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TIMBER CITY: GROWING AN URBAN CARBON SINK WITH GLUE, SCREWS, AND CELLULOSE FIBER

Alan Organschi[i], Andrew Ruff[ii], Chadwick Dearing Oliver[iii], Christopher Carbone[iv], Erik Herrmann[v]

ABSTRACT: The mid-rise city of the Anthropocene age[1] is formed from materials extracted, smelted, sintered, or synthesized through intensive fossil-energy based industrial processes with significant environmental footprints. Predictions of dramatic global population growth and urbanization suggest that the demands for these materials and processes will rise sharply over the next 30 – 50 years, setting the stage for a significant global spike in greenhouse gas emissions associated with the construction of new buildings and infrastructure. This paper and associated research project examines an alternative: the transformation of dense urban centers into massive carbon sinks, made possible through the broad implementation of emerging mass timber[2] construction technologies and regulatory and economic policies that promote timber building in cities and sustainable management of source forests. By assessing the carbon storage capacity of a basic structural module—a mass timber assembly applicable to a range of mid-rise urban building types—and deploying that module at the scale of a multi-story mixed-use urban district, the paper extrapolates both direct and associated benefits of a systemic shift from a mineral- to forest-based building economy and describes a supply chain model that places resilient, bio-diverse forests in synergy with convivial, densely populated cities.

KEYWORDS: Mass timber, Cities, Forests, Carbon sink, Implementation, Design and assessment tool

1 INTRODUCTION

The forest is a natural carbon sink, absorbing carbon dioxide (CO_2) through the process of photosynthesis and storing it as molecular carbohydrates in the woody matter and soils of the forest biome. Wood fiber harvested from forests continues to sequester carbon until it is re-released as CO_2 during the aerobic decay or combustion of the material. The dense city, historically considered antithetical to the healthy forest, is in its current state a significant source of CO_2 and other greenhouse gas (GHG) emissions, not only in its operational energy consumption but also in the industrial energy demands and process emissions embodied in the physical materials that give urban buildings and infrastructure their form.

The Timber City project is an interdisciplinary examination of the potential ecological and economic linkages between the industrial production of construction material and the morphology of contemporary cities. As a model of material and structural design, environmental assessment, and land-use and planning policy, it seeks to answer the anticipated need for new construction to serve a rapidly urbanizing population, exploiting both the inherent spatial, material and infrastructural efficiencies of dense urban building morphologies and the unique carbon storage capacity of structural timber assemblies. It synergistically links sustainably managed forest supply with urban construction demand, increasing the economic value of wood fiber while incentivizing the protection and potential expansion of global forests. It offers the construction of new and revitalized cityscapes as a critical tool in the global effort to mitigate climate change by turning dense urban settlement into a continuous carbon sink functioning at the scale and capacity of the forests that are its renewable source. It posits the process of photosynthesis as a valuable form of material production energy, as opposed to the more energy-dense but environmentally deleterious forms of energy—primarily fossil hydrocarbons—that fuel the manufacture of other GHG emissions-intensive classes of structural material.

As a means of tracking the potential flow of carbon from forests into dense cityscapes, the Timber City model employs a prototypical module of structural mass timber assembly, assessing its wood content, its molecular carbon storage capacity, and the demands its extraction places on the source forests from which it is

[i] Alan Organschi, Yale School of Architecture, Yale University, USA, Gray Organschi Architecture, TimberCity.org
[ii] Andrew Ruff, Gray Organschi Architecture, USA TimberCity.org
[iii] Chadwick Dearing Oliver, Global Institute for Sustainable Forestry, Yale School of Forestry and Environmental Studies, Yale University, USA
[iv] Christopher Carbone, Bensonwood, USA
[v] Erik Herrmann, Taubman College of Architecture and Urban Planning, University of Michigan, USA

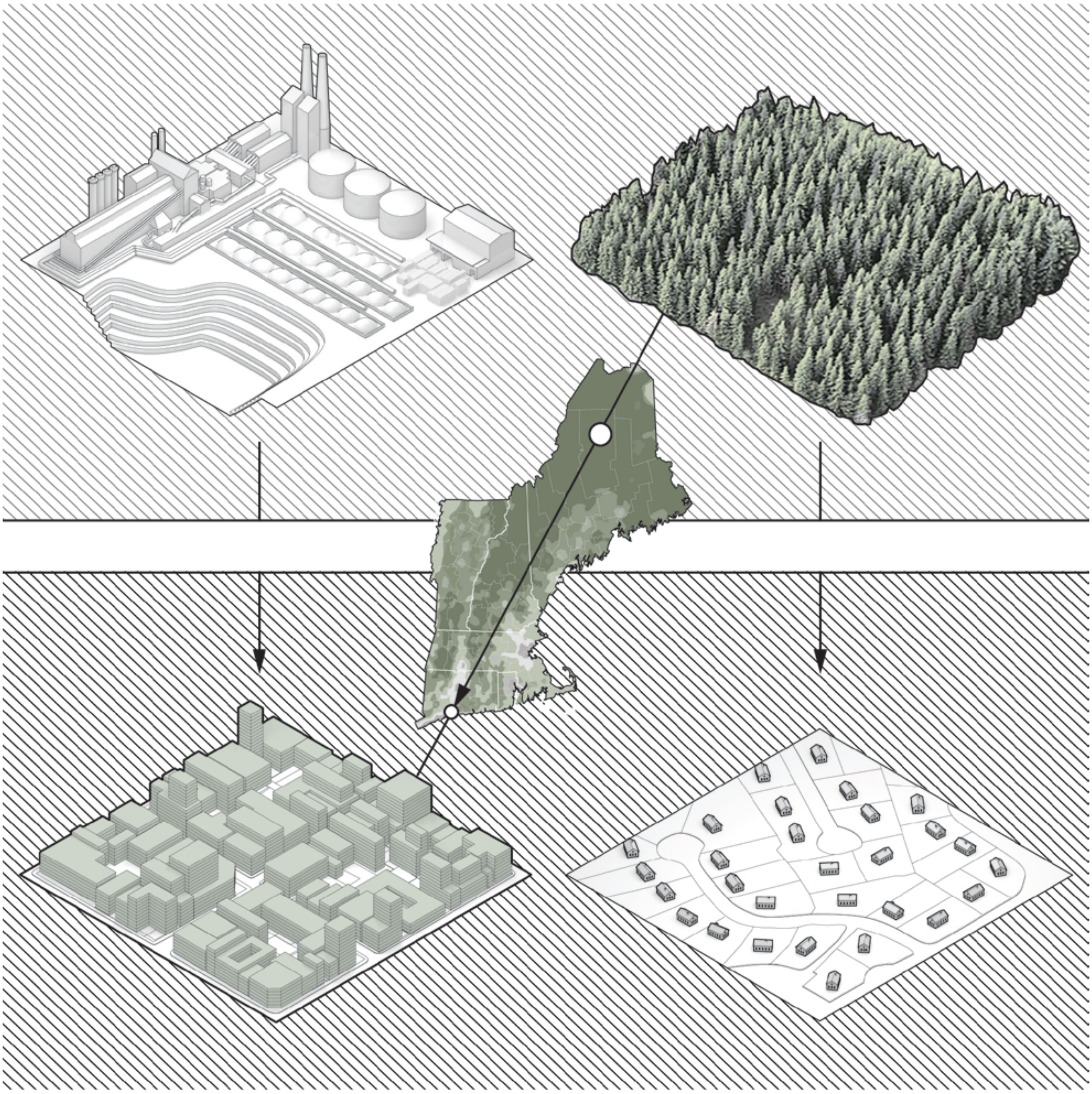
EMBODIED CARBON

STEEL *- 0.46 mT carbon / 1 mT steel*

A single tonne of structural steel requires extensive and intensive industrial processes to excavate 1.5 tonnes of iron ore and 720 kilograms of coal, heat them in a furnace until they produce molten iron, and finally cast the liquid steel into structural members.

TIMBER *+ 0.48 mT carbon / 1 mT lumber*

A single hectare of forest contains 118 mT of carbon within the biomass of the trees, with an additional 60-75 mT of carbon stored within the soil. Harvesting and processing trees into lumber only requires 1/5 to 1/3 mT carbon per mT of manufactured forest product.



As cities have grown denser and taller, the primary material pallette has shifted from stone and wood to steel and concrete. While urban settlements use land more efficiently than low-density sprawl, the carbon-intensive materials that form contemporary cities pose serious environmental threats.

CITY *7,250 people per square kilometer*

The rapid decentralization of developed countries during the middle of the 20th century created enduring patterns of urban sprawl that have propogated globally. In the United States, light-framed homes constructed of dimensional lumber constitute the primary structural typology of low-density developments.

SUBURB *2,400 people per square kilometer*

LAND USE

Figure 1*: Proposed redirection of forest materials*

drawn. It then applies that module of assembly and assessment to a mid-rise (6-12 story) city district in New Haven, Connecticut, using a hypothetical structural typology that includes a range of urban building morphologies typical to the post-industrial cities of the northeastern United States. Finally, it proposes a computational tool that calculates potential urban building densities while quantifying their carbon sequestration capacity, identifying suitable regional forest and industrial supply chains while calculating the emissions avoided in the substitution of structural biomass for mineral based building materials. By extrapolating the structural module and its sequestered atmospheric carbon beyond the limitations of the individual building to the larger scale of the city district, the Timber City initiative models both an interdisciplinary platform for research and development and a vertically integrated supply chain that steers carbon from the forest to the city, sequestering it in durable structural materials rather than allowing it to off-gas as industrial emissions.

2 OVERVIEW OF RELATED RESEARCH

2.1 Global Urbanization and Building Material Consumption

Humanity has officially entered the urban age.[3] For the first time in history, a majority of the world's population now lives in cities and demographic projections anticipate even further dramatic increases in the urbanization of the planet. Based on current urban morphologies, land-use patterns, and construction practices, urban land areas would need to triple their 2000 footprint in order to accommodate projected urban global population growth by 2030.[4] As urban land area increases, there will be a corresponding increase in physical infrastructure-- the homes, offices, buildings, and roadways that form the contemporary city—and the demand for material required to construct that expanding physical realm will climb accordingly. By 2030, the OECD predicts steel demand will increase from 1,537 million tons to nearly 2,000 million tons,[5] while the demand for concrete will increase from 1 billion tonnes in 1990 to nearly 5 billion tonnes in 2030.[6] In light of this dramatic demographic shift and the significant increase in land-, energy- and resource consumption that it will entail, it is critical that we reconsider both the spatial morphologies of human settlement and the industrial materials and methods with which we build them.

2.2 Re-forming Human Settlement: Current Impacts

On a continent as timber rich as North America, it is not only a conceptual irony but also a significant environmental hazard that wood—a renewable material with demonstrably low extraction impacts and processing emissions and energy demands—has been used almost exclusively to construct the land-, infrastructure-, and energy-intensive sprawl of suburbia.[7] Meanwhile, the structurally demanding building morphologies of dense, higher rise 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.[8] Throughout relatively recent building history, but in an accelerating trend over the past century, architects and engineers achieved significant advances in building technology through the development and deployment of increasingly complex material systems that relied on the combustion or chemical transformation of fossil hydrocarbons for their manufacture. Concrete, steel, glass, aluminum, and then plastic and carbon fiber composites—each representing a refinement in industrial engineering and processing— have produced buildings that were ever-stronger, taller, and safer than their predecessors. Yet this technological revolution and the succession of advanced building assemblies that has followed in its wake has also coincided with the near exhaustion of finite material resources and the poisoning of the planet's atmosphere, water, and soils. Today, the annual contribution of the building sector to global anthropogenic carbon emissions represents well over a third of mankind's annual carbon footprint.[9]

2.3 Offsetting the Construction Carbon Spike

Until recently, efforts to reduce the global environmental impacts of the building sector have focused largely on operational efficiencies and putative benefits that would accrue over a building's service life. Embodied or direct energies and emissions of building production were considered to be relatively insignificant in comparison to the voracious energy consumption of poorly insulated building envelopes and inefficient mechanical systems.[10] Although concerns focused on building operational energy performance led to a series of important refinements in contemporary building assemblies, their technological and material intensification has had the unintended side effect of exacerbating the sharp spike in carbon emissions associated with the construction phase of a building's life cycle.[11] In light of recent efforts to mitigate sudden steep increases in atmospheric carbon concentrations, this up-front expenditure of CO_2 in the material processing and construction phase of a building's lifetime will likely prove to be a flawed material investment strategy. By using energy- and emissions intensive classes of primary structural material we compound the impacts to a planet already experiencing the dramatic effects of anthropogenic climate change. Mass timber construction techniques offer a means to reverse those effects while providing material capable of building the cities mankind will need in the near future.

2.4 Broad-scale Benefits of Mass Timber Construction

The comparative merits of mass timber relating to its light weight, workability and rapid assembly, ductility and seismic performance, hygroscopic moderation of indoor air quality, low density and thermal performance, and fire resistance have been elsewhere thoroughly articulated.[12] But by specifically isolating its potential role in mitigating anthropogenic greenhouse gas emissions, we better understand it as a powerful environmental tool and as an antidote to detrimental patterns of building material consumption. Reduced material processing emissions, the photosynthetic absorption of CO_2 in the cyclical regrowth of harvested forests, and the sequestration of carbon bound-up in harvested wood products are compounding benefits when applied at increasing scales.

According to researchers at the University of Canterbury, a mid-rise, steel or concrete building contains approximately 1,500 tonnes of net embodied CO_2 emissions, whereas the same building constructed of mass timber has a net sequestration 610 tonnes CO_2,[13] making the timber construction net carbon positive before the building is even operational. The 2,100 tonnes difference between the two material assembly systems does not include emissions avoided in the substitution of timber, nor the CO_2 absorption associated with the regrowth of replacement forests, but it entirely offsets the initial carbon spike of the construction phase of the non-timber buildings the researchers modelled.

2.5 Density Matters

In its current predominant allocation as the light structural material of low-rise housing, wood's capacity to sequester carbon comes at the significant cost of land area and attenuated infrastructural networks. The destructive impacts and costly material demands of suburbanization and the transportation and energy systems upon which it depends are well-known. The consumption of greenfield area has direct impacts on the ecosystem and the services it might otherwise provide: the disruption of hydrologic systems through the concentration of storm water in hard-piped drainage systems and the resulting diminishment of natural water filtration, the loss of habitat and the replacement of the carbon absorbing biomass of forests and grasslands by significantly weaker carbon sinks of lawns and gardens, the expansion of the impervious surfaces of roadways and parking areas and the attendant microclimatic effects of urban heat islands. By purely arithmetic comparison, a ten story multifamily residential building structured in laminated timber products, a height which currently exceeds the limits of the International Building Code, would sequester 17,567 tonnes of CO_2 per hectare;[14] while the light framed Type 5 wood constructed building currently allowed by American building regulation, at maximum allowable height of five stories and credible zoning density could store 6,839 tonnes of CO_2 per hectare; the average suburban single family house, the current repository of American structural wood products, holds only 751 tonnes of CO_2 per hectare.[15] When the carbon storage capacity of timber construction material is considered beyond the boundary of the individual building, it is clear that net benefits only accrue in the context of increasing urban density.

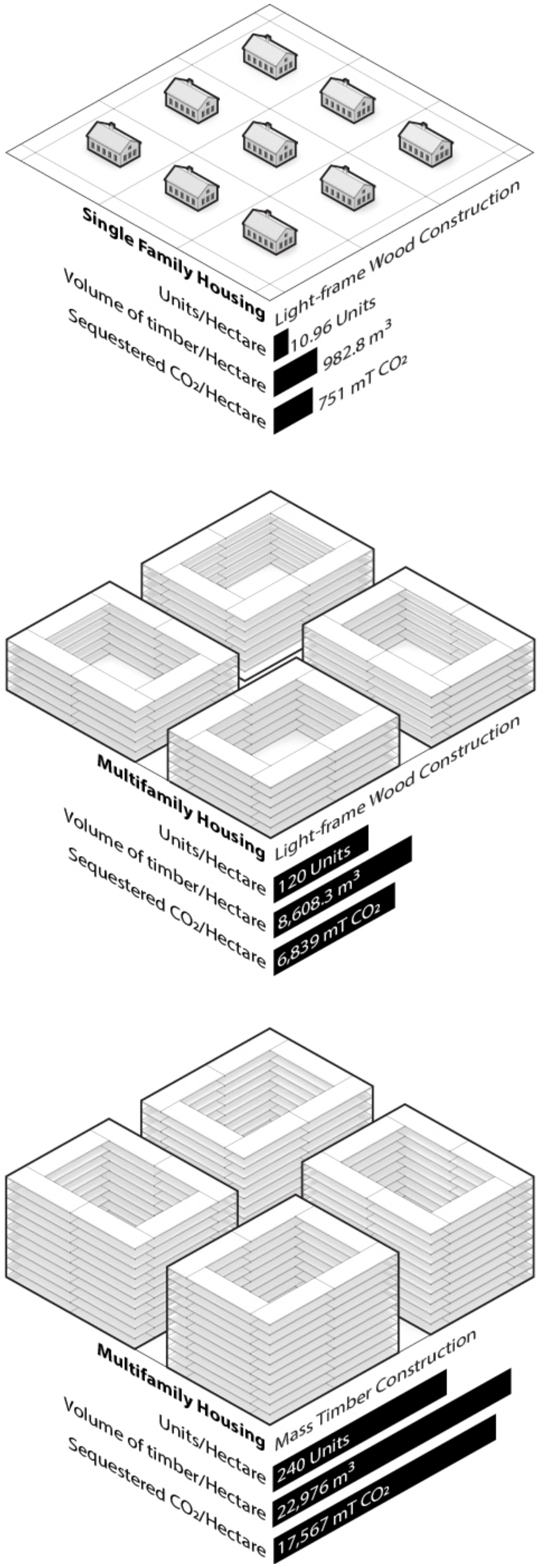


Figure 2: *Carbon, material and land use implications of building morphologies and timber building systems*

2.6 Engineered Specificity and the Promise of Structural Laminated Timber

Wood's anisotropic behaviour, its natural heterogeneity, the unpredictable defects of the raw material, and the variation in the properties, processing requirements, and performance characteristics of the fiber (dependent on species as well as the solar exposure, soil, rainfall, and the topography of the forest stand in which it grew) have been timber's greatest disadvantage in a marketplace demanding predictability and uniformity of high-strength structural products. It has also proved a disincentive to a building industry seeking economies of scale, repetitive manufacturing procedures, and homogenous raw material. But well-established analytical protocols and industrial practices 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 length of engineered flooring or a massive structural panel—is a set of well-established procedural steps designed to eliminate defects, catalogue 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 lamella allow the strongest and highest-quality material found in a tree to be positioned where it can do the most work within a structural layup. Digital analysis and material optimization systems that are increasingly industry standard can produce enormous efficiencies in the use of the trees we cut.[16] They also promise a more comprehensive approach to our forests as a renewable resource, optimizing the use of a range of species with lower structural values, and enabling foresters to manage forest stands in ways that better emulate natural growth.[17]

2.7 Sustainable Forest Supply

Scientists have long understood the role of forest biomes in maintaining the health and vitality of the biosphere—in which humanity is included—yet the value of natural systems has proven difficult to quantify.[18] Assessments of natural ecosystems strike a balance between measuring inherent environmental services (carbon storage, water filtration, diverse habitats, genetic material storage, timber and non-timber forest products, tourism and recreation) and speculation on the economic value of alternative uses for forest lands (agriculture, livestock grazing, and human settlement). Within this long-standing conflict between conservation and development, commercial timber harvesting is often associated with other extractive and destructive industries, justified by the argument that truly sustainable forestry management is difficult to achieve in practice and uncompetitive as an economic enterprise.[19] Yet this cultural reticence to promote increased timber harvesting due to fears of deforestation largely ignores the realities of global forest stocks and the strategic benefits of implementing widespread sustainable forest management.

Current reports estimate the global consumption of wood at an annual volume of 3.4 billion cubic meters. Meanwhile, increased awareness of forest management practices has encouraged retention of existing forests and encouraged afforestation in developed countries, resulting in a net annual forest growth rate between 6 and 17 billion cubic meters per year.[20] The 2.6 billion cubic meters of unutilized wood fiber growth—based on conservative global growth estimates—represent both an oversupply of a natural resource commodity and an enormous opportunity to integrate forest products into global carbon markets, specifically through the development of durable, industrially produced mass timber structural members and the buildings they can form. Unlike the vast majority of forest products that are viewed as inexpensive at best and disposable at worst, structural building materials are value-added products that are integrated into large-scale projects intended to stand the test of time.

Timber-based carbon sequestration operates as a multiplier throughout the natural and built environment, and in global carbon accounting. At the molecular level, cellulose aggregates 1,500 glucose monosaccharide rings into polysaccharide molecular structures containing 9,000 carbon atoms. Within the forest ecosystem, carbon is sequestered throughout the morphology of each tree—in the roots, the trunk, the branches, and the leaves—but also within the soil biome that supports it.[21] As forestland is harvested and processed into primary industrial products, waste materials are transformed into carbon-sequestering biomass and recycled into processed materials such as cellulose nanofiber and pulp. The carbon storage half-life of manufactured forest products ranges from three years for paper to 80 years in traditional dimensional lumber, but the carbon benefits of timber harvesting extend beyond consumer products and back to the source forests. According to a 2005 study published by the Consortium for Research on Renewable Industrial Materials (CORRIM), manipulating the frequency of sustainable timber harvests significantly impacts the total carbon sequestration potential of a forest system.[22] By increasing the frequency of harvesting cycles from a natural mortality rate of 120 years to a much more intensive harvesting rate of 45 years, forests are able to increase their life cycle total gross sequestration and emission avoidance from approximately 225 metric tons of carbon per hectare to nearly 280 metric tons of carbon per hectare.[23] In addition to its carbon benefits, a 45-year mosaic harvesting rotation—or "debt then dividend" approach—produces a heterogeneous and diverse array of habitats, preserving conservation forests within each harvesting block while encouraging a range of stand structures.[24] By distributing annual harvests over a delineated regional landscape, and by deliberately orchestrating harvest patterns to produce complex compositions of forest stands, the single module of a timber harvest can be multiplied to produce a landscape that is healthy, bio-diverse, and resistant to perennial natural disturbances of fire, disease, and infestation.

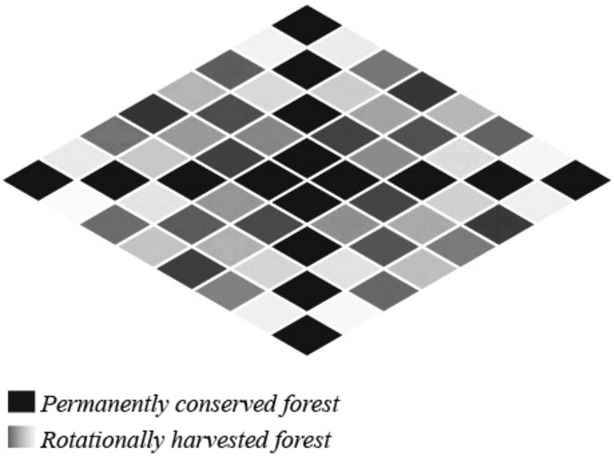


Figure 3: *Schematic 45-year mosaic harvesting pattern*

3 TIMBER CASE STUDY: 9th Square District, New Haven, CT

3.1 Urban Building Site and Source Landscape

While European architects and engineers have accelerated their adoption of mass timber structural systems over the past decade, their North American counterparts have only recently begun to undertake serious inquiries into the potential of mass timber architectural assemblies as a replacement for steel and concrete. Despite efforts to develop local manufacturing capacity, orient forest management practices towards producing structural timber, and nurture fledgling carbon markets, the health and growth of the mass timber supply chain is ultimately dependent on increased demand for mass timber buildings.

An inner city district of New Haven, Connecticut, a former coastal industrial center in New England—a five state region of the Northeastern United States that borders New York—serves as a prototypical urban condition in which to test the carbon sequestration capacity of the Timber City model. New Haven's network of underutilized buildings and empty lots within a compact downtown core constitute the inventory of sites for the introduction of an array of new mass timber building types. Adjacent empty land slated for multi-story development suggests greater opportunity for further extrapolation of carbon benefits and regional source forest capacity.

3.2 National and Regional Capacity

The extensive but underutilized forests of the region, ranging from the spruce stands of Maine to the mixed hardwood forests of central and southern New England serve as potential material sources that offer a means to revitalize a once thriving rural economy while reducing the building industry's carbon emissions and environmental impacts. The different forest biomes of the United States cover 766 million acres—one-third of the entire country—sequestering nearly 17 billion tonnes of carbon in their aboveground and belowground biomass, according to metrics from the U.S. Environmental Protection Agency and the U.S. Forest Service.[25] Despite a robust forest products industry and a strong demand for a wide range of forest products, the United States has managed to sustain an annual net growth of 4.5 billion cubic feet of timber, after accounting for natural mortality and harvest volume.[26]

Regionally, New England's forests—particularly those in Maine, Vermont, and New Hampshire—have exhibited robust growth over the past century, with recent annual net growth totals exceeding 350 million cubic feet of softwood and hardwood timber. Translated into mass timber structural components, this volume of unutilized forest flux could produce 103,550 mid-rise residential units, a volume of construction equivalent to rebuilding every New Haven residence twice annually.

Due in part to conservation and afforestation efforts by civic and non-profit organizations and to shifting global supply chains for paper pulp—a major economic driver for Maine's forest industry in particular—the volume of underutilized timber will likely increase in the future. By introducing mass timber architectural typologies into proximate urban centers, demand for New England forest resources will not only increase to absorb current excess capacity, but will encourage more sustainable harvesting patterns and produce valuable, carbon-sequestering forest products.

3.3 The Timber City Structural Module

The application of mass timber to specific urban contexts will ultimately demand a range of more specific architectural solutions, but for the purposes of this study we have developed an adaptable and replicable structural module constructed from mass timber assemblies. In order to capitalize on the environmental and economic benefits of mass timber construction—particularly within a speculative carbon-based market—we have designed and analyzed replicable timber assemblies that maximize their capacity to sequester carbon while remaining flexible, efficient, and readily adaptable to a variety of site conditions. Each assembly incorporates standardized mass timber elements that are available to the North American building industry: glue-laminated beams and columns, cross-laminated vertical panels, nail-laminated decking panels, and cellulose insulation.

Intended to serve as a quantified example of mass timber's potential to be readily deployed into existing cities, the basic architectural module is designed to function as a prototypical infill or a freestanding building within a dense urban context. The Timber City architectural module features an 80'x24' floor plate, capable of accommodating both commercial and residential tenants in a range of site configurations. The plan is organized by a CLT spine that extends the entire 80' length of the module. We have chosen to locate the central 48'x8' CLT core—consisting of egress stairs, mechanical chases, and an elevator shaft—at the centerpoint of the spine in order to maximize the module's shear capacity, though modifications can be made in response to address site conditions. Additionally, four 8' wide CLT transverse shearwebs span between the spine and the core, providing the primary transverse shear resistance of the prototype. A network of glulam beams extend perpendicularly from the core and spine, connecting to glulam columns along the perimeter of the module. The beams support nail-laminated timber (NLT) floor slabs, topped with structural plywood sheathing in order to create a diaphragm action.

The capacity for mass timber buildings to reach heights exceeding 10 stories has received attention from researchers, designers, and the media, but for the purposes of this study we have developed an architectural module that extends 8 stories, featuring a 19'-10" ground level floor-to-floor height and 11'-1" floor-to-floor heights for the upper 7 stories. The module was designed to function both as a freestanding building and as a unit within a larger spatial aggregation, with an optimized construction sequence originating at the module's core. Constructed from a series of vertically-oriented CLT panels, the core reaches a total height of 107'-0" and provides the primary structural rigidity to the entire module.

3.4 Structural Analysis

In order to determine the specific lateral load capacity of the module, the spine, core, and shearwebs were modelled in Visual Analysis 12 (VA) as "plate" elements and given the stiffness properties of Eastern White Pine ($E = 1.1x10^6$ psi). The spine was modelled as a plate element of thickness 5.5", and the other elements were modelled at 6.875" thickness. Floor slabs were also modelled as "plate" elements and given a thickness of 7.25" and stiffness of #2 SPF lumber. In modelling the core CLT walls, the modelled thickness was set to the aggregate thickness of all the longitudinal layers (e.g. a 7-lam CLT has 4 longitudinal layers @ 1.375" thick or 5.5" of total thickness in the longitudinal direction).

The spacing of structural beams and columns transverse to the CLT spine was set to 16' on center. This resulted in a 20' beam span for beams carrying 16' of tributary width, and a 24' span for the end beams, carrying 8' of tributary width. Floor slabs were set to span 16' from beam to beam through one-way action. Beams were assumed to be a glue laminated timber with $E = 1.8\ 1x10^6$ psi and aFb =2400 psi. A two-hour fire rating was desired, and calculations for the beams and NLT panels were performed according to American Wood Council Technical Report No. 10 and Chapter 16 of the National Design Specification for Wood Construction 2015. CLT panels were assumed to be encased in gypsum wall board to obtain their fire ratings, but it is possible that the spine would be able to achieve the desired fire rating by increasing the panel thickness by 2 laminations. Variations from this base model might be employed for better structural performance, including the change of the floor system from NLT panels to glue laminated (lumber or strand) or CLT panels. Additionally, composite concrete/timber floor systems could be employed to make the floors stiffer and more comfortable to the occupants.

After conducting a fire analysis, beam sizes were set to 12" wide x 24" deep for the 24' span, 12"x20" for the 20' span. The edge beam away from the CLT spine was set to 10"x24", and the edge beams against the CLT spine was set to 5" x 15". Edge beams on the building side away from the spine were modelled as continuous over top of the columns, so each 80' run is made from a 48' and a 32' beam. The location of this beam splice alternates from the 3rd to the 4th column at each floor level. Columns vary in section, with the first floor having 16" square columns, floors 2-4 have 14" square, and floors 5-8 having 12" square columns.

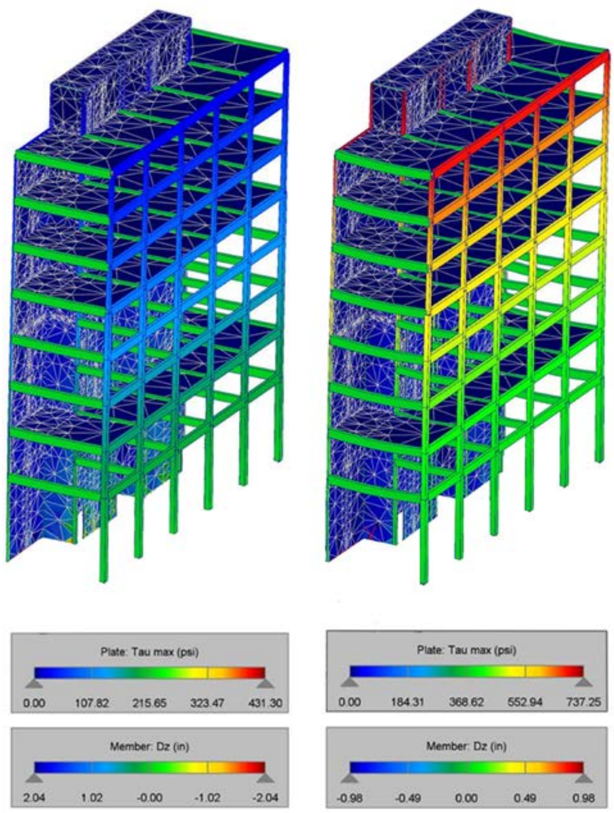


Figure 4: *Structural analysis of wind and gravity loading on prototypical mass timber architectural module*

In sum, the total quantity of various timber assemblies within this module weighs a combined 394,519 kg, resulting in a gross CO_2 sequestration volume of 722 tonnes. By applying the embodied carbon ratios for each timber assembly as provided by Circular Ecology's ICE Database, the net sequestered volume of CO_2 in the Timber City module amounts to 374 tonnes, with each level of the eight story structure responsible for a net sequestration of approximately 46.9 tonnes of CO_2. As these quantities reflect cradle-to-gate take-offs based on the ICE Database, further research into manufacturing sites and forest sources proximate to each module's specific construction site would yield a more accurate quantity of carbon actually sequestered.

3.5 The Timber City Typology Deployed

The Timber City development model seeks to leverage the role of mass timber structural systems as a carbon-sequestering multiplier within the natural and built environment. Rather than developing bespoke architectural solutions for specific lots, the Timber City model strategically deploys mid-rise, mass timber buildings throughout an existing city in order to create a

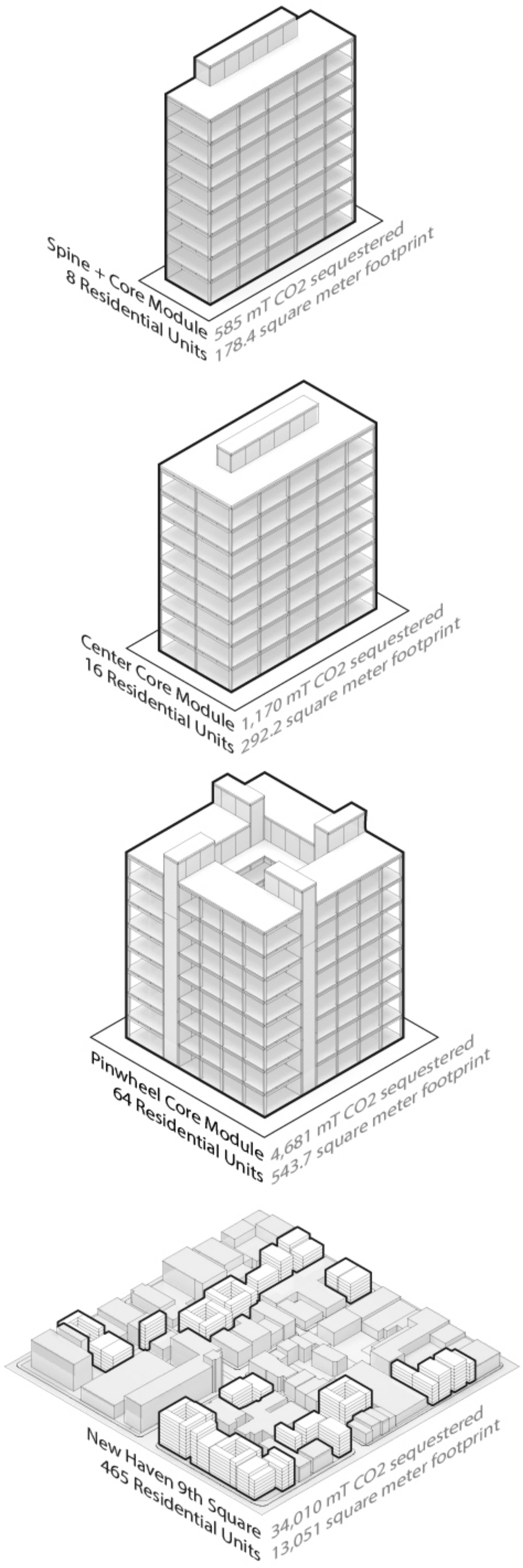


Figure 5: *Variable aggregations of a prototypical mass timber architectural module throughout an existing city*

critical mass of carbon-sequestration within the urban fabric.

As the proposed site for the deployment of mass timber buildings, New Haven's downtown Ninth Square district is zoned for business and commercial uses, with a relatively dense FAR of 6.0. By adapting the Timber City architectural module to the city's existing lot distribution and zoning regulations, the total deployment area of timber buildings covers 13,000 square meters of land and creates 82,950 square meters of occupiable building floor space. Constructed from 44,500 cubic meters of mass timber, the proposed buildings in the Ninth Square would sequester 34,000 tonnes CO_2, equivalent to removing 7,700 passenger vehicles from the road for one year. Furthermore, the benefits of mass timber buildings have a multiplier effect when considering the implications of increased sustainable harvesting practices in regional forests.

The Timber City model proposes a 45-year rotational mosaic harvesting pattern that creates a heterogeneous collection of wildlife habitats and permanently preserves stands of forest within each harvesting plot. Under conventional harvesting practices, the Ninth Square mass timber buildings would require a single clear-cut of 542 hectares of Northeast Spruce-Fir forests, but if considered sustainably—with land set aside for a 45-year rotational harvest—32,520 hectares would be required to produce that volume of timber buildings in a single year.[27] The larger tract of land however, would be capable of producing the same volume of timber each year indefinitely, while encouraging a range of forest stand types and correlated biodiversity.[28] Using the volume of timber buildings in New Haven's Ninth Square as a baseline consumption demand, the secondary forest carbon uptake of a sustainably managed forest would amount to an initial first year increase of 755 tonnes CO_2 beyond the forest's natural carrying capacity, an increased sequestration rate that would remain constant for the 45-year rotation schedule, at which point the forest will have regrown the entire volume of harvested timber.[29]

More immediately, mass timber buildings avoid significant greenhouse gas emissions associated with concrete and steel construction. Using the University of Canterbury study as a base comparative metric, New Haven's Ninth Square timber infill buildings would avoid emitting a net volume of 83,070 tonnes CO_2, equivalent to the annual emissions of 18,800 passenger vehicles. Combined with the carbon sequestered within the buildings' structural timber, a timber infill strategy for the Ninth Square would offset the average annual vehicle emissions for 26,500 passenger vehicles. With 465 residential units, the nearly 1,200 inhabitants of New Haven's Timber City would effectively be able to drive emissions-free for 22 years.

4 SOFTWARE SYSTEMS

The Timber City model integrates natural resources, industrial supply chains, design professions, and development armatures into a streamlined, efficient, and agile organization capable of deploying mass timber buildings into complex urban environments. In order to more effectively communicate the potential of mass timber to affect the balance of global carbon distribution, we are in the process of developing an ancillary Timber City software application capable of calculating and visualizing the benefits and ramifications of developing mass timber cities. Designed for a primary audience of architects, engineers, planners, and developers, the application will integrate municipal geospatial data with mass timber structural typologies in an effort to demonstrate the carbon, urban, and architectural implications of mid-rise, mass timber buildings.

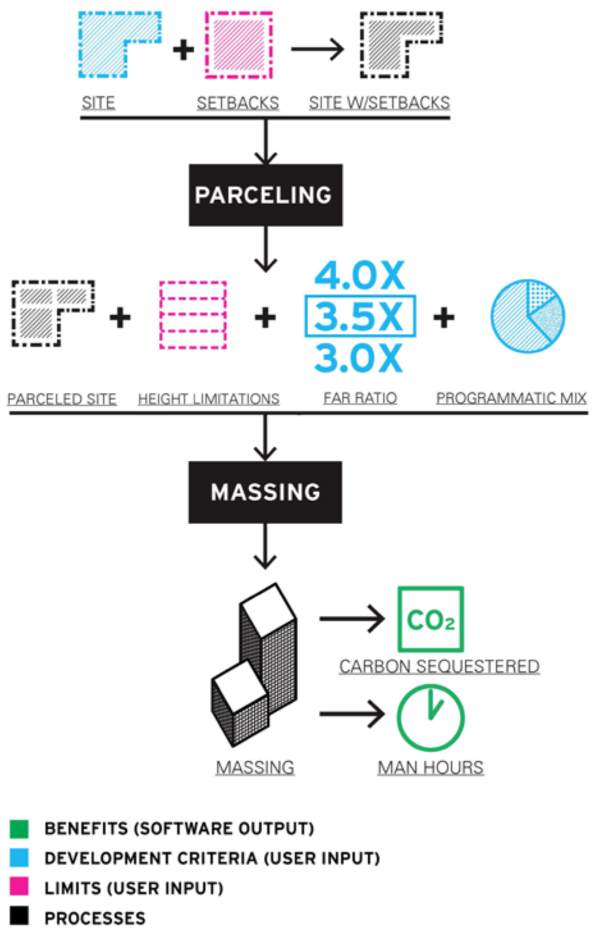


Figure 6: *Schematic application interface*

Intended to serve as a complement to existing, more comprehensive design programs, the Timber City application will be robust, intuitive, and readily integrated into a variety of industry-standard software platforms as an analytical module. While existing modelling software prioritizes detailed simulations and extensive prediction scenarios for developing sustainable building solutions in response to certification regimes, the Timber City application focuses on early design decisions that have dramatic impacts on the carbon implications of the proposed building's material, form, and spatial distribution. The user will input a selected lot or site, and the application will reference available municipal GIS data to overlay required setbacks, height limitations, and easements. Once the application determines the buildable lot area, the user will select a desired programmatic mix, FAR ratio, and associated structural scheme from a schematically engineered set of mass timber systems. Based on the structural data, selected program ratios, and site conditions, the application will utilize a custom-built Grasshopper algorithmic modelling component to generate a set of possible massing options in McNeel Rhinoceros, accompanied by summary reports detailing each option's impacts on carbon sequestration, regional jobs, and source forests.

By creating explicit and reciprocal connections between a building's design and its potential environmental and economic impacts, the Timber City application will allow architects to quickly articulate the range of benefits offered by mass timber buildings. Additionally, given the applications' intuitive and dynamic interface, policy makers and developers can analyze the implications of deploying mass timber buildings throughout existing cities. As the proposed scale and density of mass timber buildings increase, the application will be able to visualize and demonstrate the multiplier effect of timber to simultaneously sequester a critical mass of carbon and to produce convivial, liveable, and healthy urban centers.

5 CONCLUSION

5.1 Carbon Econometrics

The current production of our urban environment consumes finite resources of global energy and material while irreversibly transforming the surfaces of the earth. That footprint, both metaphorical and literal, will increase well beyond sustainable limits in the next half century. In light of mounting evidence of sharply accelerating global climate change and demographic projections of a tripling of urban population, the idea that by building densely with cellulose fiber we might exploit this massive need for new building to help *offset* carbon emissions rather than exacerbate them holds real potential. Profound ecological and environmental synergies between the forest and the dense city begin to emerge in the face of recent research in building life cycle impacts, forest science and carbon accounting, and mass timber engineering and production technology.

The current low financial cost of fossil fuels that indirectly subsidizes steel and concrete processing and transport make an economic value proposition for mid-rise urban timber construction somewhat challenging in the market of high strength structural products. However, if carbon emissions and extraction impacts are monetized through regulatory protocols governing common resources or through economic instruments like a carbon tax or cap and trade regime, then the economic benefits of an intensified and urbanized demand on the timber supply chain will begin to balance its arguably significant environmental value.

5.2 Forest Preservation: Past Abuses; Future Challenges

It is important to state emphatically that this compilation of data should be by no means understood as unfettered advocacy for the indiscriminate harvesting of all global forest biomes. On the contrary, each forest stand within a forest must be closely analyzed for the import and value of the non-commercial ecosystem services it provides as well as for the risk that even sustainable harvest and silvacultural management might pose.[30] The crude economic calculus that underlies unregulated, predatory and destructive commercial forestry practices seeks either to homogenize wood fiber (as with pulp) or unnaturally select trees of high financial—and often great biological—value for isolated removal with significant immediate damage and long-term biological impact to the surrounding forest. The intense and imbalanced market demands that sponsor more destructive extraction methods are today giving way to opportunities and techniques that seek economic advantage in wood's broad applicability and renewability, rather than in its homogeneity or in the aesthetic appeal of a particularly prized piece of wood. Forest harvests must reflect the nuance of biodiversity and habitat as they relate to forest stand dynamics and forest soil protection and they must balance the value of forest ecology against the material and energy demands of the construction sector. The preservation of large areas of historically diverse forests must be achieved by the expansion and the efficient utilization of new and secondary forest land.

5.3 Re-Structuring of Building Practice, Regulation, and Policy

In light of both these challenges and opportunities, and in the face of environmental impacts of mineral and fossil hydrocarbon-based structural alternatives, the broad redeployment of wood as the new high-performance construction material for dense, mid- and high-rise urban building may offer a credible approach to the building and infrastructural demands of projected global urbanization. The development of innovative industrial mass timber techniques, products, and assemblies, and their application to larger urban buildings, has recently captured the attention of engineers, architects, forest scientists, environmental advocates, and, most recently, building regulators, real estate developers and city administrators. The relaxation and in some cases elimination of height restrictions for wood buildings in several countries, and the adoption of mass timber structural assemblies by many country's building codes, has prompted increasing investment in large scale timber buildings in cities in North American, Europe, and Oceania. These technical and political developments herald a shift from material consumption patterns and building practices that have dominated urban construction and building typologies for well over a century and that today we must understand as entailing great environmental risk. Instead of utilizing steel or concrete, the architecture of the future city might be harvested from trees.

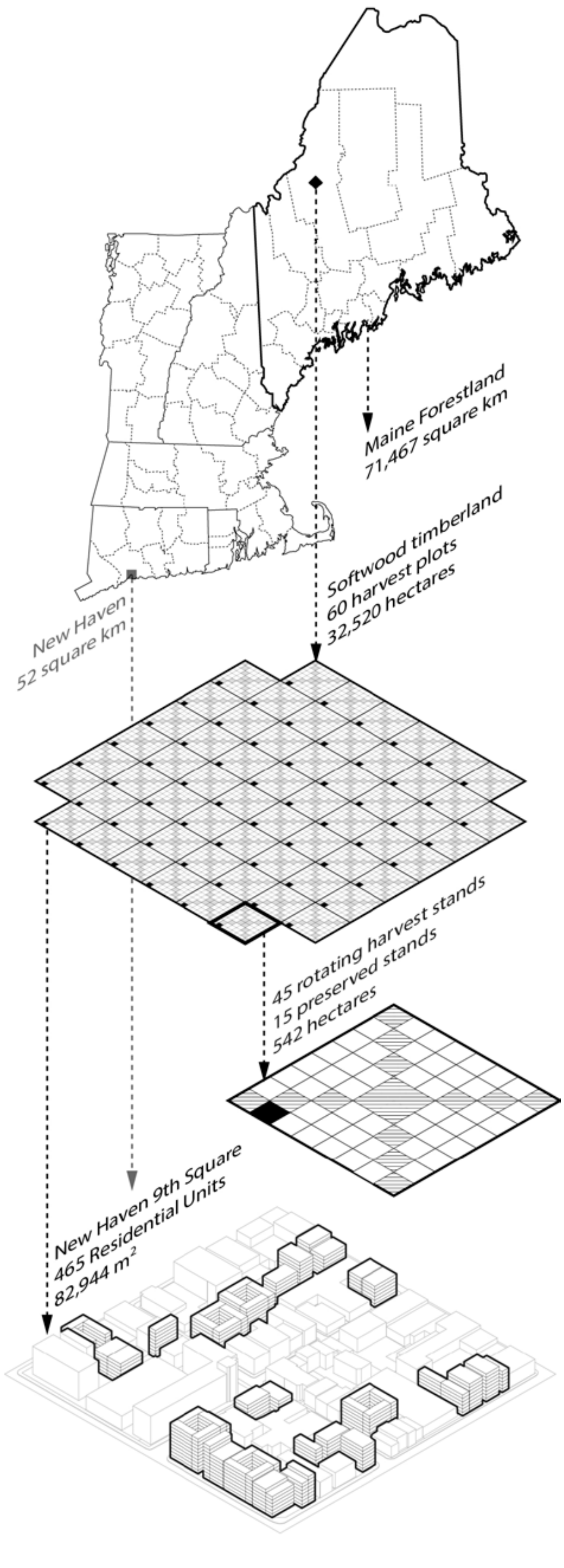


Figure 7: *Proposed material flow and land-use impacts when transferring forest biomass to urban environments*

[1] The current geological age, distinguished from the prior Holocene by the anthropogenic forces that have altered the function of earth systems, as identified by Paul Crutzen and the Anthropocene Working Group

[2] For the purposes of this article, the term “mass timber” refers to any structural element, member, panel comprised of adhesive, fastener- (nail- or bolt-) laminated lamella of solid wood and meeting the cross-sectional dimensional criteria for fire resistive Heavy Timber (HT) construction as defined by the International Code Council in its description of Type 4 Heavy Timber or Mill Construction.

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