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Research Report

A trait-based approach to both forestry and timber building can synchronize forest harvest and resilience

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Abstract

Along with forest managers, builders are key change agents of forest ecosystems' structure and composition through the specification and use of wood products. New forest management approaches are being advocated to increase the resilience and adaptability of forests to climate change and other natural disturbances. Such approaches call for a diversification of our forests based on species' functional traits that will dramatically change the harvested species composition, volume, and output of our forested landscapes. This calls for the wood-building industry to adapt its ways of operating. Accordingly, we expand the evaluation of the ecological resilience of forest ecosystems based on functional diversification to include a trait-based approach to building with wood. This trait-based plant-building framework can illustrate how forecasted forest changes in the coming decades may impact and guide decisions about wood-building practices, policies, and specifications. We apply this approach using a fragmented rural landscape in temperate southeastern Canada. We link seven functional groups based on the ecological traits of tree species in the region to a similar functional grouping of building traits to characterize the push and pull of managing forests and wood buildings together. We relied on a process-based forest landscape model to simulate long-term forest dynamics and timber harvesting to evaluate how various novel management approaches will interact with the changing global environment to affect the forest-building relationships. Our results suggest that adopting a whole system, plant-building approach to forests and wood buildings, is key to enhancing forest ecological and timber construction industry resilience.

Keywords: building traits, resilience, construction ecology, functional diversity, forest management

Significance Statement

The proposed plant-building trait-based approach helps to characterize the consequential but understudied relationship between wood-building practices and forest ecosystem resilience and adaptability. This integrated trait-based approach reveals the urgent need to synchronize forestry and wood construction practices and provides tools to account for expected and unexpected changes. The results point to implications for environmental and economic planning, building technics, forest ecosystem health and diversity, and large-scale carbon cycle dynamics. The approach can be applied to different biomes and wood construction systems worldwide to assess and guide forest management and wood design initiatives that, only when considered together, can most fully enhance ecosystems' resilience and combined forest-building long-term carbon storage.

The impact of wood building on forests

Forests, particularly trees, are crucial components of the timber construction industry. Wood provides many functions in buildings, from structure to enclosure and insulation, and it is increasingly being relied upon in global efforts to decarbonize the construction industry through carbon storage in long-lived wood products (1, 2). Forests have historically been shaped by anthropogenic forces and managed to meet society's current and future needs (3). However, in service of our rapidly growing interest in using wood buildings as a global carbon sink, we remain unaware of the direct and indirect effects that global change drivers—climate warming, land-use change, and natural disturbances—will have on the intricately linked forests and wood-building systems. This rapid global change is creating an increasingly dynamic, uncertain, and unpredictable future for established timber and wood products, making long-term planning in forestry management and the viability of new and existing wood construction approaches challenging.

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While a multitude of approaches to forest management exist and are applied worldwide (3, 4), extant forest management practices are often dominated by a "command-and-control" or top–down approach driven by demand for a sustainable yield of timber optimized for wood construction and other short- and long-lived wood products (3). The wood-building industry has a long history of influencing silvicultural and management practices, promoting economic profitability and forestry efficiency through clearcutting, monoculture plantation, or silvicultural interventions that favored only a few merchantable tree species and the simplification of forests (5). Additionally, the rapidly increasing use of wood in tall construction and increased mechanization of forestry operations have accelerated the supply and demand for higher timber volumes, further exacerbating the simplification of forests and impacting everything from forest structure and composition to carbon and soil dynamics (6, 7). Timber products, such as cross-laminated timber (CLT), are one example of such high wood volume, monospecies wood products being promoted and advertised by the wood construction industry as a viable way to reduce the high emissions and carbon footprint of construction (8). Such pressure toward homogenizing forest structures and species composition across large landscapes negatively affects species diversity, putting forest ecosystems at greater risk of climate change and natural disturbance impacts. With the increasing uncertainty and disturbances affecting our forests due to global changes, such simplification of the forest poses a threat to its durability and capacity to adapt to rapidly changing environmental conditions. This forest homogenization poses broad concerns about ecosystem vulnerability (9) and limits what species could be used throughout not just the building industry but paper, plastic, and other industries as well.

Confronted with a changing and more uncertain future, several challenges must be incorporated into alternative forest management and wood-building approaches to ensure the resilience of both wood construction and forest systems. Here, we define resilience as the system's capability to resist, recover, or adapt following pulse and press disturbance (e.g. discrete events but also climate change) to continue providing key functions and services (10). Maintaining taxonomic, functional, and structural diversity in forest ecosystems has been shown to be essential to guarantee their resilience, and it is vital to ensure the carbon sequestration potential of forests and the provisioning of other ecosystem services we rely on (10, 11). For a more dynamic and complex way to approach the challenges of global change, forest management should contribute to overall ecosystem resilience to environmental stressors (12–14). However, this needs to be accompanied by a similar increase in the flexibility of wood-based industries/markets. Yet, while tree species richness is a good indication of the diversity of a community, it does not provide specific information about the diversity of biological functions and ecological services provided by the species present and therefore offers little guidance on environmental impacts on the harvest output and building capacity of a forest's timber. A recent approach advocates using species' biological characteristics, known as functional traits, that better match to ecosystem resilience and adaptability. Functional traits are morphological, physiological, and phenological plant characteristics that influence an individual's performance in terms of growth, survival, or reproduction (12, 13). Plant trait-based approaches scale up species traits to predict community- and ecosystem-level dynamics, responses to environmental change, and ultimately forest ecosystem response to management approaches and climate change (14).

Plant functional trait-based methods have been proposed to guide forest management practices focused on ecosystem services and functions (15) to better foster forest ecosystems' adaptive capacity (16). Messier et al. (17) have suggested the functional complex network approach as a pathway for forest managers to increase the resilience and adaptability of forest ecosystems. In broad terms, the functional complex network approach promotes the regeneration and/or plantation of functionally diverse tree species. It prioritizes such diversification efforts in those forest stands that contribute the most to the overall functional connectivity and landscape-level forest resilience. This approach has been illustrated by Aquilué et al. (18), who clustered tree species into functionally similar groups to compare the outcomes of favoring or planting functionally rare species in a southeastern (SE) Canadian forest landscape. The functional complex network approach has also been compared with traditional forest management approaches across a study region by Mina et al. (19) and was shown to increase ecological resilience to unexpected global change stressors. Yet, the functional complex network approach is not based on the needs of the wood industry, and such diversification poses a risk to the long-term viability of the building industry that historically relies on a few tree species to function efficiently.

In this paper, we expand the concept of plant functional traits to wood buildings. We evaluate if and how the building industry could use a functional trait-based approach to characterize wood's physical, mechanical, and building-related properties. Therefore, just as ecologists have moved from a species-centric model to functional traits, the wood industry needs to move from a species-centric organization of timber-building products and reorganize around building functional traits. The wood industry requires methods for describing the exchanges and functional linkages between forests and buildings; selecting wood-building practices that are aligned with the need to promote functionally diverse tree species, forests, and plantations; and identifying which tree species to harvest, in what proportion, and where (20, 21). To do so, we first need to better understand the viability of currently un- and underutilized wood species in construction and assess the impact of forestry management practices on harvest output and species composition. Finally, if we are to increasingly rely upon wood to decarbonize the construction industry, architects, engineers, and designers must deepen their understanding of the impacts that future environmental stressors will have on the harvest output and species composition of forests to help guide new methods and approaches for future wood construction.

The forest-building approach

We introduce the forest-building framework as a trait-based approach that couples plant and wood-building traits (Fig. 1). We expand a plant trait-based approach to include building traits to

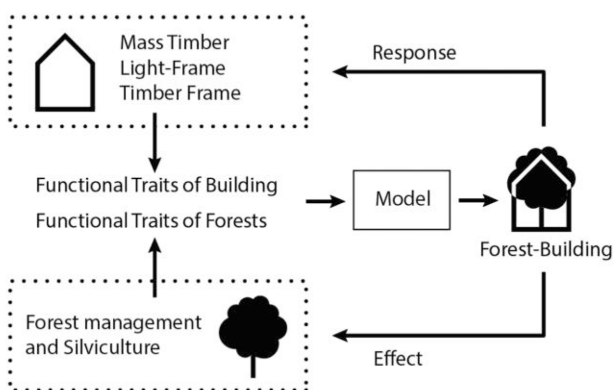

Fig. 1. Conceptual diagram of the forest-building approach.

Table 1. List of 35 eastern North American tree species (either present—marked in bold—or with potential in the reference landscape) by building groups, key characteristics, and common uses. Species in bold are those currently present in the region.

Building group	Key characteristics	Species	Common uses
BG1	Conifers, low density, average max height, average diameter at breast height (DBH), low shrinkage, soft and low mechanical strength	***A. balsamea***, ***T. canadensis***, ***P. strobus***, ***T. occidentalis***	Construction lumber, paper (pulpwood), plywood, and other utility wood purposes
BG2	Conifers, med-high density, average max height, low DBH, medium shrinkage, average compression and hardness, average mechanical strength	***P. abies***, *P. taeda*, *P. rigida*, ***P. glauca***, ***P. rubens***, *P. mariana*, ***P. resinosa***	Utility poles, posts, railroad ties, paper (pulpwood), and construction lumber
BG3	Deciduous, medium density, average max height, medium DBH, high shrinkage, high compression and hardness, high mechanical strength	***Larix laricina***, *Prunus serotina*, *Betula populifolia*	Utility poles, posts, rough lumber, boxes/crates, and paper (pulpwood)
BG4	Deciduous, medium density, medium max height, medium DBH, high shrinkage, medium compression and hardness, medium mechanical strength	***A. rubrum***, *U. americana*, *B. papyrifera*, *Q. macrocarpa*, *F. americana*, *J. nigra*	Veneer, paper (pulpwood), boxes, crates/pallets, musical instruments, turned objects, and other small specialty wood items
BG5	Deciduous, low density, low to high max height, medium to high DBH, medium shrinkage, low to medium compression and hardness, low mechanical strength	*Acer saccharinum*, ***Populus tremuloides***, ***Populus grandidentata***, *Tilia americana*, *Liriodendron tulipifera*	Boxes/crates, veneer, plywood, and various utility purposes
BG6	Deciduous, medium to high density, low to medium max height, average DBH, high shrinkage, high compression and hardness, high mechanical strength	*Quercus rubra*, *Quercus velutina*, *A. saccharum*, *Fagus grandifolia*, *Quercus alba*, *Quercus coccinea*	Cabinetry, furniture, interior trim, flooring, and veneer
BG7	Deciduous, low density, medium to high max height, average DBH, medium shrinkage, medium compression and hardness, low mechanical strength	*B. alleghaniensis*, *Betula lenta*, *Carya cordiformis*, *Carya glabra*	Veneer, plywood, interior trim, furniture, and paneling.

characterize the performance of tree species in timber building. This plant-building trait-based approach is conceived to reveal the changes in forest management and wood construction needed to develop more resilient forest ecosystems and wood construction industry in response to global change. To do so, we extend the plant trait-based functional complex network approach to forest management introduced by Messier et al. (17) and Aubin et al. (22) to explicitly consider timber production for buildings. Previous research has relied on the functional network approach to enhance the overall adaptive capacity of forest ecosystems to uncertain future environmental conditions (17–19, 22, 23). Through an analysis of forest- and building-related indicators, one can characterize the "push," the impact climate change, natural disturbances (18, 21), and/or various forest management approaches have on forest harvest output volume, species composition, and wood-building capacity, and the "pull," the landscape-scale impacts of extant silvicultural practices driven by demand from the specific wood construction techniques of any forest-building system. Understanding these whole system impacts will help planners, forest managers, and builders work together to achieve more resilient forests and wood construction systems (24).

The functional traits of buildings refer to the characteristics of wood design, manufacture, construction, maintenance, and end-of-life processes which influence various performative characteristics in wood construction. The species that share similar building traits can be clustered into groups based on the resemblance of their traits rather than their genus or family (Table 1 and Tables S1 and S2). The main advantage of clustering species into functional building groups is that it provides a meaningful way to identify species with similar building traits. This clustering simplifies the application of wood construction specification and decisions to support the substitution of species which promote more functionally diverse forests and plantations. This is accomplished by substituting species with similar building traits yet different ecological traits (Tables 1 and 2). By clustering species into groups with similar building traits, builders and architects can specify wood from within a particular group that has similar utility in building while also providing an understanding of the interaction between ecological and construction-related traits (Fig. 2). Of course, no single tree species can tolerate all environmental stresses simultaneously nor can they be used in all building applications, and our approach is built upon this very idea. Whereas extant practices based on optimizing tree species useable in construction rely on choosing trees with known building applications (often based on professional opinion and historical practices) and for which tools and data are available (25, 26), maximizing the resilience and adaptability of forest ecosystems is based on increasing the variance of traits that reflect the diversity of fundamental ecological strategies to cope with known and unknown stressors (27, 28) and maintaining ecological processes and services and relies on building practices to adapt to these changes.

As a case study, we illustrate how to apply the forest-building framework across the Central Quebec region, a fragmented rural landscape with mixed temperate/boreal forests in SE Canada previously studied in Mina et al. (19). Using the process-based forest landscape model LANDIS-II (29), we simulated long-term forest dynamics (2010–2200) under different climate scenarios (current, warm, and hot). We analyzed the harvested timber outputs considering three management alternatives to the business-as-usual (BAU). The first scenario followed a climate change adaptation (CCA) approach that promotes a few drought-tolerant species without explicitly considering other functional traits. Two additional scenarios were simulated and followed the functional diversification network (FDN) approach, aiming at ensuring and maximizing the representation of all functional traits as a means

Table 2. List of 35 eastern North American tree species (either present—marked in bold—or with potential in the reference landscape) by ecological groups and key characteristics. For details, see Mina et al. (19) and Aquilué et al. (23).

Ecological group	Key characteristics	Species
CON-Bor	Conifers, late seral, intermediate to drought intolerant	***A. balsamea***, ***P. abies***, ***P. glauca***, ***P. mariana***, ***P. rubens***, ***P. strobus***, ***T. occidentalis***, ***T. canadensis***
CON-Pin	Conifers, early seral, drought tolerant	***P. resinosa***, *P. rigida*, *P. taeda*
NHW-Es	Northern hardwoods, early to mid-seral	***B. alleghaniensis***, *B. lenta*, ***B. papyrifera***, ***B. populifolia***, *P. serotina*
NHW-Ms	Northern hardwoods, mid to late seral, resprout	***A. rubrum***, *A. saccharinum*, ***A. saccharum***, ***F. grandifolia***, *U. americana*
NDC-Es	Northern deciduous, early seral, low seed mass	***L. laricina***, ***P. grandidentata***, ***P. tremuloides***
CHW-Ms	Central hardwoods, mid-seral, tap root, resprout	*C. cordiformis*, ***F. americana***, *J. nigra*, *L. tulipifera*, *T. americana*
CHW-Dt	Central hardwoods, early seral, drought tolerant, high seed mass	*C. glabra*, *Q. alba*, *Q. coccinea*, *Q. macrocarpa*, *Q. rubra*, *Q. velutina*

to increase ecological resilience. The FDN scenarios were simulated with two different levels of landscape-scale harvesting intensities (FDN15 and FDN25; see details below). We then analyzed the harvested output to show the impact of different forest management practices and changing climate on species composition and current and future wood construction practices. We conclude by proposing practical recommendations for adapting current forest management and timber-building strategies to challenges associated with global drivers of environmental change in our study landscape, provide guidelines for extrapolating the forest-building approach in other forested regions, and discuss the potential of the forest-building framework to foster the resilience and adaptability of forests through wood building.

Results

We conducted our experiment by comparing the harvest output and harvested species composition for management treatments under selected climate change scenarios. This approach allowed us to explore the harvest output of each species and building group under increasing levels of climate-induced stress at the landscape level.

Forest-building trait interaction

Figure 2 shows the interaction between ecological and building groups in the study region. We found that the species primarily used in construction (BG1 and BG2) belong to only two ecological groups (CON-Bor and CON-Pin). BG1 and BG2 gather coniferous species (*Abies balsamea*, *Tsuga canadensis*, *Pinus strobus*, *Thuja occidentalis*, *Picea abies*, *Pinus taeda*, *Pinus rigida*, *Picea glauca*, *Picea rubens*, *Picea mariana*, and *Pinus resinosa*) from the CON-Bor and CON-Pin ecological groups. Each building group has drought-tolerant, intolerant, shade-tolerant, and intolerant species, so they are somewhat diversified (Table 2). Other species that may reduce fire spread (deciduous) and bring more resilience to insects known to affect conifer forests are missing from these groups. This implies that species used in construction may be limiting the ecological response of forests and plantations where they grow. In contrast, BG4 has a more diverse interaction between building and plant functional groups, as it includes a variety of deciduous/hardwood species from four separate ecological groups. *Acer rubrum* and *Ulmus americana* are northern hardwoods, mid to late seral, and resprouting (NHW-Ms). *Betula papyrifera* is a northern hardwood, early to mid-seral (NHW-Es). *Quercus macrocarpa* is a central hardwood, early seral, drought-tolerant, and high seed mass (CHW-Dt). While *Fraxinus americana* and *Juglans nigra* are Central hardwoods, mid-seral, tap root, and resprouting (CHW-Ms).

Changing forest harvest output and functional composition

Figure 3 shows the harvest output and species composition according to building groups for the study region over a simulated period of 190 years. Implementing CCA and FDN forest management and silvicultural practices was shown to have increased harvest output by up to 40% over the study duration when compared with current methods (BAU). The increased harvest output for the CCA and FDN approaches can be attributed to practices which increased the harvesting of species with abundant functional trait redundancy (shared functional traits carried by multiple species), followed by the planting of species from ecological groups not currently present in the region that improve the long-term resilience of the forested landscapes as well as harvest output of species not targeted within BAU. The relationship between increased harvest output and increased forest functional diversity is further exemplified when comparing the CCA and FDN approaches (see supplementary material Section 3 and Table S3). The FDN15 scenario shows an increase in total harvest output of between 20 and 35% when compared with CCA, depending on the severity of the climate change scenario. Furthermore, increasing the harvest rate of the FDN approach from 15 to 25% over 5 years (FDN15 and FDN25, respectively) was previously shown to improve functional diversity and network connectivity (22), and our results demonstrate that such approaches will also increase harvest output across the study region by 20% across all climate scenarios.

While our results show that CCA and FDN promise to increase harvest output across all climate scenarios, they also result in significant changes in harvested species composition toward many under- and nonutilized wood species when compared with BAU. Over the study period, climate warming resulted in declining harvested output for common cold-adapted, drought-intolerant softwood construction species (BG1). The decline was counteracted by an increase in drought-tolerant softwood species (BG2) and in noncommercial hardwoods (BG4 and BG5). Regardless of the climate change scenario, the total harvested output of construction species (BG1 and BG2 combined) for each management scenario remained relatively constant over the study period. The maintenance of combined harvest output for BG1 and BG2 can be attributed to silvicultural and management practices, supporting planting species more resilient to climate change than those grown under the BAU strategy. Previous studies have shown that in mixed temperate forests, such as our study region, increased forest productivity and harvest output may be due to the planting of species suited to a longer growing season, rising mean temperature and CO_2 concentration, and a moderate increase in precipitation (21, 30). For FDN15 and FDN25, the dominant construction species of the study region shifts from *A. balsamea* (BG1) to a mixture of species from BG1 and BG2 and

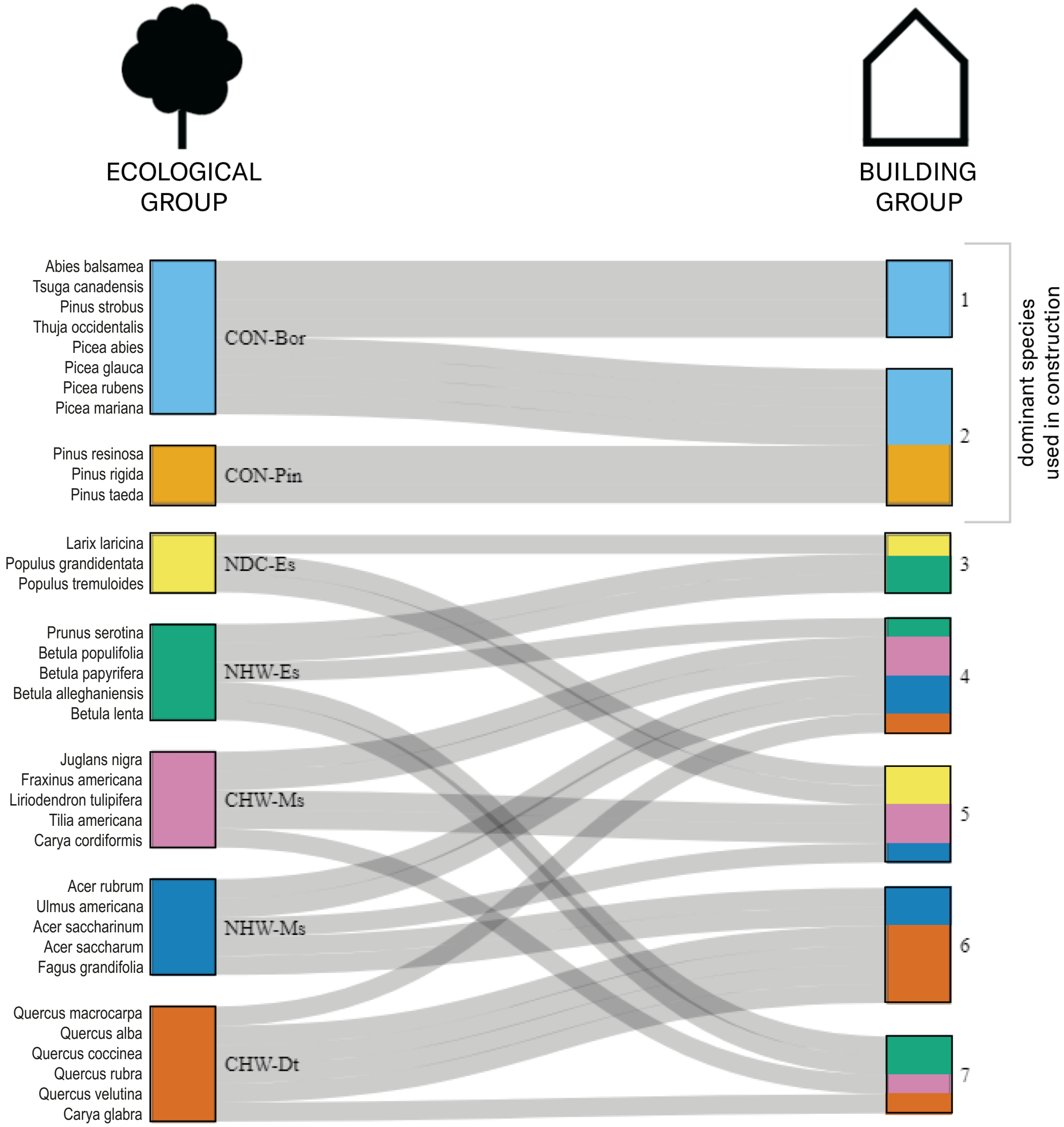

Fig. 2. The interaction between ecological and building groups. By clustering tree species into groups with similar building traits, builders and architects can specify wood from within a particular group that has utility in building and simultaneously support the goals of maximizing the ecological resilience and adaptability of the forests. See Tables 1 and 2 for species and key characteristics of building and ecological groups. For further information on the trait selection and clustering methods, see supplementary material Section 1.

finally to *P. resinosa* (BG2). In contrast, the species transition for CCA maintains a high mix of softwood species (BG1 and BG2), while BAU shifts primarily to *P. glauca* (BG2).

The most significant factor increasing harvested output for the study region was an increase in harvested output of hardwood species in response to climate warming. Our results show an increased harvest output of hardwood species, from BG4 and BG5 in particular, across all management scenarios: BAU 15–36%, CCA 13–32%, and FDN 16–42%. The hardwood species also experienced a composition change, with *A. rubrum* declining significantly throughout the study and being replaced by a diverse mix of northern and central hardwood species. These findings indicate that introducing or promoting a few key species with various plant functional traits (e.g. oaks, pines, and other selected hardwoods included in BG3–7) may significantly increase the harvest output of all building functional groups all without reducing the provisioning of dominant species currently used in building (BG1 and BG2).

Discussion

Studying and managing buildings and forests as a coupled human and natural complex system (31) contrasts past and current closed-system methods of today's forestry and building industries, evident in both foresters' and builders' tools and techniques (32). For example, architects and builders often uncritically promote the increased use of wood for its apparent ability to sequester carbon over the long term. Conversely, many foresters and

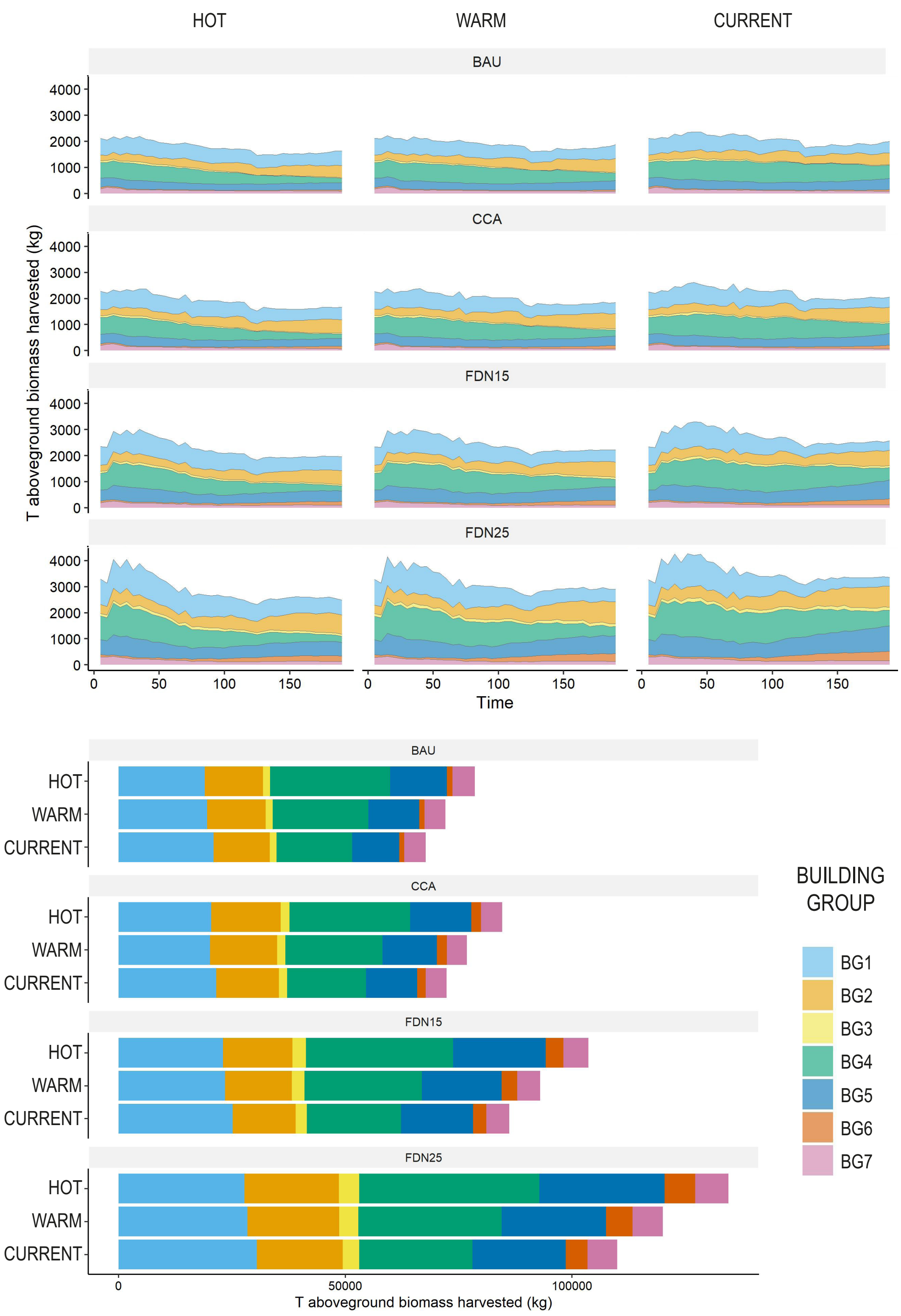

Fig. 3. Above: aboveground biomass harvested (kg*10^3) by species building functional group (Table 1) under the different scenarios (columns, climate; rows, management treatment). Below: Total harvested biomass (kg*10^3) for the study period (190 years) organized by building groups. For aboveground biomass harvested by ecological functional group, see Fig. S4.

conservationists would argue forests are critical terrestrial systems for carbon sequestration and climate change mitigation (33). Each group's response is framed by tools and methods which not only reinforce disciplinary boundaries but also treat both forests and buildings as isolated systems in ways that not only fetishize carbon but do so in a way that prevents them from actualizing the greater potential of an open, synchronized, complex forest-building system (24). Such methodological limitations of closed-system approaches will prevent many positive insights into the biophysical mitigation potential of wood construction systems. The forest-building framework proposed here addresses both points, using state-of-the-art models of forest ecosystem dynamics and a novel trait-based approach to building to evaluate climate change and forest management scenarios' impacts on harvest outputs and, therefore, wood availability in the near future. We find the following:

- We need diverse forests for resilience to global change, just like we need diverse timber economies, products, and futures. To do so, it requires a coupled model of forest-building.
- Extant wood species used in construction are not resilient to global change (Fig. 2). Species used in wood construction must be diversified to increase the ecological resilience of forests and plantations and the socioeconomic resilience of the whole coupled system.
- Global change drivers such as climate warming will make harvest volume and species compositions of forests and plantations increasingly variable (Fig. 2). Wood construction must be more flexible, adjusting and adapting to forest output capacities as well as to the need of a more functionally diversified forest to guarantee ecological resilience, not the other way around.

There are many other considerations architects, designers, wood mills, manufacturers, and other wood-building stakeholders will need to navigate to become more resilient and adaptable to the pulsing spatiotemporal dynamics of each tree species throughout their region as climate changes (34). For example, under current management approaches (BAU), the harvest output of extant species used for wood building will gradually decline. In contrast, climate-adapted species not currently used in wood buildings, including select softwoods (BG2) and hardwood (BG3-BG7), will increase relative abundance. In contrast, under alternative approaches (e.g. CCA and FDN), extant species used in construction (predominately BG1 and BG2) may experience a significant period of higher harvest output (0–50 years) due to their abundance in the study region. This pulse of high BG1 and BG2 harvest is followed by a long period of decline (50–190 years). The species planted to replace those harvested come from less abundant ecological groups to promote changes in forest composition. Therefore, if the construction industry relies on a limited selection of wood species, then the risk of such an uncertain future harvest output is significant when evaluating future wood-building strategies.

Two possible ways the wood industry can approach this uncertainty in harvest output and harvest species compositions are (i) a more dynamic and flexible approach to wood utilization and (ii) increasing wood construction system adaptability to wood species not currently used (BG3-BG7). There are several ways to achieve a dynamic approach to wood utilization. First, wood harvest output can be matched with wood construction type. During periods of high harvest output, it may be beneficial to adopt construction systems with high wood utilization and long life cycles, such as mass timber (Fig. 4a–d). While on the other hand, in periods of low wood harvest, low wood volume utilization strategies, such as light-frame construction, may be preferable to ensure the wood harvested can supply the demand from the construction industry (35). While producing fewer wood buildings might seem like a suitable option, this may not be desirable as one of the primary benefits of wood is the substitution effect of not building with higher emitting types of construction (24, 36). Adaptable material systems, and adaptable timber production facilities, are thus critical in a carbon-neutral world.

A second complementary option is to increase the tolerances of the wood construction systems to accept species not currently used in construction (BG3-BG7). While some of these species are unsuitable for building, more hardwood species should be considered for use as structural members in post and beam construction and in many architectural finishes, cabinetry, and veneers. Recent research into novel wood products such as mixed species CLT panels, wood fiber insulation, and other engineered wood products show a promising direction for increasing the full spectrum of possible harvest outputs, making both wood products and buildings more resilient and adaptable to changes in harvest output and species composition (37–39). Finally, as one of the longest-lived wood products, wood buildings have the potential to sequester carbon, otherwise likely to be emitted through other wood utilization approaches (24). Therefore, finding new ways to use a more diverse species composition in wood construction stands to significantly increase total wood-building carbon sequestration across the study region and will need future investigation.

Implications of forest-building system management and future perspectives

We have shown that future global changes impacting forested landscapes' ecological adaptability and resilience (22) may lead to significant changes in harvest output and species composition, which would undoubtedly impact the building industry. Yet, by extending the plant trait-based approach to include building-related properties, the wood industry and forestry stakeholders can now synchronize the functional traits of species across the whole lifespan from the forest to the building by designing new products and specifying low-value and underutilized species with desired ecological characteristics that increase the functional resilience of the forest ecosystems. This mutually beneficial interaction lies at the heart of the forest-building approach. This framework is fundamentally at odds with the current "command-and-control" paradigm in forestry and construction (5). We demonstrate that designing forest-building landscapes as functionally rich, well-structured complex networks can increase ecological resilience to climate change while maintaining or increasing the harvested biomass output needed to support the increasing demands of wood building. Yet, to do so, wood-building practices must change to become resilient and adaptable to a more temporally dynamic and species-diverse harvest output (Fig. 4b). Recent work into the utilization of restoration pine in California shows a promising direction for further research (Fig. 4d). Grouping tree species into a few forest-building groups dramatically simplifies the ability for builders to select an appropriate mixture of wood to use in building according to the harvest output that best supports forest ecological resilience and maximizes functional diversity. Future work is necessary to better assess and characterize the building traits of many wood species; yet, the results provided in this paper will help promote research into the development of underutilized or not utilized tree species that are likely to be favored in different regions of the world as we are adapting our silviculture to promote a greater diversity of tree species with highly diverse functional traits.

Materials and methods

Study area

We conducted our study in the Central Quebec region of SE Canada (Fig. 5). Located between the northern Appalachian

Mountains and the St. Lawrence River, this 692,600 ha region is typical for temperate biomes in North America and is a rural mosaic of forest stands (~50% of the surface), croplands, and development. The humid continental climate has an extensive seasonal temperature range and relatively abundant annual precipitation without a dry season. Vegetation transitions from northern hardwoods to mixed wood with southern boreal conifers. The study region is dominated by northern deciduous tree species (primarily maples from BG4) with patches of monoculture conifer stands (BG1) resulting from past anthropogenic disturbances, including harvesting (40). Currently, the most abundant tree species are maples (*A. rubrum* and *Acer saccharum*), balsam fir (*A. balsamea*), and yellow birch (*Betula alleghaniensis*).

Functional traits, building traits, and clustering

To illustrate the forest-building approach, we organized the 35 tree species in the study region and 42 other species found in neighboring forested ecoregions across Canada and the United States according to their ecological and building traits. Including additional species allowed us to cover a more extensive array of traits and functions from species with the potential to grow in the study area while providing a more expansive representation within each functional group. For the plant traits, we used the same nine traits of fundamental ecological importance and descriptors of resistance to and recovery capacity from natural disturbances previously applied to evaluate the management approaches in the study area (19)—wood density (stem dry mass per stem fresh volume, g cm^{-3}), leaf nitrogen content per leaf dry mass (mg), seed dry mass (g cm^{-3}), maximum tree height (m), leaf area per leaf dry mass (specific leaf area, m^2 kg^{-1}), leaf phenology type (evergreen/deciduous), root architecture (tap/shallow), tolerance to drought (index: 1 [intolerant] to 5 [tolerant]), and tolerance to shade (index: 1 [intolerant] to 5 [tolerant]). To characterize each species for building, we selected functional traits of relevance for wood construction. Wood properties of concern in construction relate to physical properties, mechanical properties, natural durability and treatability of wood, preservative treatment, fire safety, bonding, finishing, and workability (8). We selected 10 building traits: wood density (stem dry mass per stem fresh volume, g cm^{-3}), height (m), diameter (m), wood shrinkage (radial, tangential, and volumetric), modulus of rupture (kPa), modulus of elasticity (kPa), compression parallel to grain (kPa), and side hardness (N). Traits relevant for each property are summarized below: While important building traits such as rot resistance and fire resistance are available for species commonly used in construction, most of the species in our study currently have low utilization in construction and have yet to be studied; for more details on the clustering methods, trait selection, and data sources, see supplementary material Section 1.2.

We clustered all 77 species into 2 grouping systems. The first grouping was based on plant functional traits and the second on building traits. The clustering is based on two dissimilarity matrixes that gather how to reassemble any pair of species, ecologically and for building, respectively. Applying distance measures to both dissimilarity matrixes (18, 23) clustered the 77 tree species into 7 ecological on the one hand and 7 building groups on the other hand (BG1-7) (Fig. 2, Figs. S1 and S2, and Tables 1 and 2). The ecological groups were categorized as follows: late seral, drought-intolerant conifers (Con-Bor); early seral, drought-tolerant conifers (Con-Pin); early- and mid-seral northern hardwoods (NHW-Es); mid- and late seral northern hardwoods (NHW-Ms); boreal deciduous pioneers (NDC-Es); mid-seral central hardwoods (CHW-Ms); and drought-tolerant central hardwoods with large seed mass (CHW-Dt). Similarly, each building group contains species which share key characteristics and common uses in construction (Table 1 and Fig. S3). Building groups 1 through 5 were represented by some of the 35 species currently present in the landscape, while building groups 6 and 7 gather species that are not now present in the study region and only introduced through the management treatments of the CCA and FDN (see Table 1 and Fig. 1). The three most abundant groups were soft conifers (BG1 and BG2, predominantly pine and fir) and medium-hard deciduous species (BG4, maples and birches). For further details on trait selection and clustering methods, see supplementary material Section 1.

Model description and experimental design

We used LANDIS-II, a spatially explicit, process-based forest landscape model to simulate future forest development and evaluate potential harvest outputs (29). This model can simulate forest successional dynamics in interconnected grid cells integrating stand- and landscape-scale processes such as succession, management, and disturbances. LANDIS-II has been extensively applied and evaluated in multiple landscapes across North America (41–43). LANDIS-II is built on a core module interacting with multiple extensions to represent ecological processes or generate specific output data. To simulate forest succession—regeneration, growth, competition for resources, and mortality—we used the PnET-Succession v3.4 extension (29). This ecophysiological submodel incorporates the direct effects of environmental drivers (e.g. temperature, precipitation, solar radiation, and CO_2) on forest dynamics, and thus, it is well suited to model responses to novel climate conditions. Details of the parameterization, calibration, and evaluation of LANDIS-II for the study area are found in Diaz-Balteiro et al. (27), and the design and implementation of the management and climate scenarios are given in the online supplementary material, with further details also given in Mina et al. (19) and Aquilué et al. (23).

Climate scenarios

The focus of this study is not to study the impact of climate change on forests but to assess the effects of silviculture and forest management practices under various future projections to illustrate the uncertainty of harvest output, species composition, and the need for a more integrated and adaptable forest-building system. We applied the same climate change projections and scenarios used previously in this study region by the authors (19). Future forest dynamics were simulated with projected climate scenarios based on standard Representative Concentration Pathway (RCP) emission scenarios (IPCC, 2013) as simulated by the Canadian Earth System Model version 2 global circulation model (CanESM2; (44)). We compared a scenario of current climate, representing the continuation of normal climate conditions (1961–2000), with two hypothetical future climates: (i) moderate emissions (RCP 4.5: approximately +5°C mean annual temperature in 2081–2100 relative to 1961–2000, slight increase of annual precipitation, and intermediate rise in CO_2 levels; warm) and (ii) high emissions (RCP 8.5: approximately +8.5°C, slight increase of annual precipitation, and drastic increase of CO_2 levels; hot). See supplementary material Section 2 for details about preparing climate scenarios and choosing the climate model and emission projections.

Management scenarios

The effect of forest management treatments—harvesting and planting—in LANDIS-II was implemented using the Biomass-Harvest

Fig. 4. a) Mass timber manufacturing facility near the study region (Art Massif, Saint-Jean-Port-Joli, Quebec) and b) test samples of a mixed hardwood veneer and glulam beam (photos: Osborne et al. (48)). c) Sample of a custom CLT panel utilizing low-value ponderosa pine (38). Popular industry CLT panel manufactured with black spruce (90% by volume) and other common building spies (spruce, pine, and fir; typically known as SPF).

extension v4.3 (45). This module removes biomass based on user-defined prescriptions, determining priority cohorts to harvest, as well as the percentage of the area suitable for harvesting/removal at each time step within a management unit (46). Four management strategies were considered in our simulation experiment: BAU, CCA, and two variants of the FDN approach (FDN15 and FDN25). BAU was designed to reflect conventional forest practices in the region, aimed at sustaining current timber demand from various short- and long-lived wood product industries. The CCA treatment seeks to transform current practices to adapt forest ecosystems to a changing climate. It increased compositional diversity by promoting tree species better adapted to a warmer climate via enrichment planting. The FDN treatment aimed at enhancing compositional diversity, widening the spectrum of functional traits in tree communities, and boosting functional connectivity by prioritizing increased harvesting, enrichment planting, and assisted migration across the landscape, based on the principles of the functional complex network approach (17). The FDN management strategy involved harvesting the most abundant species from well-represented functional groups to promote the regeneration of species from less represented groups or to enrich forest stands with new species from less represented groups through assisted migration. BAU and CCA subdivided the region into management units based on ownership, with similar silvicultural prescriptions applied in private and public forests. For BAU, CCA, and FDN15, landscape management intensity reflected harvest levels across the region (~15% of the forest landscape was made allowable for harvesting every 5 years). For FDN25, we increased the management intensity to reflect harvest levels necessary for the enrichment planting of an additional 10 species with functional traits absent in our landscape but present in neighboring bioregions (25% allowable harvesting every 5 years). Further explanations on individual silvicultural prescriptions, data, and assumptions behind the design of the management scenarios as well as the functionality of the harvesting module are available in supplementary material Section 3 and Table S1.

Study design and future work

Simulations were run across the forested region on a 1 ha grid over 190 years (2010–2200). To evaluate functional and compositional changes in the forest harvest output, we assessed aboveground biomass by forest-building functional group. While significant disturbances that could affect harvesting (and salvage logging) are not included in this study, we added a low-impact harvesting

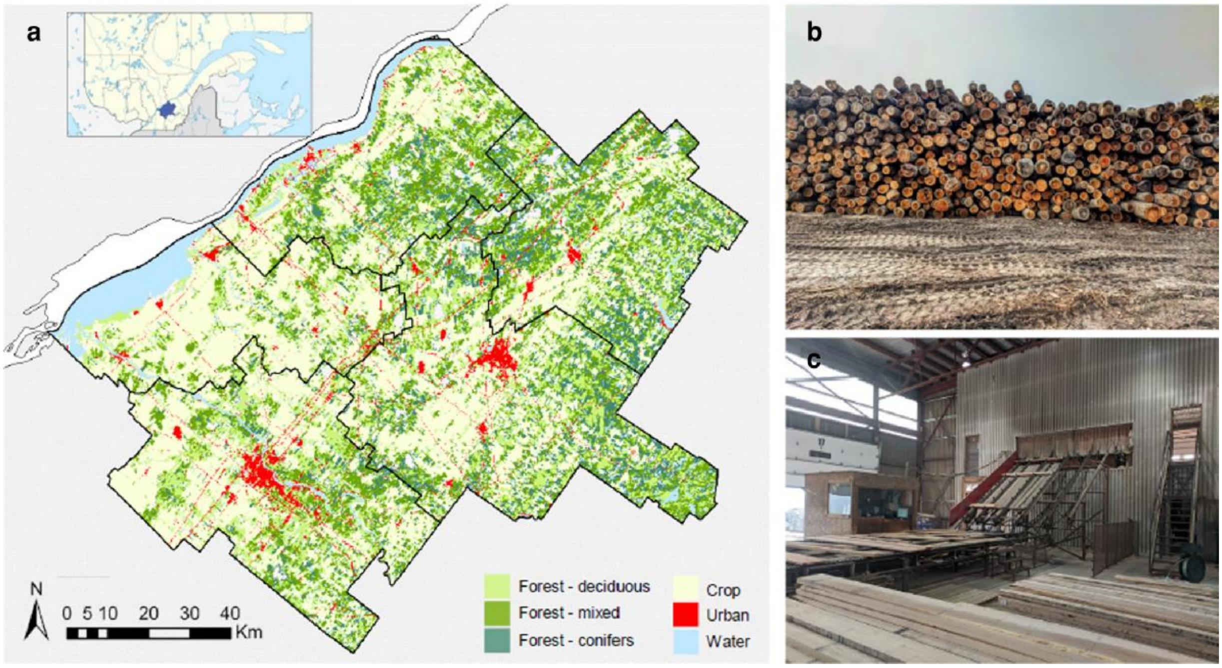

Fig. 5. a) Central Quebec study area in SE Canada. b) Spruce, pine, and fir logs aging before (c) typical softwood milling seen throughout the region (photos: Osborne et al. (48)).

prescription called "background disturbance," in which some cells are randomly disturbed to emulate disturbances typical to the region (e.g. small windthrow events and small-scale mortality) and to add some variability to the model runs (19, 21). Biomass from these "background disturbances" was not included in calculating harvesting outputs for species or building groups.

Additionally, our study assumes all biomass harvested would be suitable for use in wood buildings. Efforts to increase forest diversity described above require further analysis of tree species' suitability to different wood construction systems and vice versa. The species, utilization efficiency, volume, and lifespan of the wood in each category would influence the resilience and longevity of wood buildings and require further investigation. The main limitation of our analysis was the lack of specific trait data for species and various building-related traits. While we characterized all species in the study location according to their building traits, building-specific traits such as fire resistance, rot resistance, and workability were only available for species most commonly used in construction (47). Additionally, many indices, such as flame spread index, have not been consistently applied across the literature, and future work is required to make them suitable for the forest-building approach.

Supplementary material

Supplementary material is available at *PNAS Nexus* online.

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Author contributions

P.O. conceived and planned the research. P.O. prepared the building trait data, performed building trait clustering with support from N.A., and built tools for analyzing the harvest output. N.A. provided ecological trait data and clusters. M.M. designed harvest scenarios and ran simulations. P.O. analyzed outputs and interpreted the results with support from N.A., M.M., K.M., M.J., and C.M.. P.O. led the writing of the manuscript with editorial support from all authors.

Data availability

The data that support the findings of this study (model input files and trait data) will be permanently archived in the Zenodo digital repository. A version of the model input data is already available at https://doi.org/10.5281/zenodo.8184010. Technical model documentation of LANDIS-II and its extensions is available at https://www.landis-ii.org/. The code of the simulation model is distributed under an open-source license and is freely available at https://github.com/LANDIS-II-Foundation.

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