes and mechanical systems in search of any and all potential operational efficiencies have been critical exercises that will yield, over time, some long-term savings in fossil energy consumption and CO_2 emissions. But anyone who has studied the building life cycle recognizes that the front-loading of emissions embodied in the production of technologically intensive, high-performance building materials and assemblies will take decades—and in the most energy-efficient buildings as much as building lifetime—to offset.[6] And as global temperatures rise, cooling loads will rise too; increased demands on enclosure assemblies and mechanical systems in summer months may effectively erase the benefits of performance upgrades[7] and leave their initial ecological costs (measured in embodied emissions) unrecovered. In any currency—dollars, euros, renminbi, or carbon emissions—return rates on investments are expected to keep ahead of inflation. And in our current condition, characterized by an inflationary trend in CO_2 emissions that we are hoping desperately to arrest, the econometric significance of environmental *first* costs and impacts of embodied emissions is far greater than their minority share of overall building life cycle emissions might suggest. A compounding factor in this time-sensitive economic equation is that many of the materials essential to the technical systems that have made our recent buildings perform so well have entailed, in their extraction and manufacture, the intensive

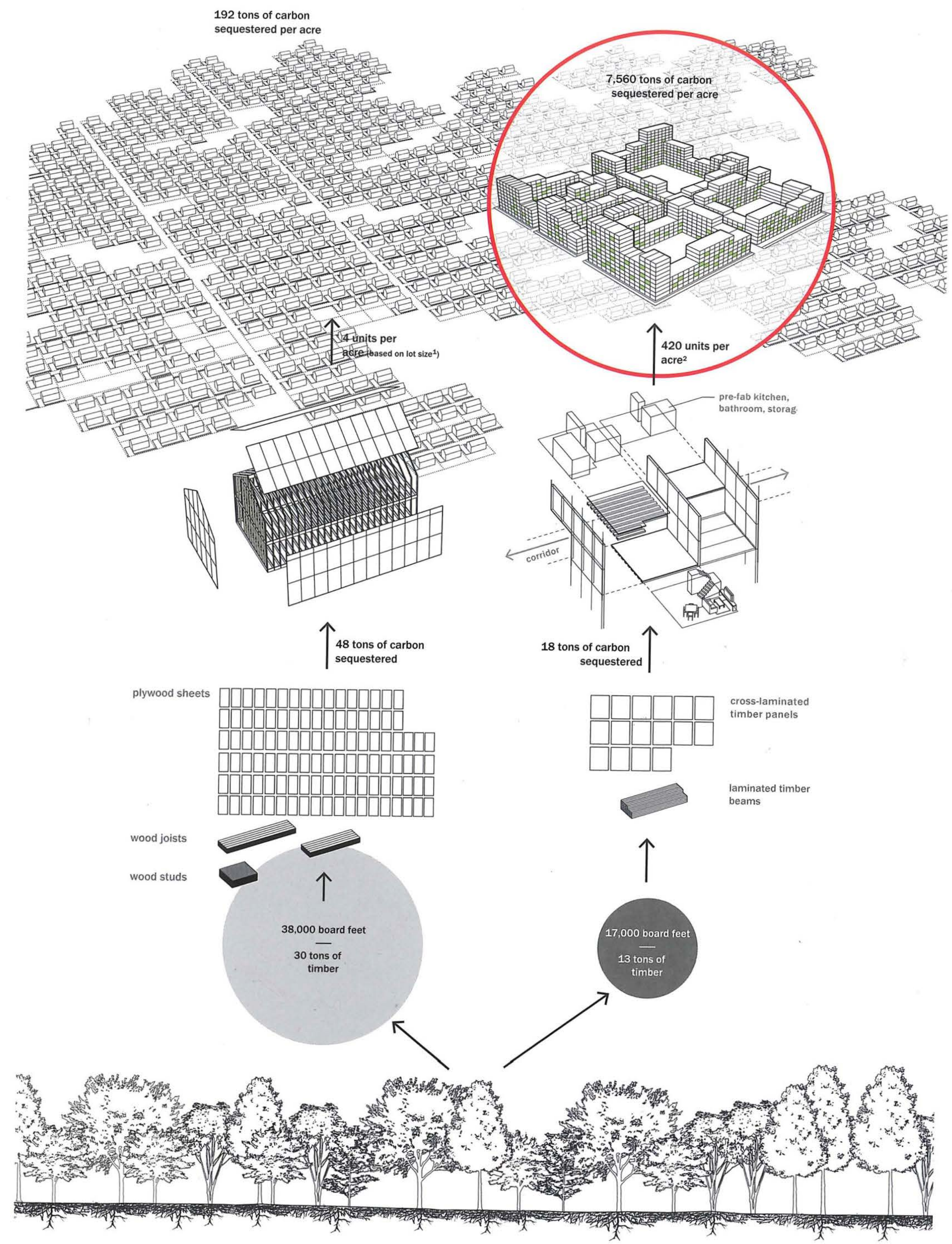


1. IMPACTS OF MINERAL EXTRACTION

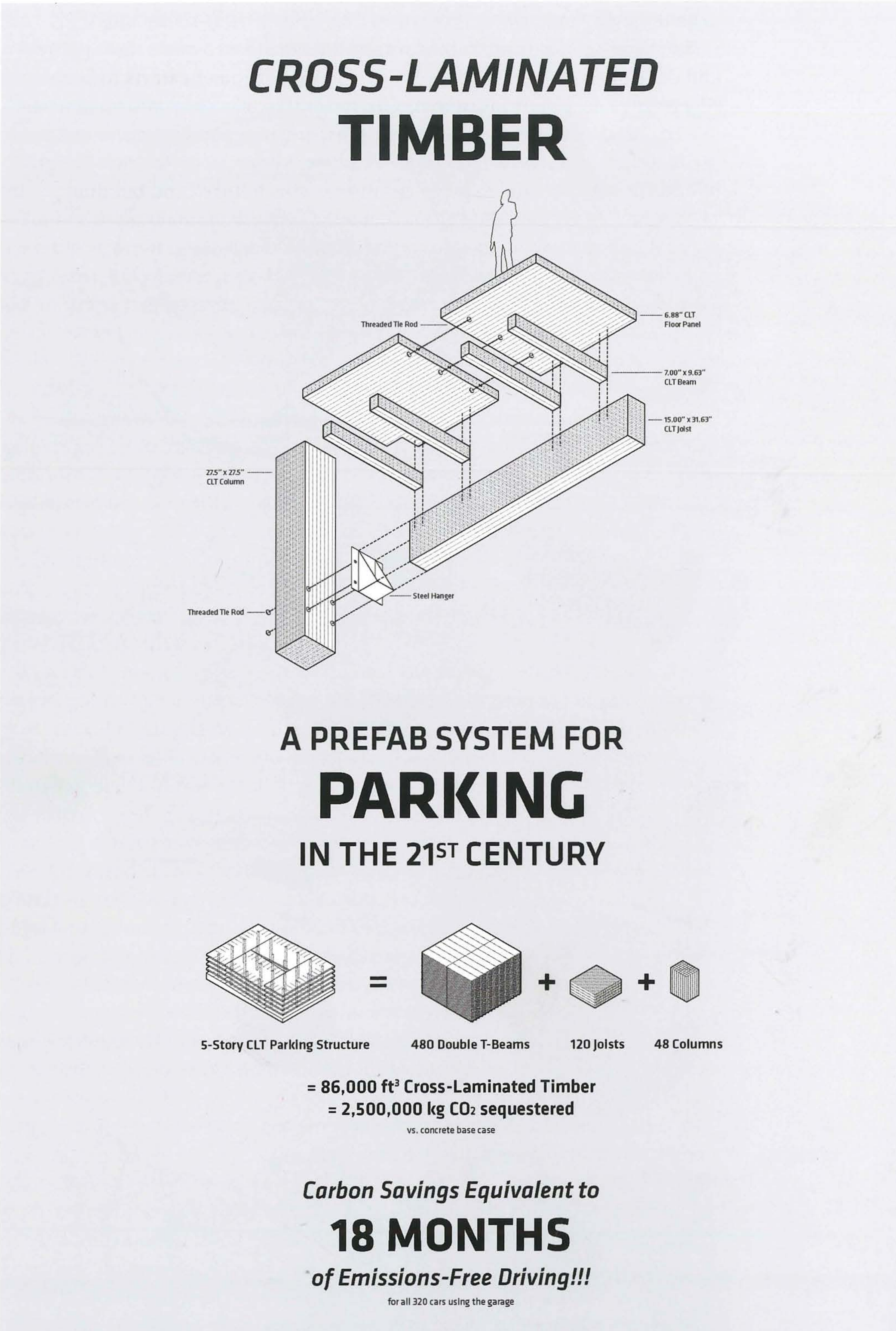
use of petrochemicals (either as an energy source or a synthetic component), enlarging their carbon footprints significantly as compared to poorer-performing alternatives.[8]

The spatial dimension of this argument is measured at two scales: that of the land area we disrupt in building human settlement and that of the volume of building material we call upon to do it. The benefits compound each other when we build dense cities using dense structural formations of timber to produce familiar mid-rise building morphologies and uses: the sequestration of approximately 1.6 metric tons of atmospheric CO_2 in each ton of timber utilized and maintained in buildings[9]; the uptake of CO_2 in the replacement of forest stocks over a 40-to-60-year growth cycle; the avoidance of fossil fuel emissions embodied in the manufacture of alternative, mineral-based structural products.[10] We must add to this complex but critical calculus of material expenditure and carbon emissions the important factor of potential energy savings and impact reduction that we capture by redirecting resources away from the production of attenuated suburban infrastructural systems with their energy-gobbling and heat-absorbing networks of roads and parking lots; their overtaxed, rickety, and electrically leaky power grids; and their forest-fragmenting, land-degrading organizations of buildings.[11] These benefits and offsets exploit global demographic shifts in population and wealth to cities that are already underway[12] and redirect the consumption of new building materials that will inevitably result.

As a brief thought experiment, consider the savings (with interest!) that would accrue in reconfiguring the structural components of what was once central to the American Dream: the studs, joists, rafters, and plywood sheathing and subfloors of an average 2,400-square-foot, single-family suburban house. If the wood fiber contained in the 38,000 board feet (30 metric tons) of light sticks and thin veneers that form the skeletal system of suburbia were instead laid up as dense, structurally efficient glue-laminated assemblies to produce equivalently sized, similarly programmed units of mid-rise urban housing, we would shift approximately 1,500 households onto an area of land that would hold only about 30 families in freestanding wood-framed suburban houses (fig. 2). The costs of producing better-performing building envelopes and mechanical systems would be shared by many, relieving the individual homeowner of the increasingly onerous demands of maintaining a freestanding high-performance home.[13] Mass timber, previously underutilized in the heavy-bearing structures associated with urban dwelling and the cityscape, might now be embedded in parking garages, bridges and overpasses, commercial buildings, and industrial facilities, storing carbon reserves in a symbiotic offset of the carbon emitted by the drivers and cars that use them (fig. 3). The land area left undisturbed by exodus to suburbia, potentially freed of its modestly diffuse, yet physically burdensome population, unencumbered by impermeable soil cover, and increasingly diversified biologically with hydrological systems intact, is now a biomass producer and high-functioning collector of CO_2. Carbon is a structural asset, the dense urban center its parsimonious bank.



2. REDIRECTING TIMBER TO THE CITY



Redeploying material and reorganizing land at these scales might be easily dismissed as unworkable fantasy. But considered more thoroughly and developed econometrically, this structural argument starts to bear real loads. The accounting anticipates inevitably massive investment in the material and technology required to house shifting populations in necessarily better-performing building envelopes. It incorporates the findings of current research and experimentation in silviculture[14] and building production. It assigns value to an economic symbiosis found in forest supply and construction demand, which has both environmental implications and immediate application around the globe. Well-argued speculations in wooden "skyscraper" engineering[15] have served as exciting provocations. But less height-ambitious versions, six- to twelve-story mid-rise, mixed-use timber buildings completed or under construction in London, Finland, Austria, Germany, Canada, and Australia, along with heavy timber vehicular bridges in Canada and the Netherlands and a timber parking garage in Sweden, are all the proof needed to pursue the development of the cityscapes imagined here. And the carbon benefits are quantifiable and easily projected across larger urban developments with greater economies of scale.

For a range of reasons, old (in some cases, ancient) yet still evolving tectonic procedures of stacking, bundling, through-bolted assembly, and more recently glue laminating failed to catalyze a manufacturing revolution in mass timber construction during the last century of rapid building expansion. But today, they are beginning to reveal wood's secrets and yield potential solutions to architects, planners, and policy makers searching for sustainable yet durable building systems. The very material properties of wood and structural timber that have made its performance in building difficult to predict and therefore resistant to industrial standardization are now proving, when understood, exploited, and properly applied, to be great assets with significant collateral benefits. Qualities of structural wood long held to be potential liabilities—its low density, combustibility, complex anisotropic strength characteristics, constant hygroscopic absorption of moisture—are proving through new research and product development to be sustainable technological assets.

It is perhaps wood's natural heterogeneity, the unpredictable defects of the raw material, and the variation in the properties, processing requirements, and performance characteristics of the fiber (depending on species and growing region) that have been timber's greatest disadvantage in the marketplace of high-strength structural products. The varying properties of different species drawn from the same forest and even the differing structural capacity of timber sawn from the same tree have been a disincentive to a building industry seeking economies of scale, repetitive manufacturing procedures, and homogenous raw material. But analytical protocols and industrial practices that are already in place at a basic level in mass timber manufacturing may provide the seeds for a more tolerant and holistic use of the structural materials available in the forest.

Ingrained in the technological processes of timber glue lamination—whether for a piece of engineered flooring or a massive structural panel—

is a set of well-established procedural steps designed to eliminate defects, catalog the wood fiber based on quality and structural capacity, and distribute it efficiently within a structural member. The sorting, grading, and re-sawing, the removal of flaws (unsound knots or checks), and the subsequent finger-jointing of small boards into longer, structurally improved sticks allow the strongest and highest-quality material found in a tree to be positioned where it can do the most structural work. Current standard practice in the industrial layup of a glue-laminated beam, for example, places the higher-grade laminations at the more structurally critical tension and compression edges of the member; the weaker, lower-quality fibers fall in the less demanding midsection.

Digital analysis and material optimization systems that are increasingly industry standards can produce enormous efficiencies in the use of the trees we cut. They also create the potential for a more comprehensive approach to our forests as a renewable resource, optimizing the use of a range of species with lower structural values, that in turn enables us to manage forest stands in ways that better emulate natural growth. The current insatiable commercial demand for the perfect piece of wood—whatever the preference, be it straight, stable, rot-resistant, beautifully figured, behaviorally predictable—has promoted the predatory practice of culling only certain commercially "hot" or well-known species from global forests, or plucking the finest, most recognizably profitable trees from a particular stand, while leaving lesser-known and commercially underutilized trees and thereby distorting the ecological balances of the forest. Timber plantations, which often favor monocultures over more ecologically diverse forests with natural growth through a succession of species, have proven profitable in some cases but, with the wrong microclimate or soil type, have led to erosion and soil degradation while producing wood of decreasing quality.[16]

By developing an array of structural products and assemblies that seek to exploit existing techniques in mass timber production and to utilize a greater diversity of plant fiber growing naturally in our forests, we can promote healthy silvicultural diversity while fixing increasing amounts of carbon in the structural products we specify. Recent experimentation anticipates the broader use of mixed-species layups; these distribute woods with different properties within customized configurations designed for varying structural demands and applications. New products already in the pipeline include hybridized structural members and assemblies that take advantage of the lightness, appearance, renewability, or tensile strength of timber while introducing small, optimally configured amounts of glass and carbon fiber, steel, or reinforced concrete to magnify performance.[17] Today our use of structural timber is limited to a narrow spectrum of commercially familiar species and grades of solid lumber. The processes inherent in mass timber technologies might offer a promising means to broaden our use of this abundant resource. In the United States, we have only begun to develop new mass timber systems as commercial products; teach their principles, means, methods, and potentialities in our design and engineering schools; measure and articulate their environmental benefits; and adopt their solutions in the professional arena.

For those with justifiable anxiety about the 15 to 20 percent of global deforestation directly attributable to the harvested wood products industry, who might recoil at the prospect of the mass destruction of the planet's forests in our zeal to craft new cities from wood, it is important to acknowledge historic abuses and potential mismanagement. The economics of our past destructiveness—the undervaluing and misapplication of certain wood species and products, the simplistic and inefficient uses of their fiber, and the rather crude exploitation of forests as an unregulated and infinite source of profit—all contributed to historic damage and degradation. But the intense and imbalanced market demands that sponsored those predatory practices are now giving way to promising techniques that seek economic advantage in wood's broad applicability and renewability, rather than its mere homogeneity, and that reflect the sophistication and nuance of our current understanding of forest stand dynamics.[18] The challenge today is a system-wide accounting that seeks to balance the potential productivity of forest ecologies in relation to the material and energy demands of the construction sector. The solution lies in a mix of approaches to the preservation of historically diverse forests and the expansion and utilization of new forest land by developing sustainable material and economic demands for its wood and exploiting its processes of carbon uptake and storage.[19]

Although architects, engineers, policy makers, and builders tend to think of themselves as producers, as *makers* of the built environment, we are, in fact, mass consumers. And like all consumers who draw directly or indirectly on often finite supplies of material and call up complex, technologically intensive processes in our demand for goods, we have an embodied energy and emissions problem.[20] Through professional reflex, commercial convention, or cultural habit, we pull hard on the demand end of a complex economic chain without completely understanding or assessing the actual environmental (and inevitably socioeconomic) predations and impacts of what it supplies.

In doing so, we speculate with considerable risk in a black market: *black* in the metaphorical sense because the building systems we call into being and the complicated processes of producing them contribute each year to a significant uptick in the amount of carbon introduced into the atmosphere by human activity; a *black market* because we conduct a constant and complex exchange of material and energy that is unregulated and crudely measured. As professionals, we *speculate* in this black economy by making risky transactions on a daily basis, calling upon enormous physical resources with promises of significant profits in energy efficiency, impact reduction, and renewability. The econometrics are tricky and highly contested; the techniques of carbon cost-benefit analysis are clumsy and subject to conflicts of interest and undue influence. The boundaries of the systems we can reliably assess are so narrow, the mechanism of exchange so far-reaching, the infrastructure of resource extraction, processing, delivery so pervasive, and the cycles of carbon uptake and release so immediate—a photon striking a leaf's chlorophyll, the sudden firing of a basement boiler, the pulsation of refrigerant pumps—and yet so global in dimension and so geologic in duration that our claims for the performance of our buildings and the impacts of their manufacture are, at best, constantly changing and, at worst, woefully inadequate or even willfully misleading.

In the physical economics of converting raw material into the finished product of building, we will ultimately account for what Lionel Robbins described as "a relationship between ends and scarce means." In seeking his potential "alternative uses" in an exchange already taking place at a global scale, it would be grandiose to suggest that the sole solution to pending planetary crisis is the adoption of mass timber in the construction of new, densely built environments. But as the window for climate action narrows and shifting urban demographics create new demands for physical resources, it seems obvious that the carbon held both in forests and, potentially, in an array of urban buildings is an asset we should develop and manage.

Alan Organschi is a design principal and a partner at Gray Organschi Architecture in New Haven, Connecticut. He is also a lecturer at the Yale School of Architecture and coordinates Yale's first-year graduate housing studio. Organschi has lectured on architecture, technology, and the ecological impacts of design at universities and public and professional forums in the United States, Canada, and Europe.

1. James Hansen et al., "Target Atmospheric CO_2: Where Should Humanity Aim?" *Open Atmospheric Science Journal* 2 (2008): 217.

2. Hansen, "Target Atmospheric CO_2," 217.

3. Ernst von Weizsäcker et al., *Factor Five: Transforming the Global Economy Through 80 Percent Improvements in Resource Productivity* (London: Earthscan, 2009), 143–70.

4. Weizsäcker, *Factor Five*, 51.

5. Miro Ristimäki et al., "Combining Life Cycle Costing and Life Cycle Assessment for an Analysis of a New Residential District Energy System," *Energy* 63 (2013): 168–79.

6. I. Sartori and A. G. Hestnes, "Energy Use in the Life Cycle of Conventional and Low-Energy Buildings: A Review Article," *Energy and Buildings* 39, no. 3 (2007): 249–57; Ristimäki, "Combining Life Cycle Costing," 168–79; Vikas Khanna, Bhavik R. Bakshi, and L. James Lee, "Carbon Nanofiber Production: Life Cycle Energy Consumption and Environmental Impact," *Journal of Industrial Ecology* 12, no. 3 (2008): 394–410.

7. Zhengen Ren, Xiaoming Wang, and Dong Chen, "Climate Change Impacts on Housing Energy Consumption and Its Adaptation Pathways," in *Mitigating Climate Change: The Emerging Face of Modern Cities*, ed. Anshuman Khare and Terry Beckman (Berlin: Springer, 2013), 207–22.

8. Jennifer O'Connor and Jim Dangerfield, "The Environmental Benefits of Wood Construction" (paper delivered at Eighth World Conference on Timber Engineering, Lahti, Finland, 2004), 171–77.

9. Dominique Gauzin-Müller, ed., *Sustainable Architecture and Urbanism: Concepts, Technologies, Examples* (Basel: Birkhauser, 2002), 32–43.

10. Chadwick Dearing Oliver et al., "Carbon, Fossil Fuel, and Biodiversity Mitigation with Wood and Forests," *Journal of Sustainable Forestry* 33, no. 3 (2014): 248–75.

11. Eero Puurunen and Alan Organschi, "Multiplier Effect: High Performance Construction Assemblies and Urban Density in US Housing," in Khare and Beckman, *Mitigating Climate Change*, 183–206.

12. Barney Cohen, "Urbanization in Developing Countries: Current Trends, Future Projections, and Key Challenges for Sustainability," *Technology in Society* 28, no. 2 (2006): 63–80; Karen C. Seto, Burak Güneralp, and Lucy R. Hutyra, "Global Forecasts of Urban Expansion to 2030 and Direct Impacts on Biodiversity and Carbon Pools," *Proceedings of the National Academy of Sciences of the United States of America* 109, no. 40 (2012): 16083–88.

13. Puurunen and Organschi, "Multiplier Effect," 183–206.

14. Oliver et al., "Carbon, Fossil Fuel," 248–75.

15. Michael Green and J. Eric Karsh, "The Case for Tall Wood Buildings: How Mass Timber Offers a Safe, Economical, and Environmentally Friendly Alternative for Tall Building Structures," http://cwc.ca/wp-content/uploads/publications-Tall-Wood.pdf (Vancouver: mgb Architecture + Design et al., 2012), accessed August 4, 2014; Barbara Porada, "The Timber Tower Research Project: Re-Imagining the Skyscraper," *Arch Daily*, June 6, 2013, http://www.archdaily.com/384032/the-timber-tower-research-project-re-imagining-the-skyscraper, accessed August 4, 2014.

16. Chadwick Dearing Oliver and Roger Mesznik, "Investing in Forestry: Opportunities and Pitfalls of Intensive Plantations and Other Alternatives," *Journal of Sustainable Forestry* 21, no. 4 (2005): 97–111.

17. Nikolaos Plevris and Thanasis C. Triantafillou, "FRP-Reinforced Wood as Structural Material," *Journal of Materials in Civil Engineering* 4, no. 3 (1992): 300–317; Juliano Fiorelli and Antonio Alves Dias, "Analysis of the Strength and Stiffness of Timber Beams Reinforced with Carbon Fiber and Glass Fiber," *Materials Research* 6, no. 2 (2003): 193–202.

18. Chadwick D. Oliver and Bruce C. Larson, *Forest Stand Dynamics* (New York: John Wiley and Sons, 1996).

19. Oliver et al., "Carbon, Fossil Fuel," 248–75.

20. Manfred Lenzen, Richard Wood, and Barney Foran, "Direct versus Embodied Energy: The Need for Urban Lifestyle Transitions," in *Urban Energy Transition: From Fossil Fuels to Renewable Power*, ed. Peter Droege (Oxford: Elsevier, 2008), 91–120.