# Forest-Building: a new approach for the integrated design of forests and buildings

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## Abstract

Along with forest managers, architects and 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, this dissertation expands 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 is used illustrate how forecasted forest changes in the coming decades may impact and guide decisions about wood-building practices, policies, and specifications.

The objectives of this dissertation thesis are twofold. First, to develop methodological approaches for exploring how different wood construction systems respond to changes in forest management, natural disturbances and climate change, this I call Forest-Building. Second, to provide tools for the wood construction industry and designers on how to adapt their practices to better support more resilient and adaptable forest landscapes facing global changes. To address these challenges, a Forest-Building impact assessment approach was developed to model the effects of wood construction on forest ecological resilience. This includes: (1) the development of the Forest-Building and functional building traits concept; (2) applying the functional building traits concept to evaluate the resilience and adaptability of wood construction approaches; and (3) the development of a dynamic Forest-Building carbon model to compare the carbon sink potential of existing and resilient wood construction approaches under increasing climate change and forest management approaches.

Part 1 introduces the functional building traits concept and provides the foundation of Forest-Building approach and its use at the core of a plant-trait based approach to wood construction. Seven functional groups based on the ecological traits of tree species in the region are linked to a

similar functional grouping of building traits to characterize the push and pull of managing forests and wood buildings together. A process-based forest landscape model was used 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 provisioning of wood for the construction industry.

Part 2 investigates the potential of the building-traits concept and outlines how to apply this plant-trait based approach to assess the resilience of existing wood construction approaches. It was found that the dominant approaches being used to offset construction industry emissions (such as single species CLT) are not resilient to climate change and alternative forest management approaches and may only be suitable in very limited regions. The results reveal the need to diversify the wood construction industry with key building and ecological traits to bring important benefits in terms of social and ecological adaptation.

Finally, Part 3 applies a multi-scale land-based biogenic carbon assessment of a combined Forest-Building system based on traits of different species and the adaptability of wood construction approaches. 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 and increasing regional forest and building carbon sinks.

**Résumé**

Aux côtés des gestionnaires forestiers, les architectes et les constructeurs sont des agents clés du changement de la structure et de la composition des écosystèmes forestiers par la spécification et l'utilisation des produits du bois. De nouvelles approches de gestion forestière sont préconisées pour accroître la résilience et l'adaptabilité des forêts au changement climatique et à d'autres perturbations naturelles. De telles approches appellent à une diversification de nos forêts basée sur les traits fonctionnels des espèces qui modifieront radicalement la composition, le volume et la production des espèces récoltées de nos paysages forestiers. Cela oblige l'industrie de la construction en bois à adapter ses modes de fonctionnement. En conséquence, cette thèse élargit l'évaluation de la résilience écologique des écosystèmes forestiers basée sur la diversification fonctionnelle pour inclure une approche basée sur les traits de la construction en bois. Ce cadre de construction végétale basé sur les traits est utilisé pour illustrer comment les changements forestiers prévus dans les décennies à venir peuvent avoir un impact et guider les décisions concernant les pratiques, les politiques et les spécifications de construction en bois.

Les objectifs de cette thèse sont doubles. Tout d'abord, développer des approches méthodologiques pour explorer comment différents systèmes de construction en bois réagissent aux changements de gestion forestière, aux perturbations naturelles et au changement climatique, ce que j'appelle la construction forestière. Deuxièmement, fournir des outils à l'industrie de la construction en bois et aux concepteurs sur la façon d'adapter leurs pratiques pour mieux soutenir des paysages forestiers plus résilients et adaptables face aux changements mondiaux. Pour relever ces défis, une approche d'évaluation de l'impact de la construction forestière a été développée pour modéliser les effets de la construction en bois sur la résilience écologique des forêts. Cela comprend : (1) le développement du concept de construction forestière et des traits fonctionnels des bâtiments ; (2) l'application du concept de traits fonctionnels des bâtiments pour évaluer la résilience et l'adaptabilité des approches de construction en bois existantes ; et (3) le développement d'un modèle dynamique de carbone de construction forestière pour comparer le potentiel de puits de carbone des approches de construction en bois existantes et résilientes dans le cadre de changements climatiques et d'approches de gestion forestière croissants.

La partie 1 présente le concept de traits fonctionnels des bâtiments et fournit les bases de l'approche de construction forestière et de son utilisation au cœur d'une approche de la construction en bois basée sur les traits végétaux. Sept groupes fonctionnels basés sur les traits écologiques des espèces d'arbres de la région sont liés à un groupement fonctionnel similaire de traits de construction pour caractériser la poussée et l'attraction de la gestion conjointe des forêts et des bâtiments en bois. Un modèle de paysage forestier basé sur les processus a été utilisé pour simuler la dynamique forestière à long terme et la récolte du bois afin d'évaluer comment diverses nouvelles approches de gestion interagiront avec l'environnement mondial en évolution pour affecter l'approvisionnement en bois pour l'industrie de la construction.

La partie 2 étudie le potentiel du concept de traits de construction et décrit comment appliquer cette approche basée sur les traits végétaux pour évaluer la résilience des approches de construction en bois existantes. Il a été constaté que les approches dominantes utilisées pour compenser les émissions de l'industrie de la construction ne sont pas résilientes au changement climatique et aux approches alternatives de gestion forestière et peuvent ne convenir que dans des régions très limitées. Les résultats révèlent la nécessité de diversifier l'industrie de la construction en bois avec des traits de construction et écologiques clés afin d'apporter des avantages importants en termes d'adaptation sociale et écologique.

Enfin, la partie 3 applique une évaluation du carbone biogénique terrestre multi-échelle d'un système combiné forêt-bâtiment basé sur les traits de différentes espèces et l'adaptabilité des approches de construction en bois. Nos résultats suggèrent que l'adoption d'une approche globale de système, de construction végétale pour les forêts et les bâtiments en bois, est essentielle pour améliorer la résilience écologique des forêts et de l'industrie de la construction en bois et pour augmenter les puits de carbone régionaux des bâtiments.

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I gratefully thank my research collaborators, Dr. Núria Aquilué and Dr. Marco Mina for supporting my research with technical advice related to the modeling of the functional complex network approach, trait clustering and LANDIS II. Further gratitude goes to Dr. Sheng Xie for the time spent with me working in the ANSE modeling framework required for my final chapter. I look forward to future research collaborations to come.

Finally, I want to give thanks to my wife, Alex, for her unending support and love that has got me through the difficult task of concluding my research.

## Contribution of Authors

This transdisciplinary thesis has been written as a compilation of the following co-authored manuscripts that are either published or in preparation for submission to disciplinary specific peer reviewed journals and was completed with collaborations from various researchers in the fields of forestry, ecology and hard wood product carbon assessment. *Co-authors of the articles contributed conceptual discussion, provided LANDIS II forest simulations data from previous studies*(Mina et al. 2022)*, and participated in the review of written materials.* I was responsible for the conceptual framework, design of all chapters, compilation of data and processing, building and carbon model development, analysis of data, and writing and editing. I am the first author of each chapter and sole author of the tables and figures produced in this thesis.

**Chapter 4**

Osborne, Peter, Núria Aquilué, Marco Mina, Kiel Moe, Michael Jemtrud, and Christian Messier. 2023a. "A Trait-Based Approach to Both Forestry and Timber Building Can Synchronize Forest Harvest and Resilience." *PNAS Nexus* 2 (8): pgad254. https://doi.org/10.1093/pnasnexus/pgad254.

**Chapter 5**

Osborne, Peter.  2024. "Wood in transition: diversifying wood construction to cope with forest change." [Manuscript in preparation for submission].

**Chapter 6**

Osborne, Peter. 2024. "Enhancing forest carbon sinks through functionally adaptive wood construction." [Manuscript in preparation for submission].

# Table of Contents

# Abbreviations

| Acronym | Abbreviation |
|---|---|
| ANSE | Abstract Network Simulation Engine |
| BAU | Business-As-Usual |
| BC-HWPv1 | British Columbia Harvested Wood Products, version 1 model |
| BG | Building Group |
| CBA | Cost-Benefit Analysis |
| CBM-CFS3 | Carbon Budget Model of the Canadian Forest Sector |
| CBM-FHWP | Carbon Budget Model Framework for Harvested Wood Products |
| CCA | Climate Change Adaptation |
| CFS | Canadian Forest Service |
| CLT | Cross-Laminated Timber |
| CSA | Canadian Standards Association |
| DL | Dimensional Lumber |
| DLT | Dowel-Laminated Timber |
| EEIO | Environmentally Extended Input-Ouput |
| FBI | Forest-Building Index |
| FDN | Functional Diversification Network |
| FDN | Functional Diversity |
| FR | Functional Redundancy |
| GHG | Greenhouse Gas |
| GLT | Glued-Laminated Timber; Glulam |
| HRA | Harvest Resource Availability |
| HRI | Harvest Resource Index |
| IO | Input-Output |
| LCC | Life Cycle Costing |
| LSL | Laminated Strand Lumber |
| LVL | Laminated Veneer Lumber |
| MCA | Multicriteria Analysis |
| MFA | Material Flow Analysis |
| MSR | Machine Stress-Rated |
| MT | Mass Timber |
| NFCMARS-HWP | Carbon Budget Model for Harvested Wood Products |
| NLGA | National Lumber Grades Authority |
| NLT | Nail-Laminated Timber |
| OSB | Oriented Strand Board |
| OSL | Oriended Strand Lumber |
| PSL | Parallel Strand Lumber |
| RCP | Representative Concentration Pathway |
| SCL | Structural Composite Lumber |
| SFA | Substand Flow Analysis |
| SFO | Sustainable Forest Operations |
| SLCA | Social Life Cycle Assessment |
| S-P-F | Spruce-Pine-Fir |
| SR | Species richness |
| TF | Timber Frame |
| UNFCCC | United Nations Framework Convention on Climate Change |

# Tables

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# 1 Introduction

This dissertation critically examines the relationship between wood building design and forestry (as well as buildings and forests) to address the social, ecological, and economic challenges in the face of profound global change.  The climate is warming and becoming more erratic: it is no longer suitable to look at the past to help understand current and future trends and patterns (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES 2016). Forest ecosystems' adaptive responses to rising temperatures, environmental changes, and episodic climatic events are still uncertain (Figure 1). In many of Canada and Quebec's forests, species ranges and plant communities are predicted to shift, and environmental stress is forcing alterations in ecosystem structure and composition (Christian Messier et al. 2016). Precipitation shortfall or long-lasting drought periods may intensify tree mortality and increase forest vulnerability to wildfires and disease outbreaks (Aubin et al. 2018; Aquilué et al. 2020). These climate disturbances will drive acute regime shifts, and compounded human and natural disturbances will bring new scenarios with unknown impacts on forest ecosystem dynamics and the communities they support (Seidl et al. 2017). Moreover, changes in disturbances regimes could modify forest ecosystems' current carbon sink-source ratios and positively feedback on climate warming. Recent large insect outbreaks in North America have converted carbon-sink forests to carbon sources (Werner A Kurz, Stinson, and Rampley 2008), and the increased frequency of stand-replacing fires during the next century could exert the same effect on forest carbon balances. With all of this said, how can architects and designers rethink their relationship with wood in order to increase the resilience and adaptability of forests while maintaining or increasing the wood building carbon sink?

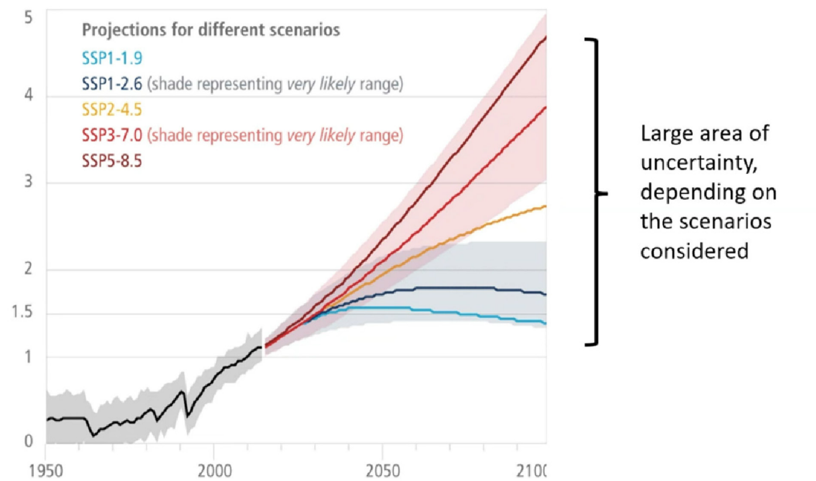



*Figure 1 – The large area of uncertainty in future climate conditions makes planning for the future wood construction a challenge. Adapted from IPCC (2023)*

These changes present new challenges for all stakeholders along the supply chain, from forest to building, rural communities to foresters, architects and engineers, owners and users, and particularly to all species and biodiversity inhabiting forests. This approach of studying buildings and forests as coupled complex adaptive systems stands in contrast to the current closed-system approaches of today's forestry and building industries (Srinivasan and Moe 2015; Oliver C.D. et al. 2014; Ibañez, Hutton, and Moe 2020). This closed system approach is evident in the tools and methods of both foresters and builders alike. For example, architects and builders often uncritically promote the increased use of wood for its apparent low carbon potential and ability to sequester carbon (Ercin and Hoekstra 2012; Alvarez and Rubio 2016; Brunet-Navarro, Jochheim, and Muys 2016). Inversely, many foresters and conservationists would argue that forests are the best carbon stores (C. D. Oliver 2001; Ni et al. 2016; Alam, Kilpeläinen, and

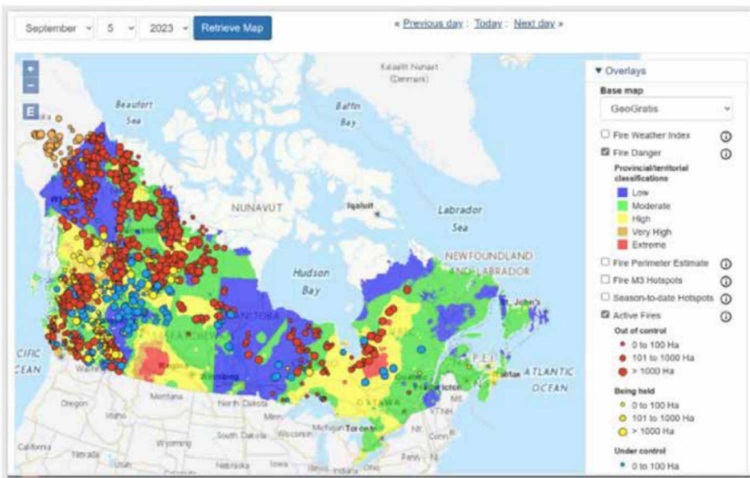
Kellomäki 2012). Through the lens of an isolated or closed-systems approach, both groups promote the preservation of the planet's forests as the best response to the current climate crisis. Each group's response is framed by tools and methods which reinforce disciplinary boundaries that treat both forests and buildings as isolated systems in ways that not only fetishize carbon(Swyngedouw 2010) but do so in a way which prevents them from seeing the greater potential of an open, synchronized, Forest-Building system(Oliver C.D. 2014, 201). When carbon, or any criterion, is treated singularly as a target through a closed system-perspective, numerous social, economic, and ecological problems result. As but one emblematic example, Life Cycle Analysis(LCA) biogenic carbon accounting of timber buildings begins upon material extraction ("cradle") and is divorced from the operative landscapes(e.g. forests). In methodological terms, this treats the forest as an infinite reserve and, paradoxically, excludes the carbon dynamics of forests from the assessment. These methodological limitations of closed-system approaches prevent any positive shifts in future practice in forestry and building. A more dynamic and complex way to approach the biogenic carbon potential of wood buildings is to consider the uncertainty of future conditions and the need to adapt both buildings and forests to these uncertainties. In the forest, this could mean management approaches that will diversify forests to reduce risks. In the building industry, this could mean using adaptive, multi-species wood assemblies integrated with diverse forest management approaches and designing buildings based on duration and next-uses.

In addition, through closed-system approaches, extant modes of forestry, building and urbanization externalize matters of economic, ecological and social significance. These externalizations manifest through various forms of unequal and uneven relations between stakeholders (Emmanuel 1972; Amin and Pearce 1976; Hornborg 1998; 2012; Foster and

Holleman 2014; Scheidel et al. 2018; Givens, Huang, and Jorgenson 2019) and methodologically contradict motivations surrounding many popular concepts like sustainability and resilience — ever-present within current forestry and architecture discourses. This results in significant underdevelopment (S. G. Bunker 1985; S. Bunker 2005; Smith 2008) and ecological load displacement (Hornborg A. 2009; Sommer 2019). Forestry has disproportionately adverse effects on rural and indigenous communities (S. Bunker 2005; Alvarez and Rubio 2016). These effects are exacerbated by current trends in construction like the single species high wood volume construction, the trading of carbon and ecosystem services that privilege inaction through trade-offs of money for social-ecological devastation (Martinez-Alier 2002; Kosoy and Corbera 2010; Alvarez and Rubio 2016). I argue that the current conceptions of sustainability and resilience are framed under a command and control paradigm, which is counterproductive in a world where things change quickly and where we need to make decisions that foster adaptability (Holling and Meffe 1996). Thus, presently, forestry and architecture deploy tools and frameworks which are misleading and reduce the economic, social, and ecological complexity—that is, the potential to adapt — of the forests (Klaus J. Puettmann, Coates, and Messier 2009; Christian Messier, Puettmann, and Coates 2013) and building systems (Moe 2017).

In short, the assumption that 'wood is good '— as both a source of materials and sink for biogenic carbon — is too simplistic and ultimately facilitates the increasingly unequal distribution of impacts between the built environment, forests, and all the other species that forests support. Such approaches result in building practices that incorrectly describe all of Canada's forests as carbon sinks, ironically resulting in increased carbon emissions through monoculture plantations, putting Canada’s forests at risk of increased disturbances and climate change (N. R. Canada and

Service 2020, Figure 2).  Thus, if wood buildings are incompletely characterized and considered, future design decisions will continue exacerbating inequities in terrestrial social-ecological systems and reduce the resilience and adaptability of our forests and built landscapes.




Screen grab from NRCan's interactive map showing active fires as of September 5, 2023.

*Figure 2 – Left: Screen capture from Natural Resources Canada's (NRCan) interactive forest fires map during the September 2023 fire season. Source: (N. R. Canada, n.d.). Right: Image of Fort McMurray residents evacuating along Highway 63 as the fire encroaches on the area during 2016 Forest Fire Season. Source: (DarrenRD 2016)*

This characterization of the relationship between forests and buildings described above is inadequate. In this dissertation, I propose a new coupled Forest-Building approach where entities of both forest and building systems interplay to create complex relations with traits and dynamics not unique to any sub-systems (Liu et al. 2007). Forest-Building systems are complex and hierarchically self-organized around heterogeneous components, with non-linear dynamics emerging from multi-scale interactions and mechanisms exhibiting continual adaptive growth cycles, accumulation, restructuring, and renewal (Gunderson 2001). Therefore, a next-generation design framework — new models for understanding, designing, synchronizing, and assessing the adaptive properties of forests and buildings — must be developed to address and understand the emergent properties, feedback, vulnerabilities and risks of these systems (Gibson, Doelle, and Sinclair 2015).

A crucial feature of a Forest-Building approach, then, is that it is not just scientific and technological but also social and political. The range of possible societal responses in the forestry and construction sectors compounds the technical uncertainties, ambiguities and conflicts inherent in their methods. How the problems and possibilities are understood and appreciated are profoundly value-laden and pervaded by disciplinary interests. Furthermore, the methods and approaches of each discipline leave strong imprints on shaping both policy and the adaptive potential of any Forest-Building system. For example, extant modes of construction apply top-down, command-and-control approaches to forests to ensure a predictable supply of merchantable lumber (Holling and Meffe 1996). This approach results in mono-culture plantations, which reduce the overall complexity of forested ecosystems and the overall adaptability and carbon sink potential of the Forest-Building system.

For several reasons, the design of buildings will be more effective if we view them as inextricably connected with forests, as they are in the world (Oliver C.D. 2014; Kalt 2018; Jantz, Goetz, and Laporte 2014; Craig et al. 2020). While the study of complexity in forests and building is relatively recent, coupling the design processes of forestry and building according to the principles of complex adaptive systems would be highly desirable and, in doing so, will ensure the adaptability and resilience of these environments within a broader range of future conditions (Paquette and Messier 2013; Christian Messier, Puettmann, and Coates 2013; Levin 2005; Kay 2002; Odum and Odum 2001; T. F. H. Allen 2015). **Yet, no existing methods or tools adequately describe the complex nature of Forest-Building**. Therefore, this dissertation aims to develop these design tools for foresters, land managers, architects, engineers, and builders to assess how their practices affect all properties of complex adaptive systems. The expanded Forest-Building design space presented in this dissertation is a transdisciplinary nexus of research methods from environmental assessment and development, multi-criteria and stakeholder analysis, system dynamics, complexity science, forestry and silviculture practices, construction ecology, and planetary urbanization, and building design. This Forest-Building design space will approach the design of forests and buildings and their social, economic, and ecological effects as a single design act and change how architects, engineers, and foresters source, design, and build our future.

## 1.1 Research Questions

Three research questions emerge in the blind spots of forestry and architecture:

1. **Integration of Forests and Building:** How do we best relate the dynamics of forests and timber buildings? How can wood-building practices be adapted to respond to the needs of forests?
2. **Indicators of wood construction resilience to changing forest compositions:** How to assess the resilience of wood construction approaches to changes in forest composition?
3. **Impact of adaptive wood construction on the Forest-Building carbon pool:** How does more synchronized and adaptive wood construction impact the building carbon sink?

## 1.2 Methodology and Sources

This dissertation is informed by a range of scholarship and methods from systems theory, complexity science, environmental assessment and development, ecological/heterodox economics, forestry and construction ecology, all through the lens of complex adaptive systems.

In order to understand the implications and design resilient and adaptable solutions, it is ever more clearly understood that bounded disciplinary or single-sector approaches are not enough. What is needed is collaboration and a profoundly transformative change in infrastructures, organizations, behaviours, markets, governance practices and even disciplinary cultures and epistemes more widely. These are the challenges of a Forest-Building nexus that will shape a distinct realm of knowledge that engenders a new type of designer.

Over 100 assessment criteria, tools, and methods have been surveyed, compared and categorized according to the complex adaptive system framework in Table 9 (see Figure 53). This inventory is based on literature from a wide array of sources and disciplines. The material consists of literature describing each method, tool, and criteria, as well as material related to the application of each assessment approach. Extant methods include but are not limited to Sustainability Impact Assessment, Environmental Impact Assessment, Ecological/Economic/Social Impact Assessments, Life-cycle assessment, Life cycle costing, Environmental footprinting, Ecosystem science assessment, Environmental Impact Assessment, and Strategic Environmental Assessment, Input-Output and Environmentally Extended Input-Output, Material/Substance Flow Analysis, Energy/Exergy/Emergy Analysis, Cost-benefit analysis, Uncertainty/vulnerability/risk analysis, and Multicriteria Analysis. Authors agree that extant impact assessments pay little attention to forests' services and functions, including a wide range of ecological, political, economic, social, and cultural systems and processes that are necessary for building (Karvonen et al. 2017; La Notte et al. 2017). Therefore, a new nexus design-space is needed to combine these multiple disciplines. This dissertation presents a framework for designers to better understand the positive and negative feedback of their design decisions and wood specification and how those decisions explicitly impact the emergent ecological inequalities we see in extant forestry and wood construction practices today(Hoang and Kanemoto 2021).

## 1.3 Thesis objectives and structure

The objectives of this dissertation are twofold. First, to develop methodological approaches for exploring how different wood construction systems respond to changes in forest management, natural disturbances and climate change. Second, to provide tools for the wood construction industry and designers on how to adapt their practices to better support more resilient and adaptable forest landscapes facing global changes. To address these challenges, an integrated Forest-Building approach was developed to model the effects of wood construction on forest ecological resilience. This includes:

(1) the development of the Forest-Building and functional building traits concept,

(2) applying the functional building traits concept to evaluate the resilience and adaptability of existing wood construction approaches, and

(3) the development of a dynamic Forest-Building carbon model to compare the carbon sink potential of existing and resilient wood construction approaches under increasing climate change and forest management approaches.

Following a background on forests, buildings and impact assessment methodologies, **Chapter 4** introduces the functional building traits concept and provides the foundation of Forest-Building approach and its use at the core of a plant-trait based approach to wood construction. This encompasses a broad investigation into processes, structures, hierarchies, feedbacks, and relations within the Forest-Building system. This analysis is a study of forestry and building as a spatially explicit coupled complex adaptive system. It is informed by examples from system dynamics, environmental/ecological modelling, and by the recent work in ecology and forestry described as the functional complex network approach (Christian Messier et al. 2019; Aquilué et al. 2021a). Based on the resulting perspective of viewing Forest-Building as a complex adaptive system, the development of design guidelines and assessment methodologies will depend on the translation of system dynamics—such as cross-scale hierarchical interaction and feedbacks, nonlinear relationships which make predictions uncertain, and emergent behaviours such as self-organization and adaptability—into performative indicators and actions for foresters and architects. This approach is inspired by recent research in forest management and ecology describing the adaptability of forests using functional traits and network analysis (Violle et al. 2007; Aquilue 2018; Mina et al. 2020). In *Managing Forests as Complex Adaptive System*, Christian Messier, Klaus J. Puettmann, and K. David Coates present a new way for forests to be managed through the lens of complexity science. More recent work on managing forests as complex adaptive systems demonstrate how a diversity of functional traits and network connectivity could make forest ecosystems more adaptable, provoking forest managers and conservationists to reject the concepts of stability and predictability favouring adaptability, self-organization, and uncertainty of the new conditions which are created through their practices. *Forest-Building extends the functional complex network approach to include building*. Here, the functional traits of building refer to the characteristics of wood species impacting wood construction approach, design, maintenance and end-of-life processes and various performative characteristics such as temporal dynamics of wood demand, harvested wood product adaptability to wood species, functional overlap, durability and longevity, among others.

**Chapter 5** investigates the potential of the building-traits concept and outlines how to apply this plant-trait based approach to assess the resilience of existing wood construction approaches. I explore the performance of three 'generic' wood building construction techniques—mass timber, timber-frame, and light frame wood construction— and their resultant forest management strategies in shaping the *functional resilience and adaptability* of managed forested ecosystems in Quebec. Here, I develop and explore the ‘functional traits’ of harvested wood products and how they respond to various forest management strategies. The results demonstrate the functional traits of each wood construction approach; the functional traits of the forestry practices inherent to each method; and finally, a multi-scale indicator of wood construction resilience based on species functional traits.

Finally, **Chapter 6** applies a land-based biogenic carbon assessment of a combined Forest-Building system based on traits of different species and the adaptability of wood construction approaches. Here, I assess the land-based carbon pooling of three wood building approaches with increasing functional resilience and adaptability, established in the Chapter 5, and demonstrate the increased carbon pooling potential of a synchornized Forest-Building approach. This three-fold approach aims to establish an understanding of the complex relations among social, ecological and economic structures surrounding the use of wood in buildings in order to realize synergies otherwise overlooked by extant methods. By focusing on the exchanges of forests and buildings, we can ask how building cycles can have positive, regenerative impacts on the direct, synergistic, and emergent properties of forests, and vice versa. The need to re-evaluate disciplinary models is critically needed and the nexus-based approach towards Forest-Building reflects specific and novel forms of knowledge that will engender new types of design practices.

# 2 Background on Forests and Wood Building

Trees and the complex web of life in forest ecosystems are crucial to Canada's urban and rural landscapes. They provide multiple benefits and services to society and citizens, commonly known as ecosystem services including social, cultural and economic well-being (Costanza 2008). As global urbanization increases, the environmental challenges associated with climate change, such as rising air temperature, atmospheric pollution, and carbon emissions, are expected to have a dramatic and uneven effect on both social, economic and ecosystem health. In their study on the direct, indirect and interactive effects of climate change of forest disturbances under climate change, Seidl et al. (2017) concluded that ecosystems and society must be prepared for an increasingly disrupted future of forests (see Figure 3). Such increasing chronic and episodic disturbances puts forests, trees, and the provisioning of ecosystem services such as harvested wood products (HWP) for buildings in a uncertain future. Yet, society is asking more from both forests and wood buildings to counteract the effects of climate change through carbon sequestration and other ecosystem services. For instance, recent research has linked the use of long-lived wood products with increased carbon sequestration (Oliver C.D. 2014; Craig et al. 2020) and sustainable forest operations as a means to bring social, ecological and economic well-being to people and society (Marchi et al. 2018). In other words, global change is rapidly increasing our dependency on forests, trees, and the wood products they provide to mitigate the effects of a warming climate while at the same time making the future provisioning of those same ecosystem services and wood products more uncertain.  A deeper understanding of the complex relationship between forests and buildings is needed.

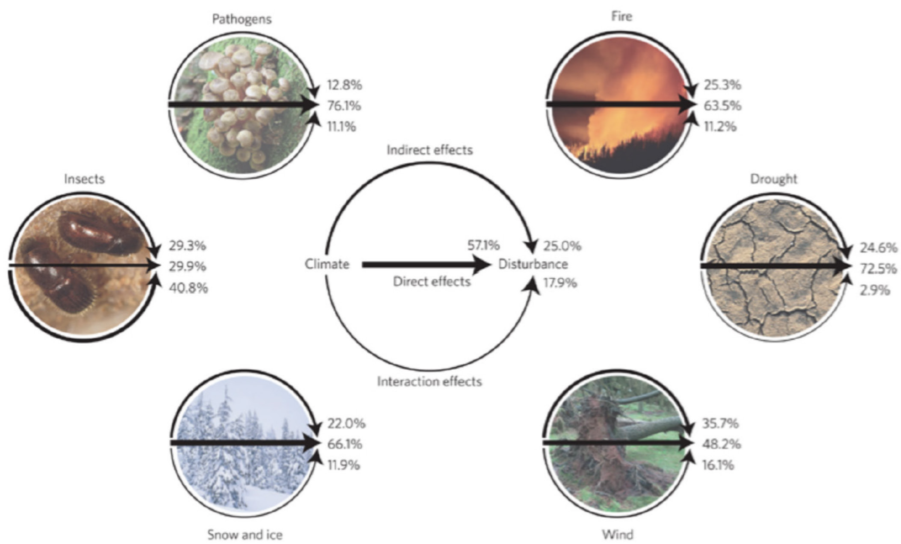



*Figure 3 – The direct, indirect and interactive impact of climate change on forest disturbances under climate change. Reproduced from (Seidl et al. 2017)*

## 2.1 Complexity in forestry and building

Complexity science is beginning to mature in the separate fields of forestry and construction ecology and the integration of these two fields into a Forest-Building framework is needed. A complex adaptive systems (CAS) framework will involve a shift away from the reductionist, command and control frameworks deployed by forest practitioners, architects and other stakeholders within the Forest-Building system towards an expanded transdisciplinary design-space inclusive to forestry, building and their interrelations (Holling and Meffe 1996). As such, to evaluate the current approaches towards sustainability within forestry and architecture needed for a Forest-Building framework, a basic understanding of complexity and CAS is necessary.  As introduced above, a CAS is an open non-equilibrium system composed of multiple interacting components whose aggregate behaviour cannot be understood through studying the isolated elements (Levin 1999; 2005; Paquette and Messier 2013; Hennigar, MacLean, and Amos-Binks 2008; Kayo, Aramaki, and Hanaki 2011; Oliver C.D. et al. 2014; Alvarez and Rubio 2016; Brunet-Navarro, Jochheim, and Muys 2016; Proto et al. 2017). CAS researchers consider how the relationship among parts and processes gives rise to collective behaviours that cannot be readily predicted by looking only at individual parts and how the system adjusts and adapts to changing conditions  (see Figure 4). This shift from a reductionist- to a complexity-based approach to the design of forests and buildings is necessary to address many of today's social, ecological and economic concerns.

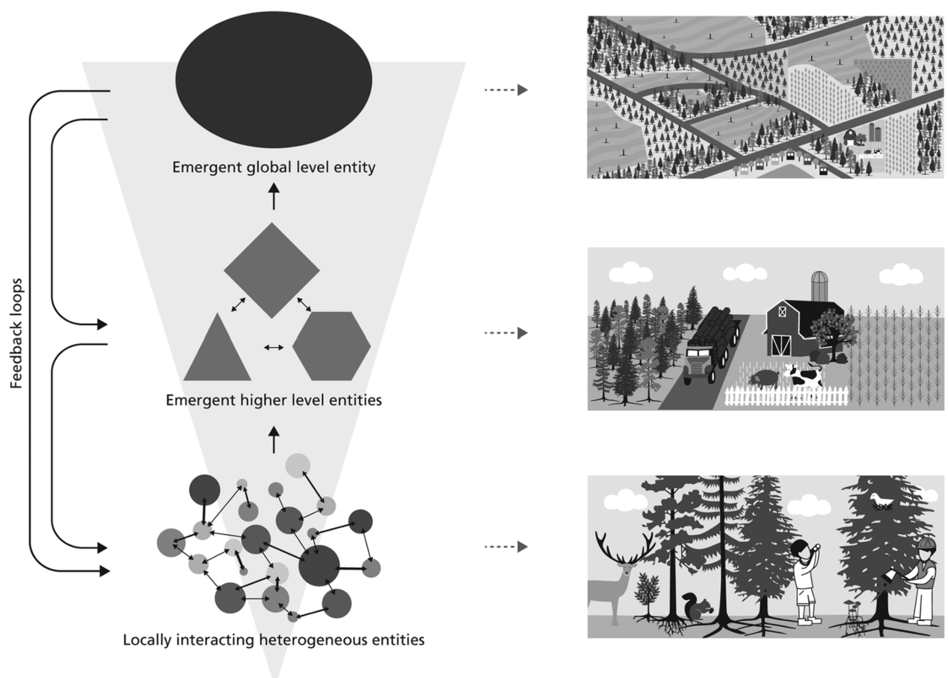



*Figure 4 - Conceptual representation of a complex adaptive system in forestry. From Filotas et al. (2014)*

Approaching the integrated Forest-Building design space as a CAS will require developing new transdisciplinary tools, methods, goals and objectives. While methods that work across the disciplinary boundaries of forestry and building do not currently exist, research in the fields of forestry management and construction ecology provide the foundations. Forest ecologists propose that forests exhibit all the necessary characteristics of CAS (see Box 1) and argue that managing the complexity of forest ecosystems is highly desirable to maintain the adaptability of forests within a wide range of conditions that allow them to provide the benefits to future generations (Gunderson 2001; Nordström, Eriksson, and Öhman 2010; Burton 2013; Parrott and Lange 2013; Paquette and Messier 2013; Chadwick Dearing Oliver and Larson 1996; C. D. Oliver 2017; Levin 2005; 1999). The study of building as a CAS is more limited, though the planetary process of building shares the characteristics of a CAS (Timothy F.H. Allen 2002; Kay 2002; Odum 2002; Kibert, Sendzimir, and Guy 2002; Srinivasan and Moe 2015; Moe 2017). Building supply chains show tendencies for self-organizational hierarchical structures, increasing complexity through feedbacks and pulsing cycles of growth and stagnation to maximize overall system performance. The connection between these two domains of knowledge lies in the fact that ecological communities, such as forests, provide the energy, materials, and information required for the ongoing maintenance of buildings and processes of urbanization.

Overall, the CAS of buildings and cities depends on flows of material and energy from forests, yet little attention has been paid to this integral relationship in either body of scholarship. These flows, along with the biophysical environment provided by the ecological systems, are the context for all societal systems such as building. In other words, they provide the biophysical surroundings and flows of energy, materials, and information required by the building system's self-organizing processes. Building systems can alter the structures in forest systems. Changes in the forest structure can then, in return, alter the context for the building systems themselves. For example, clear-cutting and plantation of monoculture forests will transform the forest ecosystem's underlying complexity, resilience, and adaptability. In turn, the successional dynamics of forests regrowth will dramatically impact the type of harvested wood products and wood buildings possible in the future. Understanding this complex, push and pull, relationship is integral to designing with wood today, and the goal of this dissertation is to do just that.

**Box 1: Properties of Complex Adaptive Systems.**
**Adapted from Puettemann et al. (2009)**

1. **Constituted relationally** - nonlinear relationships exhibit non-deterministic, quasi-chaotic behavior that makes predictions about the forest uncertain. Relationships can be expressed as monotonic, increasing or decreasing over a range of responses, or they may be nonmonotonic, increasing over parts of the range and decreasing over other parts. Nonmonotonic relationships express threshold values, where the effects of one variable can suddenly start to have a much more significant impact.
2. **Adaptive** - boundaries and elements that are difficult to determine, so that system limits are inherently ill-defined and evolve over time;
3. **Radically open** - subject to outside influences such that the system is never totally at equilibrium;
4. **Dynamic** - relationships among parts and processes of the system contain feedback loops that cross scales or hierarchies of organization. Positive or negative feedback mechanisms are common in forests. Positive feedback loops tend to destabilize systems because they accelerate or amplify changes in system states; negative feedback loops stabilize systems because they tend to inhibit or dampen changes.
5. **Complex causality** - emergent behaviors that arise from interactions among parts and processes of the system that cannot be predicted from understanding the lower levels of organization (Ponge 2005). Examples of emergent phenomena are insect and disease outbreaks, such as the mountain pine beetle, which results from cross-scale, nonlinear interactions between insect, tree, stand, landscape-scale forest practices, and changing climate conditions (Woods, Coates, and Hamann 2005). Self-organization, resilience, and adaptability are emergent properties of complex adaptive systems (Gunderson 2000; 2001; Holland, Holland, and Holland 1992; Holling 1973).
6. **Contextual** - previous states partially influence the present state of the system. Complex adaptive systems have history and likewise present settings impact next states.

## 2.3 Resilience and adaptability in forests and building

The formal recognition of the link between forests and buildings constitutes a significant divergence from current forest management and construction approaches and requires a shift from a command-and-control approach to a CAS approach. This recognition requires the acceptance that in many situations, the challenges faced by both forests and buildings are complex, 'wicked problems' with no right answer (DeFries and Nagendra 2017). Wicked problems arise from one or a combination of multiple dimensions: complexity and interdependency of components, which create feedbacks and nonlinear responses to management. This inherent uncertainty in the system functioning emphasizes the need for both forest and building to be resilient and adapt to unknown and often unknowable change. Here, resilience is the capacity of a system to cope with constant exogenous pressures and periodic disturbances and learn from that process to be better adapted to future disrupting conditions (Holling 1973; Holling and Meffe 1996; Gunderson 2000). Resilient systems have mechanisms to return or rapidly recover to the former state despite continuous degradation or sudden shifts in external conditions. Therefore, resilient forest ecosystems are those that, through self-organization, adaptive strategies, and well-established regeneration patterns, can maintain their primary functions. Holling and Meffe (1996) argue that the command and control approach focuses on an incorrect understanding of ecosystem resilience summarized above. Instead, the command and control - or equilibrium resilience - approach focuses on a near-equilibrium or steady-state understanding that reduces the range of natural variation of system structure, functions in favour of increased predictability or stability. The critical error, or what Holling and Meffe (1996) refer to as "the pathology of natural resource management," is that these top-down practices reduce the system's overall resilience, diversity and adaptability. More recently researchers have argued that resilience in production forests can be achieved through natural ecological processes or repeated intensive interventions, what they refer to as 'coerced' resilience(Felton et al. 2024). Yet, they caution that 'coerced' resilience derived from intense and repeated human inputs may in fact accelerated biodiversity loss, narrowed the range of ecosystem services provided, such as wood used for buildings, and limit general resilience and adaptability of productive forest landscapes.

From a CAS perspective, diversity – biodiversity, genetic diversity, and functional diversity- are crucial factors for ensuring an ecosystem's resilience and resistance from external perturbations (Thompson 2009). For example, some tree species will exhibit functional traits that resist fire, while others may not. Yet, while some of those species that could not resist the fire (i.e. they burn), they instead respond by spreading their seed and thus re-organizing the system to conserve the same functions, structures, and renewal capacity (Folke 2006). Therefore, in applying a top-down, command and control approach to a forest ecosystem, it is likely that the future uncertainty and variability caused by global changes - pushing ecosystems beyond their thresholds of resistance and resilience - would result in a reduction of system resilience and adaptability. Instead, we should be inspired to design our forests-building systems following a more bottom-up approach. Favouring succession and emergent diversity at multiple levels will result in a more resilient and adaptable forest capable of providing critical ecosystem services in an uncertain future.

### 2.3.1 Diversity in forests and buildings

Recently, authors have begun to overcome these command-and-control approaches and develop forest management approaches that promote forest ecosystem adaptability and diversity. As introduced above, Messier et al. (2013), and Puettmann et al. (2009) suggest that instead of applying the "homogeneity equals efficiency" paradigm to forestry, we should view forests as a CAS. Therefore we can look for inspiration for our current problem of adapting the Forest-Building system to global change by incorporating the characteristics of CAS into the development and assessment of silviculture and architectural decisions. Viewing forests and buildings through the lens of CAS does not exclude any forest management, silviculture, or construction approaches. Instead, designing forests and buildings as complex adaptive systems requires a diverse set of forest management and construction approaches to satisfy the diverse goals of each stakeholder group (Fahey et al. 2018).

Forest ecologists have argued that high species and structural (stand and age structures) diversity in forest landscapes have as essential characteristics for resilient natural ecosystems (Seidl et al. 2016; Ratcliffe et al. 2017; Timpane-Padgham, Beechie, and Klinger 2017). As an ecological concept, diversity is dependent on two main factors: the total number of species and their relative dominance. The most common way ecologists and foresters account for diversity is species richness - the total number of species at a given site. Yet, species richness does not account for the equitability or distribution of species abundance, which has presented a major problem when considering the mono-specific stands used for building products (Jost 2006). Furthermore, while the number of different species may reflect 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 or whether certain ecological niches are occupied or not.

A more recent approach advocates for the use of functional traits to better characterize ecosystem diversity (Violle et al. 2007; Christian Messier et al. 2019; Aquilué et al. 2021a). Functional traits can be defined as any characteristic that can be measured and that influences an individual's performance in terms of growth, survival, or reproduction of the species. For individual trees, functional traits for adapting to climate change and disturbances(e.g. pest, disease, drought, wind, etc.) include tree height, wood structure and density, seed size, bark properties such as thickness, specific leaf area, ability to resprout, and rooting depth (Aubin et al. 2016; 2018; Kattge et al. 2020). A full list of possible plant traits is available through the Traits of Plants in Canada (TOPIC) database (N. R. Canada 2017; Aubin et al. 2012). Researchers argue that communities (e.g. forest stands) with high functional diversity - a mixture of traits enabling adaptation to known stressors - and functional redundancy - a high recurrence of traits that enable adapting to unknown stressors - will be more resistant, resilient and able to migrate to other more desirable communities (Yachi and Loreau 1999; Laughlin et al. 2017). Thus, to face the effects of global change, we must manage and design our forests and buildings system such

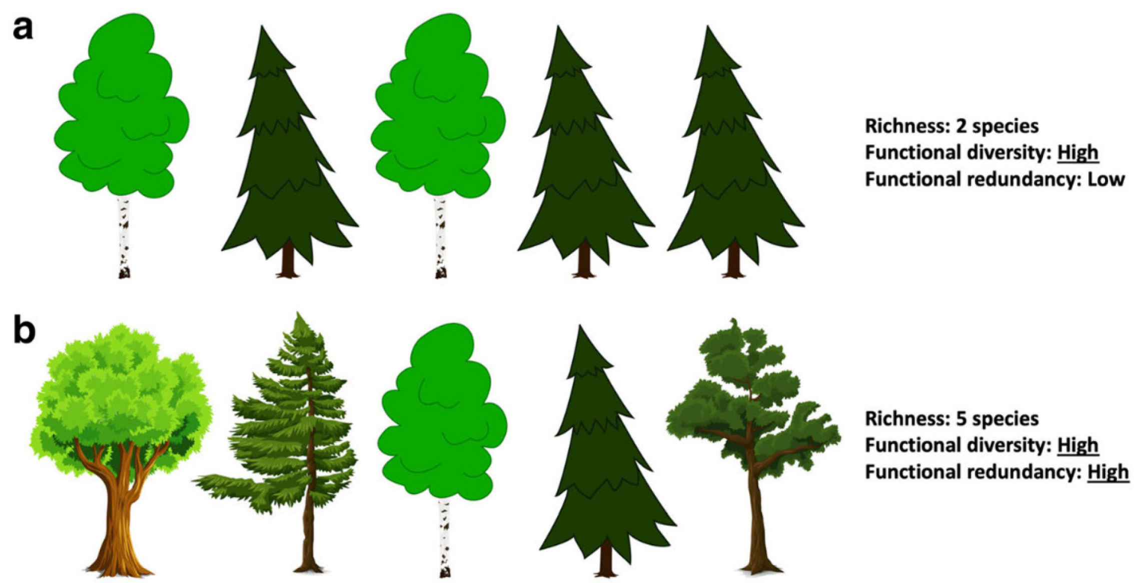



*Figure 5 – Simplified diagram illustrating the concept of functional diversity and redundancy within two different forest stands.* ***a*** *The upper stand has a high functional diversity with only two species because they have largely different functional traits: e.g., one species is an angiosperm, the other a gymnosperm. In contrast, the functional redundancy is weak and if a species disappears, several particular functional traits will be lost.* ***b*** *The lower stand also has a high functional diversity because it is composed of five different species, two gymnosperms and three angiosperms with relatively similar traits. Functional redundancy is however high in this case and if a species disappears, functional traits will be maintained in the stand. How should building practices adapt to facility the transition from a to b? Diagram reproduced from Messier et al. (2019).*

that they promote functional traits that can respond to the widest spectrum of possible futures (see Figure 5).

### 2.3.2 Functional redundancy and response diversity as a means of being resilient and adaptable

Walker (1992) proposed a paradigm shift for understanding ecosystem diversity from individual species to functional groups. In contrast to preserving diversity through species selection, he proposed that by preserving species that are functionally different, the overall ecosystem structure and function is assured and the resilience maintained. Once species within an ecosystem are classified by functionality (meaning they contribute to the same biogeochemical activities and materials flows), there are "drivers" or "keystone process species" that control the main ecosystem processes, and "passengers" species that become the "natural insurance capital"; that is, redundant or temporal complementary species that buffer the loss of the main ecosystem contributors (Folke 2006). Functional redundancy (i.e. abundance of species within a functional group) can be perceived as an insurance policy to biodiversity loss rather than a superfluous feature (Rosenfeld 2002). Functional redundancy has to be measured over the complete environmental gradient of a community to not underestimate redundant species that otherwise could become the main (even the essential) functional contributors (Ricotta et al. 2016). That is, because not all species in the same functional group may respond equally to changing environmental conditions, to offer a reliable functional diversity it is imperative to differentiate effect traits (e.g. nutrient cycling or soil retention) from response traits (Violle et al. 2007). Response diversity may be as important as functional redundancy in ensuring ecosystem resilience in response to natural disturbances, environmental changes, and anthropogenic pressures (Mori, Furukawa, and Sasaki 2013). A first experiment in Australian range lands communities with presence of grasses, forbs, and shrubs corroborated that the functional redundancy - response diversity coupling was essential for the ecosystem to persist when environmental conditions changed (B. Walker, Kinzig, and Langridge 1999). For all dominant species in a favorable grazing and precipitation scenario, there were less abundant species functionally similar adapted to much more severe conditions. Similar experiments in grassland communities demonstrated that functional redundancy enhances ecosystem resilience, but only those functional groups with high response diversity are effectively resilient to disturbances (Mori, Furukawa, and Sasaki 2013). A recent meta-analysis of forest ecosystem across five biomes that encompasses a vast gradient of land-use intensities quantified both plant effect and response traits (Laliberté and Legendre 2010). As land-use intensifies, overall functional redundancy and response diversity lessen, an ecosystem ability to respond to change is reduced.

### 2.3.3 Spatial Networks in Social and Ecological Systems

As building supply chains and forest landscapes are spatial systems, approaches to describe resilience and adaptability need to consider the spatial and temporal organization of forest stands in terms of their composition, age, size, and isolation (Turner, Donato, and Romme 2013). When considering forest landscapes as a set of individual forest stands within a landscape of natural and built environments, a network approach may help determine the ecosystem resilience (Fall et al. 2007; Urban et al. 2009; Dale and Fortin 2010; Gonzalès and Parrott 2012). Combining functional groups with a complex network approach is what Messier et al. (2019) describes as the "Functional Network Approach." Their approach describes forest stands as nodes/patches that form a network representing the functional complexity of forested ecosystems. They argue that to resist and recover from rapid climate change, compounded natural and anthropogenic disturbances, forest ecosystems may benefit from high connectivity between patches to foster adaptability to new environmental conditions. As disturbances can potentially remove entire forest patches, the remaining' landscape connectivity will be essential for forest landscape recovery (Franklin et al. 2000; Lindborg and Eriksson 2004). On the other hand, although structured connectivity fosters ecosystem resilience, it can also negatively affect the landscape when faced with a disturbance that can spread (Aquilué et al. 2020; Mina et al. 2020). For example, a highly connected forest landscape and the right environmental conditions could contribute to a disease's growing spatial distribution. Similarly, continuous forest patches with a dense understory are more vulnerable to unexpected large wildfires than rural landscape mosaics or landscapes with strategic fuel breaks. The functional network approach can be used to evaluate where and how silvicultural interventions should be performed within the landscape to most effectively enhance key network properties, namely, modularity, connectivity, and centrality.

Centrality concerns certain elements of a system whose relevance manifests by the high degree of connectedness with other system components. In a networked system, central elements have the privilege of controlling how traffic flows (Webb and Bodin 2006; Borgatti et al. 2009) and are crucial to maintaining both system structure and function (Mina et al. 2020). Extant building and forestry practices are often highly centralized systems that do not leave room for innovation, diversified learning processes, nor bottom-up emergence, all to the detriment of system's resilience (C. Messier, Puettmann, and Coates 2013). But low or inexistent centrality may cause an inefficient flow and weaken the system's response capacity when a disturbance arises (Janssen et al. 2006). In landscape ecology, centrality is attributed to ‘stepping stone’ patches that link or act as bridges between habitat reservoirs, being critical for maintaining structural landscape connectivity. Central areas in forest landscapes not only keep the forest matrix connected, facilitating a continuous flow of organisms but if more traffic crosses a landscape patch, it should harbour a more diversified genetic pool. This increased diversity can be considered a long-term insurance asset capable of responding to changing environmental conditions (Yachi and Loreau 1999; Christian Messier et al. 2019).

Connections among system components allow dynamic flows of matter, energy, and information, while transport and communication efficiency are correlated with a well-structured connectivity (Craven et al. 2016). In landscape ecology, connectivity has been mostly addressed from a biodiversity conservationist perspective, studying impacts on species viability when connectivity among suitable habitat patches breakdown or weaken (Metzger et al. 2020). Loss of forest connectivity may also limit pollen flow and seed movement, threatening the genetic diversity of plant species (Mina et al. 2018). But unregulated connectivity of susceptible locations and non-linear dynamics typically exhibited by complex systems often generate undesirable events that compromise forest landscape resilience (Aquilué et al. 2019). In fire-prone landscapes, when weather conditions are favourable, and an advancing fire front encounters large areas of dry fuel, fire creates its convective winds that favour fire spreading at high intensity, no matter the structure and composition of the underlying forest (Turner, Donato, and Romme 2013). In North America, the bark beetles and other herbivores and pathogens have steadily expanded during the last decades across continuous water-stressed forest landscapes affecting up to 20 million ha/year and potentially providing fuel for the next generation of wildfires (Ayres and Lombardero 2000; Sturrock et al. 2011).

Finally, modularity is a critical feature for system efficiency and resilience has a long recognition in biology, technology, economics, and social sciences. Modules (as structurally and functionally quasi-independent system components) have the capacity of buffering spreading disturbances and avoid system collapses (Stouffer and Bascompte 2011). When an ecosystem is organized in hierarchical modules, disturbance are often limited to the module they occur (Krause et al. 2003). If systems components are completely disconnected or the dispersal potential of the perturbation is lower than the separation between modules, the control of damage spreading is total, decreasing as modularity does (Aquilué et al. 2019). However, perfect modularity means splitting a system into independent sub-systems, likely becoming a less performing. The trade-off between modularity and connectivity/centrality is important to understand. With increasing modularity (quasi-independence) comes an increased resistance to the spread of disturbances from one module to another while at the same time it will also reduce organism, seed, and genetic flux that are responsible for increase ecosystem adaptability to those same disturbances (Raffa et al. 2008).

### 2.3.4 The functional complex network approach to Forest-Building

In Messier et al. (2019) functional network approach, a forest landscape is represented as a network of heterogeneous but adjacent elements, where forest stands are treated as nodes in the network. Species dispersal capacity is used to designate links between nodes. A source node is connected to a sink node only if at least one species at the source node is within the dispersal range of the sink node. Relative dispersal capacity within forest stands and between adjacent stands will influence the dispersal of species and, therefore, functional traits. After having characterized tree community functional diversity, metrics of network theory are applied to evaluate landscape-level functional connectivity (Saura 2011). Through an analysis of these indicators, stakeholders can evaluate the landscape-scale impacts of common silvicultural practices (e.g. tree-planting, shelterwood cutting, thinning) and natural disturbances (Aquilué et al. 2020). Aquilué et al. (2020) illustrated how to apply the functional network approach using the Haliburton Forest, a private forest in south-eastern Ontario, Canada. The authors first clustered common tree species into functional groups based on their respective response and effect traits. These functional groups are then used to characterize stand- and landscape-scale functional diversity, risk to multiple natural disturbances, and evaluate the effects of forest management scenarios of varying intensity and silviculture strategies followed. Through this approach the authors were able to propose recommendations for forest management strategies that can best address the challenges associated with climate change.

Selected functional traits that reflect how a specific tree species responds to two different types of environmental change, periodic disturbances (such as fire, pest and windfall) and chronic change (such as climate change):

- Maximum tree height (Aubin et al. 2012)
- Wood density (Miles and Smith 2022)
- Drought tolerance (Niinements and Valladares 2006)
- Shade tolerance (Niinements and Valladares 2006)
- Waterlogging tolerance (Niinements and Valladares 2006)
- Seed mass (Aubin et al. 2012)
- Mode of reproduction (Aubin et al. 2012)
- Seed dispersal vector (Aubin et al. 2012)
- Specific leaf area (Aquilué et al. 2021a)

Integrating the unique and innovative functional network approach with wood building systems and environmental assessments links the properties of trees, stands, and landscapes with the performance characteristics of wood in buildings. While there is no precedent for the application of the functional complex network approach for buildings, wood building techniques and construction systems could be clustered into groups based on the functional traits of buildings. These functional groups could then be used to characterize the stand- and landscape-scale wood demand and aligned with forest management scenarios which can supply this demand. The subsequent chapters of this dissertation will highlight new ways of thinking about the integrated nature of forests and buildings. How building and design plays a role in influencing forest species composition and how specific construction systems could potentially foster forest ecosystem resilience and adaptability. It will be possible to describe how forest ecosystems are functioning, and how wood building needs to adapt in response to forest management approaches and disturbance impact.

## 2.4 Forestry

The remainder of this chapter will present a non-exhaustive overview on past and current forest management and harvested wood products used in building in order to provide a background for subsequent chapters.

Each forestry management approach is governed by a specific framework that determines the relationships between forests and society. Throughout Canada and the United States, the Montreal Process outlines the criteria for sustainable forestry practices ("The Montréal Process: Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests" 2015). The criteria are:

(1) Conservation of biological diversity;

(2) Maintenance of productive capacity of forest ecosystems;

(3) Maintenance of forest ecosystem health and vitality;

(4) Maintenance of soil and water resources;

(5) Maintenance of forest contribution to global carbon cycles;

(6) Maintenance and enhancement of long-term socioeconomic benefits to meet the needs of society;

(7) Legal, institutional, and economic framework for forest conservation.

How to provide a "fair share" of these values equitably requires a comparison among ecosystems, the techniques for managing within ecosystems (forestry management approach, mechanized vs. horse logging, etc.), and what forms of human use of forests (i.e. timber in building, carbon sequestration, etc.) can be sustained over the long term. Forest management approaches, silviculture practices and how forest products are deployed through architecture have a profound effect on the success of forests, building and their social, ecological and economic impacts (Ramage et al. 2017). From this perspective, silviculture practices are deployed to maintain the environmental conditions that foresters deem most favourable. For example, the protected/reserve management approach applies a steady-state framework - a human misunderstanding of how forests behave - that unequally privileges a specific state of a forest ecosystem over others. For the reserve approach, the natural forest is considered undisturbed by anthropogenic change. It was assumed to be in a steady-state climax condition in which the large old trees were continually dying and replaced by younger trees growing from beneath. On the other hand, conservation-oriented forest management approaches also used the idea of a steady-state climax forests to develop silvicultural prescriptions under the assumption that each stand was all-aged and could be sustained in its natural state through selection harvest/regeneration methods. Ecologists and silviculturists approved the selection methods because they felt it was natural, scientifically based, and sustainable. Moreover, they were supported by loggers because they only had to harvest the large, valuable trees without spending time and resources cutting the others. However, forestry plantations are not closed-systems but are impacted by external chronic and episodic disturbances such as species immigration, extinction, and climate change. Recently, Messier et al. (2016) contrasted ten novel forest management approaches being advocated in different forest biomes to improve traditional forest management approaches. They evaluated each practice to consider the properties of CAS and, while some techniques fared well, most failed to acknowledge one or many CAS characteristics and did not engage with forestry products in building and other forest products.

### 2.4.1 Silviculture and forest management

The discipline of silviculture is the management and study of forests to produce desired services and products. Silvicultural practices have aimed to control the establishment, composition, structure, growth, and role of trees within managed forests. Each forestry management approach is governed by a specific framework that determines the relationships between forests and society. From this perspective, silviculture practices are the methods deployed to maintain the environmental conditions that foresters deem most favourable. Preferred tree species are established through natural regeneration, direct seeding, or planting. Composition refers to the variety of tree species and their relative abundance. The structure comprises forests' internal characteristics, including tree crowns, vigor, diameter and height distributions, the quantity and types of dead trees (snags), groundwood, and understory vegetation. Silviculturists manage tree growth and quality by manipulating tree species composition and density by removing other competing vegetation and improving site productivity.

Silvicultural activities are implemented through a series of individual practices that promote the desired species and stand characteristics within and among managed areas in a forested landscape (e.g., site preparation, promoting natural regeneration, planting, fertilization, thinning, and final harvest of individual trees or stands based on diameter or age). Individual silvicultural practices are integrated into a forest management approach, which can be viewed as a more extensive program of activities to achieve desired tree composition and growth objectives. The single greatest defining characteristic of the discipline of silviculture is the concept of silvicultural systems and their application in managing forests for societal goals. Silviculture and forest management approaches have been developed and refined over centuries in response to societal needs and pressures (see Figure 6).

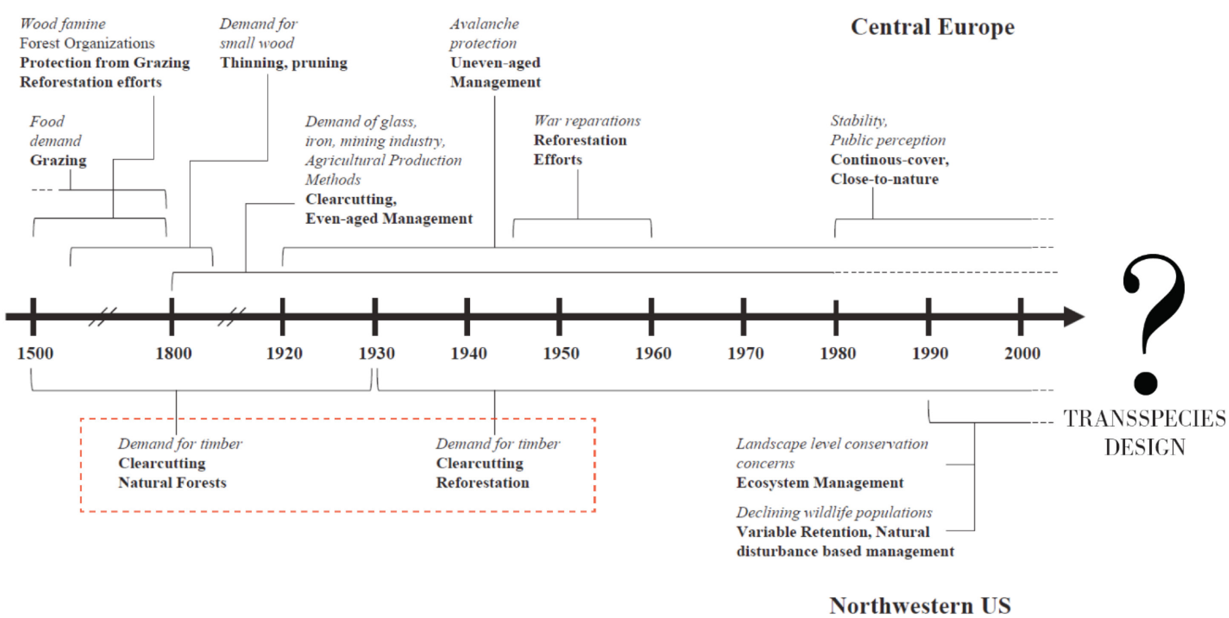



*Figure 6 - Timeline of forestry silvicultural practices designed to meet the needs of society. Adapted from Messier et al. (2015)*

Throughout most history, the dominant objective of landowners, and therefore of most silvicultural activities, has been the reliable and efficient production of wood for timber or other wood-based products. Accordingly, most silviculture practices of the past have successfully focused on developing practices have evolved primarily in response to five core principals that form the basic foundations of silviculture thinking, study, and practice today: (1) a dominant focus on trees, (2) management of stands as uniform entities, (3) applying an agricultural approach to silviculture research, (4) a scale-independent view of forestry practices, and (5) a focus on predictability. While individual practices have changed over the years based on a better understanding of their impacts or new technologies, silvicultural systems developed in nineteenth-century Europe continue to be applied throughout Canada and the world. As a result, silviculture across the globe has a common origin, and the basic structure and principles of the discipline are often considered to be independent of local conditions (Klaus J. Puettmann, Coates, and Messier 2009).

### 2.4.2 Managing forests for a variety of goals

Silviculture and forest management involves several decisions on the type of operation to employ at various stages of a tree, stand and landscape development to achieve the desired objective. Duncker et al. (2012) classify the development of a group of trees, stand or landscape into four "phases of development" according to their height and diameter. The first phase, regeneration (I), refers to the period from establishing young trees naturally or artificially until the stand has reached 2 to 3 m in height. The second phase, young (II), lasts until trees have reached pole size, i.e., 7 cm diameter at breast height (DBH). The third phase, medium (III), covers the period from trees having a DBH equal to 7 cm until the age/size when they have attained most of their potential height growth. The fourth phase, adult (IV), is reached when height growth has largely ceased, although diameter growth may continue; this phase includes the onset of senescence and eventual tree death.  These stages roughly correspond to Oliver and Larson's (1996) developmental stages of "stand initiation" (I), "stem exclusion" (II & III) which characterize pre-commercial thinning and non-merchantable trees, and "under-storey re-initiation" and "old-growth" as stage (IV).  It is important to note that the phases are not mutually exclusive in space or over time and no specific successional pathway can be predetermined (see Figure 7).  Under certain silviculture approaches, they may occur together in the same stand, e.g., in the complex stand structures characteristic of "close-to-nature" forestry. These practices affect one or more key characteristics, which subsequently influence the provision and range of ecosystem processes and services possible. Additionally, within any forestry management approach, the criteria, ecosystem processes and services to society will vary according to different stages of tree growth.

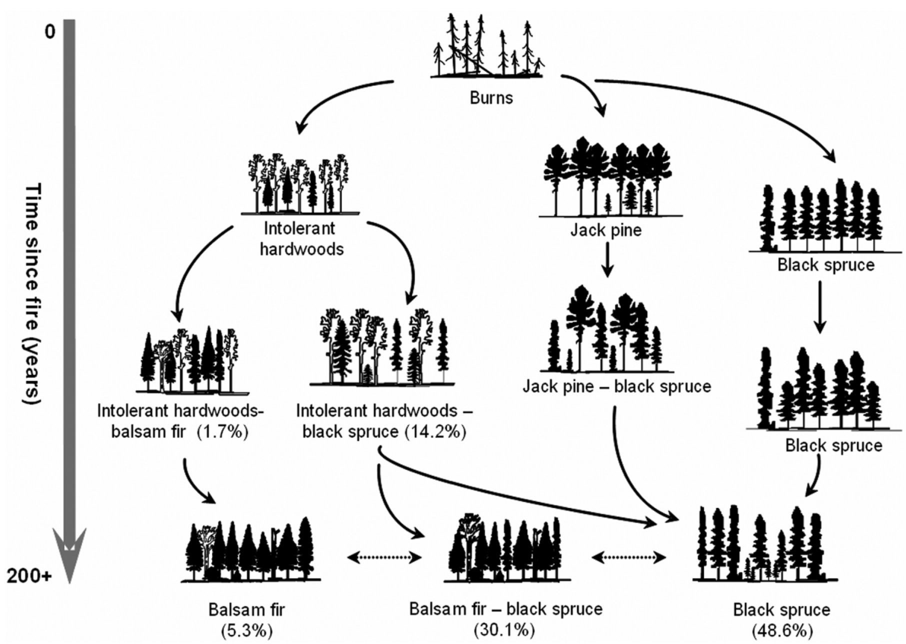



*Figure 7 - An example of multiple post-fire successional trajectories in Quebec boreal forest. Each pathway will result in a unique forest species composition and structure from which the wood construction industry will rely. How can wood design incorporate this uncertainty into the specification and design of wood buildings? Image reproduced from Filotas et al. (2014).*

# 2.5 Building

## 2.5.1 Buildings as a global carbon sink

Similar to forestry, wood buildings are increasingly being relied upon to respond to the effects of climate change (Oliver C.D. et al. 2014; Craig et al. 2020; Pomponi et al. 2020; Pomponi, Wolf, and Moncaster 2018; Fenner et al. 2018; Hoxha et al. 2020; Churkina et al. 2020; Kalt 2018). Recent research is suggesting that buildings may be able to act as a global carbon sink, using wood and other carbon sequestering materials to extend the residency time of carbon by the lifespan of buildings. For example, Oliver et al. (2014) evaluated the potential for the world's forests and long-lived wood products — such as buildings — to provide a meaningful quantity of carbon sequestration. Similarly, Craig et al. (2020) investigated the potential for mono-material wall assemblies with functional overlaps of structure, envelope, and systems may increase the overall carbon sequestration capacity of buildings. Furthermore, Ramage et al. (2017) reviewed the multiple wood construction systems, including their process, overall environmental impact, and effect on performance characteristics such as durability, structural performance, ease of assembly, and amount of wood used. While these studies begin to guide how we ought to be building with wood, all are still counting forests as resources to be extracted. There remains little attention paid to the impact on forest ecosystem resilience and adaptability. This omission may result in a further command and control mentality being applied to forestry as it supplies the construction industry with carbon credits in the form of wood. This points to the need to further research that can describe how buildings and forests can reflexively adapt and better inform one another in the decades ahead.

### 2.5.2 Net-zero and carbon-neutrality assumption

The following sections will provide an overview of the current limitations of approaches taken by the wood products and building industry to assess the carbon impact of wood construction. Several authors have highlighted the need to incorporate the biogenic carbon of wood products in product lifecycle assessments (LCA) (Lemprière et al. 2013; Helin et al. 2013; Oliver C.D. et al. 2014) and the majority of current guidelines and standards covering wood products now stipulate specific measures for biogenic carbon accounting (Hoxha et al. 2020). Current approaches used by LCA provide a simplified view that describes carbon uptake in forests as a negative emission (or sequestration) and the release of carbon as a positive emission. For certain HWPs like building materials, the carbon stored in the wood remains sequestered throughout the life of the building product, effectively delaying emissions for several decades or even centuries in some cases. Furthermore, long-term carbon storage in landfills has been recognized as having potential climate benefits (Head et al. 2021).

Yet, LCAs of HWPs and wood buildings rely upon the simplifying assumption of net biogenic carbon neutrality, where carbon harvested for use in wood products and buildings will be replaced by a similar amount of carbon that is regrown (Hoxha et al. 2020). A critique of the neutrality assumption is that it ignores temporary carbon storage and delayed emissions, which can result in potential climate benefits (Head et al. 2021). The 2003 Good Practice Guidance of the Intergovernmental Panel on Climate Change (IPCC) introduced the first methodologies for estimating and reporting biogenic carbon stocks and fluxes in HWP used in wood construction (IPCC 2003). Until then, it was assumed that the sum of carbon additions to the HWP pools from the current harvest was equal to the sum of carbon losses from the wood products harvested in prior years and that the total HWP carbon pool was constant. Instead of tracking the details of the fate of harvested carbon and forest biogenic carbon regrowth, the IPCC recommendations made the simplifying assumption that inputs are equal to outputs, thus effectively treating the carbon from wood harvest as being net-zero, ignoring any time delays associated to regrowth and storage benefits associated with HWP (Kull et al. 2019).

In their review of more contemporary LCA methods, Hoxha et al. (2020) summarized the two main approaches in which biogenic carbon uptake and release are modelled in traditional LCAs according to the IPCC Guidelines (IPCC 2019). The 'carbon neutral approach' (or the 0/0 approach), assumes that the release of $CO_2$ from a HWP at the end of its life is recovered by an equivalent uptake of $CO_2$ during the forest regrowth (see Figure 8). For this approach, there is no consideration of the temporality of biogenic $CO_2$ uptake (0) or release (0). In contrast, the second approach explicitly considers uptake and release ('–1/+1' approach) and consists of tracking the timing of biogenic carbon flows over the building life cycle (see Figure 8). Similar to the HWP carbon models described above, this LCA approach considers biogenic $CO_2$ uptake (–1) and release (+1) as well as the transfers of biogenic carbon between the different systems. Compared with the 0/0 approach, the main advantage of the –1/+1 approach is to provide an overview of all biogenic carbon flows. However, there is a risk of misleading results when only the impact of the product and construction process stages is assessed, only accounting for the biogenic carbon uptake without also reporting on the subsequent release at the end of the building of HWP lifecycle.

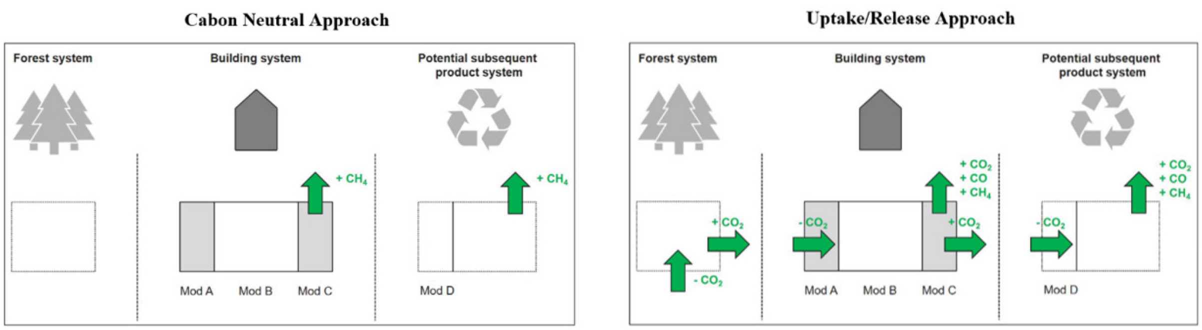



*Figure 8 – The 'carbon neutral' approach (left) and 'uptake/release' approach (right) to modelling biogenic carbon flows. The dotted lines indicate product systems that fall outside the building system boundaries. Reproduced from Hoxha et al. (2020).*

A further criticism of traditional, 'static', LCA approaches described above is that they do not consider the dynamic, temporal aspects of the carbon emissions. This can be problematic when assessing the impact of HWPs with long and varied growth periods (see Figure 9). Pittau et al. (2018) demonstrated that not all biobased products should be considered as carbon neutral. Specifically, the authors identified that HWPs have a very long rotation period due to slow forest growth periods and, therefore, should only be considered carbon neutral over equally long periods where the product life-cycle is greater than forest regrowth. In comparison to wood, biogenic materials, such as straw and hemp have relatively short rotation period and can provide an effective mitigation effect on greenhouse gas (GHG) emissions by rapidly removing carbon from the atmosphere (Pittau et al. 2018). Therefore, at a minimum, wood building lifecycles must match or exceed the forest rotation periods.

More recently, researchers have developed dynamic approaches to better capture these aspects of time in LCA. Levasseur et al. (2010) proposed a strategy based on time-dependent characterization factors. These characterization factors can be included in traditional LCA of buildings to explicitly consider the regrowth and rotation period of wood in forests. Cherubini et al. (2011) also developed specific characterization factors for biogenic $CO_2$ considering the rotation period of biomass. The longer the rotation period, the longer the residency time of $CO_2$ in the biomass and, therefore the higher the biogenic global warming score. Guest et al. (2013) extended the method proposed by Cherubini et al. (2011) to assess the impact of carbon storage in wooden products and found that carbon neutrality is achieved for a storage time of about half of the rotation period. Within the dynamic LCA approach, two scenarios can be considered related to the timing of biogenic carbon sequestration in the forest: (1) assuming that trees grow before the use of the harvested wood product, following the natural carbon cycle; or (2) accounting for the so-called 'regrowth' after harvesting, assuming an equal amount of the harvested trees would start growing right after the production process (Peñaloza, Erlandsson, and Falk 2016; Pittau et al. 2018; Figure 9). Results will vary considerably between the two approaches (Peñaloza, Erlandsson, and Falk 2016), so the selection must be justified and clearly declared.

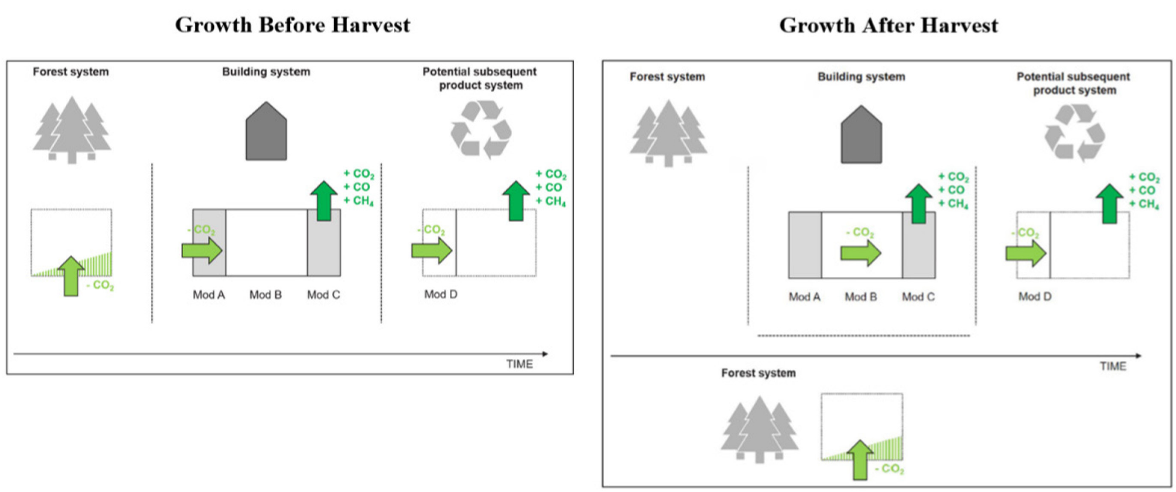



*Figure 9 – The dynamic approach to biogenic carbon uptake. Top: considering that trees grow before the use of the harvested wood product. Bottom: considering that trees grow after harvesting. The dotted lines indicate product systems that fall outside the building system boundaries. Reproduced from Hoxha et al. (2020).*

### 2.5.3 Overview of Wood Construction Approaches

Wood construction and wood products have a long and traditional history in Quebec and Canada. Today, a wide range of harvested wood products are manufactured for use in buildings in multiple applications, from structural and envelope systems to millwork and finishes. In North America, wood products dominate the structural framing and sheathing of the residential construction market. More recently, innovations in wood products have made it possible to build taller and larger public, commercial, and industrial buildings using wood as the principal structural material. This section outlines the variety of wood construction approaches currently used in building and used throughout this dissertation. This non-exhaustive list is intended to give a background on the most common harvested wood products used in building throughout Canada: the possible species used, the manufacturing process, and the utilization in building. Broadly speaking, HWP used in building can be categorized into four groups: softwood lumber and solid-sawn timber, engineered composite lumber, wood panels, and mass timber.

#### 2.5.3.1 Softwood lumber and solid-sawn timber

Softwood dimensional lumber is the most common and recognizable form of HWP used in current construction. Dimensional lumber is solid sawn wood that is less than 89 mm (3.5 in) in thickness. The maximum length of dimensional lumber is typically around 7 m (23 ft), but varies throughout Canada.  The majority of dimensional lumber used in construction is in framing of roofs, floors and wall. Lumber can be used directly as framing material and is also often used to manufacture engineered structural products such as light frame trusses, prefabricated I-joists, and built-up beams, etc.

*Figure 10 - Softwood lumber stacked and sticker after milling. (Photo: Peter Osborne)*

Softwood species in Canada are organize into commercial groups. Commercial groups simplify the supply and use of structural softwood lumber by combining species having similar characteristics and typically grown in the same region and conditions. Having a smaller number of species combinations makes it easier to design and select an appropriate species and for installation and inspection on the job site. In contrast, non-structural wood products are graded solely on the basis of appearance quality and are typically marked and sold under an individual species (e.g., Eastern White Pine, Western Red Cedar). The four major commercial groups sold throughout Canada are Spruce-Pine-Fir (S-P-F), Douglas Fir-Larch, Hem-Fir, and Northern Species. The principal species grown across Canada forested landscape are shown in Figure 11.

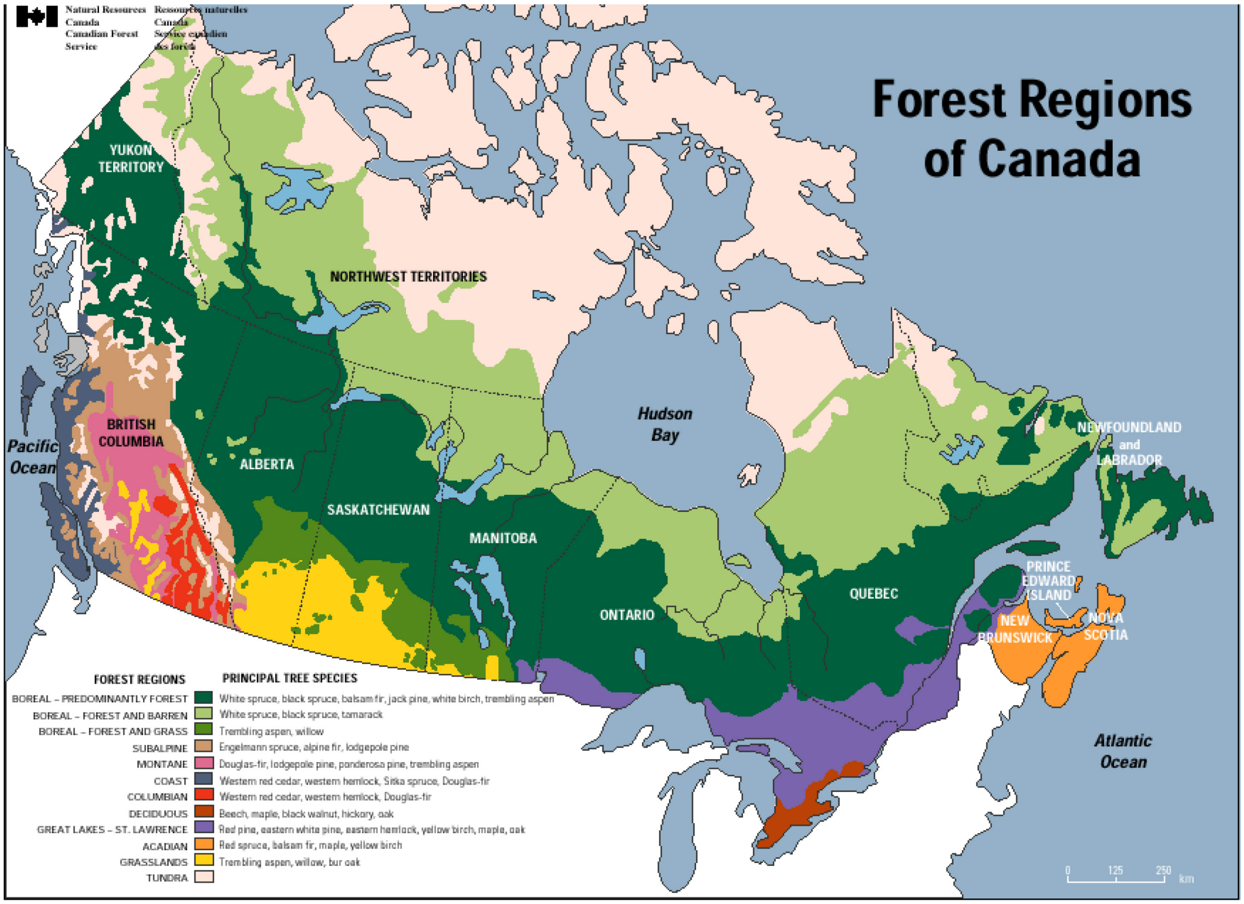



*Figure 11 – Principal tree species grown in forest regions across Canada (N. R. Canada and Service 2020).*

## Classification of lumber

Canadian dimensional lumber is manufactured in accordance with CSA O141 Canadian Standard Lumber and must conform to the requirements of the Canadian and US lumber grading rules. Each piece of dimensional lumber is inspected to determine its grade and a stamp is applied indicating the assigned grade, the mill identification number, a green (S-Grn) or dry (S-Dry) moisture content at time of surfacing, the species or species group, the grading authority having jurisdiction over the mill of origin, and the grading rule used, where applicable (see Figure 12 and Figure 13).

Lumber used for structural framing products must either visually or machine graded for their strength and other physical properties (see Table 1). Visual lumber grades represent a minimum standard describing the characteristics of the lumber. A lumber grader assigns each piece of lumber a grade based on considerations of intended use, size, quality and species. The National Lumber Grades Authority's Standard Grading Rules for Canadian Lumber maintains a published list of the permitted characteristics within each grade of dimensional lumber (NLGA 2022). Unlike visually graded lumber where the anticipated strength properties are determined from assessing a piece on the basis of visual appearance and presence of defects such as knots, wane or slope of grain, the strength characteristics of machine stress-rated (MSR) lumber are determined by applying forces to a member and actually measuring the stiffness of a particular piece following the ASTM D1990 standard. Data for bending, tension parallel to grain, compression parallel to grain, and modulus of elasticity can be analyzed with this method. MSR lumber is also visually checked for properties other than stiffness which might affect the suitability of a given piece. Given that the stiffness of each piece is measured individually, and strength is measured on select pieces through a quality control program, MSR lumber can be assigned higher specified design strengths than visually graded dimensional lumber.

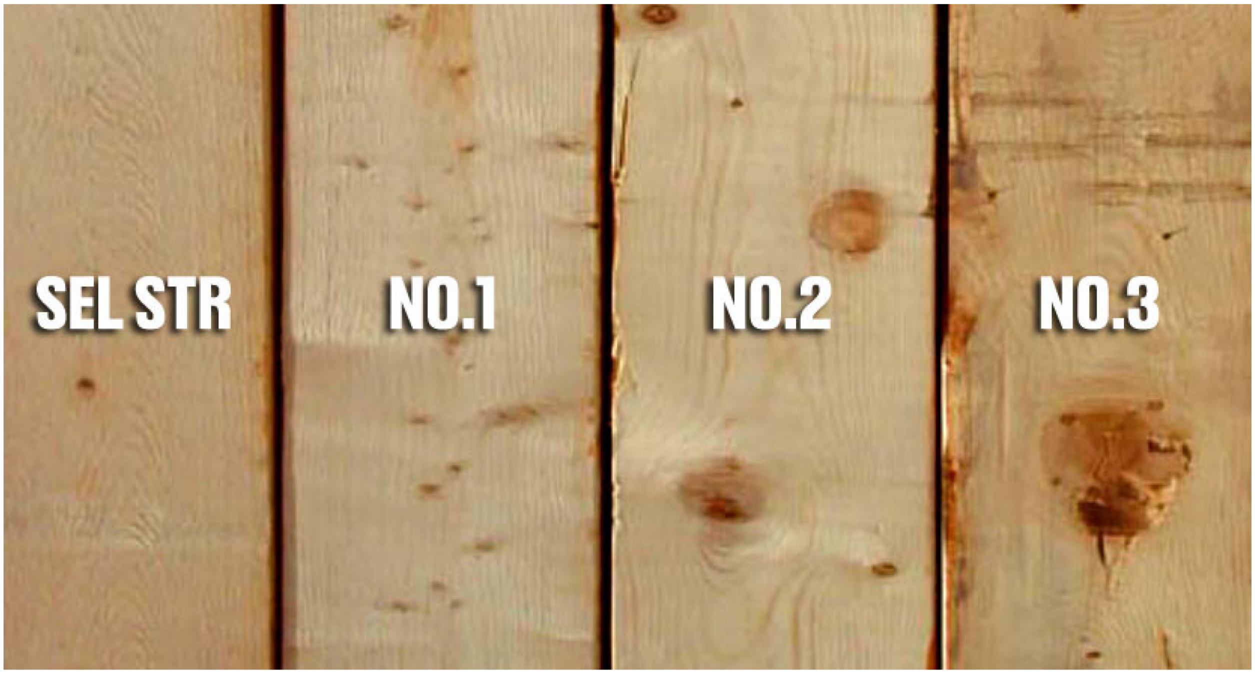



*Figure 12 - Visual guide to lumber grades. Visual grading is a method of evaluating lumber by examining its four sides for imperfections that could affect its structural integrity. A trained grader moves quickly along a grading chain to assign each piece of lumber to a visual grade. (Source: "Unraveling the Lumberyard Labyrinth: Your Guide to Lumber Grades," n.d.)*

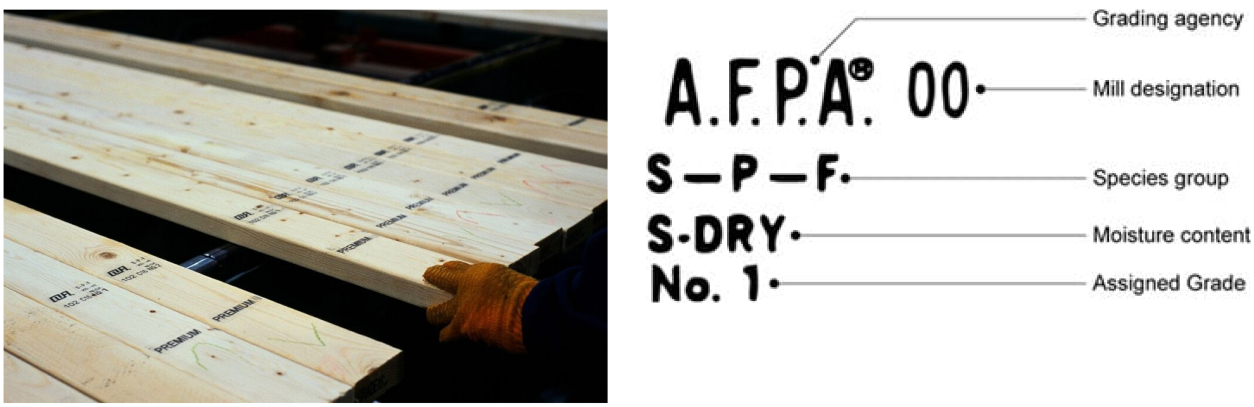



*Figure 13 – Visual grader inspecting dimensional lumber (left) and Example lumber grade stamp (Source: Canadian Wood Council 2021). (Photo: "Naturally:Wood | British Columbia's Sustainable Forestry Resource," n.d.)*

*Table 1 – Select visual grading characteristics for dimensional lumber*

| | Grades | | |
|---|---|---|---|
| **Characteristic** | **Select Structural** | **No.1 & No. 2** | **No. 3** |
| Edge of wide face knots | 3/4" | 1 1/4" | 1 3/4" |
| Slope of grain | 1 in 12 | 1 in 8 | 1 in 4 |

**Solid Sawn Heavy Timber**

Similar to dimensional lumber, solid sawn heavy timber members are commonly used as the main structural elements in building. The term 'heavy timber' is often used to describes solid sawn lumber which is 140 mm (5-1/2 in) or more in its smallest cross-sectional dimension and are common in post and beam construction methods. Large dimension timbers offer increased fire resistance compared to dimensional lumber and can be used to meet the heavy timber construction requirements outlined in the Part 3 of the National Building Code of Canada. Sawn timbers are produced in accordance with CSA O141 Canadian Standard Lumber and graded in accordance with the NLGA Standard Grading Rules for Canadian Lumber. There are two categories of timbers; rectangular "Beams and Stringers" and square "Posts and Timbers". Beams and stringers, whose larger dimension exceeds its smaller dimension by more than 51 mm (2 in), are typically used as bending members, whereas, posts and timbers, whose larger dimension exceeds its smaller dimension by 51 mm (2 in) or less, are typically used as columns. Due to the large size of the timbers, kiln drying is often impractical due the drying stresses put on the wood. For this reason, timbers are usually left green (moisture content above 19 percent), and the moisture content of timber upon delivery will depend on the amount of air drying which has taken place. Because of the tree diameters necessary to produce lumber of this size larger timbers (Sizes up to 394 x 394 mm) are generally produced in Western Canada using Douglas Fir-Larch and Hem-Fir Species commercial groups. In Central and Eastern Canada, S-P-F and Northern species are only available in smaller sizes.

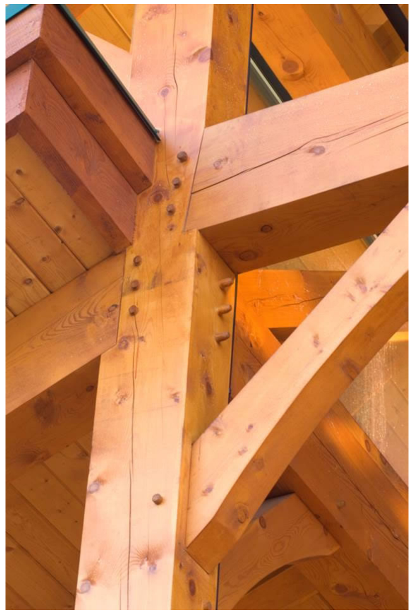


*Figure 14 - Timber used in post and beam construction. (Photo: N. R. Canada 2014)*

### 2.5.3.2 Structural Composite Lumber

Structural composite lumber (SCL) is a term used to encompass the family of engineered wood products that includes laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL) and oriented strand lumber (OSL). In general, SCL consists of dried and graded wood veneers, strands or flakes that are layered and bonded together into large billets with a moisture resistant adhesive. These SCL billets can then be resawn into specified dimensions and lengths. One manufacturing benefit of SCL is the ability to be manufactured with small, fast-growing, undervalued and underutilized species. The four primary SCL products are summarized below:

**Laminated Strand Lumber (LSL)** is one of the more recent structural composite lumber (SCL) products to come into widespread use. LSL provides attributes such as high strength, high stiffness and dimensional stability. LSL is used primarily as structural framing for residential, commercial and industrial construction. Common applications of LSL in construction include headers and beams, tall wall studs, rim board, sill plates, millwork and window framing. LSL also offers good fastener-holding strength.

Similar to parallel strand lumber (PSL) and oriented strand lumber (OSL), LSL is made from flaked wood strands that have a length-to-thickness ratio of approximately 150. Combined with an adhesive, the strands are oriented and formed into a large mat or billet and pressed. LSL resembles oriented strand board (OSB) in appearance as they are both fabricated from the similar wood species and contain flaked wood strands, however, unlike OSB, the strands in LSL are arranged parallel to the longitudinal axis of the member. The manufacturing process of LSL enables large members to be made from relatively small trees, providing efficient utilization of forest resources. LSL is commonly fabricated using fast growing wood species such as Aspen and Poplar.

*Figure 15 - Laminate strand lumber. (Canadian Wood Council 2021)*

**Laminated veneer lumber (LVL)** has been available as a construction product since the mid-1970s. LVL is the most widely used structural composite lumber (SCL) product and provides attributes such as high strength, high stiffness and dimensional stability (Canadian Wood

Council 2021). The manufacturing process of LVL enables large members to be made from relatively small trees, providing efficient utilization of forest resources. LVL is commonly fabricated using wood species such as Douglas fir, Larch, Southern yellow pine and Poplar. LVL is used primarily as structural framing for residential and commercial construction. Common applications of LVL in construction include headers and beams, hip and valley rafters, scaffold planking, and the flange material for prefabricated wood I-joists. LVL is made of dried and graded wood veneer which is coated with a waterproof phenol-formaldehyde resin adhesive, assembled in an arranged pattern, and formed into billets by curing in a heated press. The LVL billet is then sawn to desired dimensions depending on the end use application.

*Figure 16 - Laminate veneer lumber. (Photo: Canadian Wood Council 2021)*

**Parallel Strand Lumber** (PSL) provides attributes such as high strength, high stiffness and dimensional stability. The manufacturing process of OSL enables large members to be made from relatively small trees, providing efficient utilization of forest resources. In Canada, PSL is fabricated using Douglas fir. PSL is employed primarily as structural framing for residential, commercial and industrial construction. Common applications of PSL in construction include headers, beams and lintels in light-frame construction and beams and columns in post and beam construction. PSL is an attractive structural material which is suited to applications where finished appearance is important. Similar to laminated strand lumber (LSL) and oriented strand lumber (OSL), PSL is made from flaked wood strands that are arranged parallel to the longitudinal axis of the member and have a length-to-thickness ratio of approximately 300. The wood strands used in PSL are longer than those used to manufacture LSL and OSL. Combined with an exterior waterproof phenol-formaldehyde adhesive, the strands are oriented and formed into a large billet, then pressed together and cured using microwave radiation.

*Figure 17 - Parallel strand lumber. (Photo: Canadian Wood Council 2021)*

**Oriented Strand Lumber** (OSL) provides attributes such as high strength, high stiffness and dimensional stability. The manufacturing process of OSL enables large members to be made from relatively small trees, providing efficient utilization of forest resources.

OSL is used primarily as structural framing for residential, commercial and industrial construction. Common applications of OSL in construction include headers and beams, tall wall studs, rim board, sill plates, millwork and window framing. OSL also offers good fastener-holding strength. Similar to laminated strand lumber (LSL), OSL is made from flaked wood strands that have a length-to-thickness ratio of approximately 75. The wood strands used in OSL are shorter than those in LSL. Combined with an adhesive, the strands are oriented and formed into a large mat or billet and pressed. OSL resembles oriented strand board (OSB) in appearance as they are both fabricated from the similar wood species and contain flaked wood strands, however, unlike OSB, the strands in OSL are arranged parallel to the longitudinal axis of the member.

*Figure 18 - Oriented strand lumber. (Canadian Wood Council 2021)*

#### 2.5.3.3 Wood panels

**Plywood** is a widely recognized engineered wood-based panel product that has been used in Canadian construction projects for decades. Plywood panels manufactured for structural applications are built up from multiple layers or plys of softwood veneer that are glued together so that the grain direction of each layer of veneer is perpendicular to that of the adjacent layers. These cross-laminated sheets of wood veneer are bonded together with a waterproof phenol-formaldehyde resin adhesive and cured under heat and pressure (Figure 19).

*Figure 19 – The plywood manufacturing process. Left: Canadian plywood mill. (Photo: "Naturally:Wood | British Columbia's Sustainable Forestry Resource," n.d.). Right: Plywood sheet. (Photo: Canadian Wood Council 2021)*

Plywood is suitable for a variety of end uses in both wet and dry service conditions, including: subflooring, single-layer flooring, wall, roof and floor sheathing, structural insulated panels, marine applications, webs of wood I-joists, concrete formwork, pallets, industrial containers, and furniture. Unsanded sheathing grade Douglas Fir Plywood (DFP), conforming to CSA O121, and Canadian Softwood Plywood (CSP), conforming to CSA O151, are the two most common types of softwood plywood produced in Canada.

**Oriented Strand Board** (OSB) is a widely used, versatile structural wood panel. OSB makes efficient use of forest resources, by employing less valuable, fast-growing species. The manufacturing process can make use of low value and underutilized trees with crooked, knotty and deformed branching and stems which would not otherwise have commercial value, thereby maximizing forest utilization. OSB is a structural mat-formed panel product that is made from thin strands of aspen or poplar, sliced from small diameter roundwood logs or blocks, and bonded together with a waterproof phenolic adhesive that is cured under heat and pressure. Typically, in Canada OSB is made from abundant, small diameter poplar and aspen trees. OSB is also manufactured using the southern yellow pine species in the United States. Other species, such as birch, maple or sweetgum can also be used in limited quantities during manufacture. OSB panels are primarily used in dry service conditions as roof, wall and floor sheathing, and act as key structural components for resisting lateral loads in diaphragms and shear walls. OSB is also used as the web material for some types of prefabricated wood I-joists and the skin material for structural insulated panels. OSB can also be used in siding, soffit, floor underlayment and subfloor applications. In Canada, OSB panels are manufactured to meet the requirements of the CSA O325 standard. This standard sets performance ratings for specific end uses such as floor, roof and wall sheathing in light-frame wood construction. Sheathing conforming to CSA O325 is referenced in Part 9 of the National Building Code of Canada (NBC). In addition, design values for OSB construction sheathing are listed in CSA O86, allowing for engineering design of roof sheathing, wall sheathing and floor sheathing using OSB conforming to CSA O325.

*Figure 20 - OSB used as sheathing in residential construction. (Photo: N. R. Canada 2014)*

#### 2.5.3.4 Mass timber

Products such as cross-laminated timber (CLT), dowel-laminated timber (DLT), nailed-laminated timber (NLT), glued-laminated timber (GLT), and other large-dimensioned SCL products are part of a bigger classification known as 'mass timber'. Although mass timber is an emerging term, traditional post-and-beam (timber frame) construction has been around for centuries. Mass timber products can be formed by mechanically fastening and/or bonding with adhesive smaller wood components such as dimensional lumber or wood veneers, strands or fibres to form large pre-fabricated wood elements used as beams, columns, arches, walls, floors and roofs. Mass timber products have sufficient volume and cross-sectional dimensions to offer significant benefits in terms of fire, acoustics and structural performance, in addition to providing construction efficiency.

**Cross Laminated Timber**

Cross-laminated timber (CLT) is a wood panel system that has gained popularity in the U.S. and Canada after being widely adopted in Europe. It consists of layered lumber boards (usually three, five, or seven) stacked and glued crosswise at 90-degree angles, delivering excellent structural rigidity in both directions. Alternating grains improve CLT panels' dimensional stability. Finger joints and structural adhesive connect the boards. Board thickness varies between 5/8 inch and 2 inches, with board width most commonly ranging from 2.5 to 5.5 inches. The panels can be manufactured in custom dimensions, though transportation restrictions dictate their overall size. Common applications include floors, walls, and roofs. Other applications include cantilevered floors and balconies, loadbearing elevator shafts, and stairs. The panels' ability to resist high racking and compressive forces makes them especially cost-effective for multistory and long-span diaphragm applications. In structural systems, such as walls, floors, and roofs, CLT panels serve as load-bearing elements and are well suited to taller timber construction. As with other mass timber products, CLT can be left exposed in building interiors—up to 8 or 9 stories in buildings under the 2021 IBC (depending on occupancy), offering additional aesthetic attributes.

*Figure 21 - CLT panels waiting for installation. (Photo: N. R. Canada 2014)*

**Dowel-laminated timber**

Dowel-laminated timber (DLT) is a mass timber product commonly used in Europe and gaining popularity in North America. Panels are made from softwood lumber boards (2x4, 2x6, 2x8, etc.) stacked on end and friction-fit together with dowels, typically made from hardwood lumber. Similar to nail-laminated limber, DLT panels can be used for walls, floors and roofs, stairs and elevator shafts, or bent and assembled to create curved structures. DLT's all-timber design, with no metal connectors, means it can be easily processed and cut using computerized numerical control (CNC) machinery. Alternating patterns of lumber can be used to create various aesthetic appearances. DLT panels can also accommodate mechanical services and sound absorbing insulation, tucked away as part of its cut and design. DLT panels can be topped with concrete to form composite panels.

*Figure 22 - Cross-section of down-laminated timber. (N. R. Canada 2014)*

**Nail-laminated timber**

A century-old building construction material, nail-laminated timber (NLT) is made from dimensional lumber stacked on edge and fastened together with nails or sometimes screws to form a solid structural element. The boards are nominal 2x, 3x, and 4x thickness. Width is typically 4 to 12 inches. NLT gets its strength and durability from the nails/screws fastening the individual pieces of lumber.

Applications for NLT include floors, decks, roofs, and walls, as well as elevator and stair shafts. Adding plywood or oriented strand board sheathing on one face of the panel provides load-bearing capacity, allowing NLT to be used as a shear wall or structural diaphragm. NLT offers a consistent appearance for decorative or exposed-to-view applications and can include curves and cantilevers.

*Figure 23 - Ceiling made of nail-laminated timber. (N. R. Canada 2014)*

**Glue laminated timber**

Glulam is composed of individual wood laminations (dimensional lumber), selected and positioned based on their performance characteristics, and then bonded together with durable, moisture-resistant adhesives. The grain of all laminations runs parallel with the length of the members, which can be customized to create elements that are straight, curved, arched, and tapered. As one of the oldest and widely used mass timber products, glulam's application is broad and includes virtually all building types. Beyond buildings, it can serve as the primary material for major load-bearing structures such as bridges, canopies, and pavilions. It can be used as columns or beams (straight or curved), or affixed side-by-side to form panels. It is particularly well suited to long-spanning structures and custom curvilinear shapes, and combines well with hybrid assemblies and building systems. While typically used as beams and columns, designers can use glulam in the plank orientation for floor or roof decking similar to NLT.

*Figure 24 –Glued-laminated timber(Glulam) of architectural appearance grade consists of small wood laminations bonded together in parallel using structural adhesives. (Photo: Canadian Wood Council 2021)*

## 2.6 Exploring carbon sequestration in wood buildings and forests with system dynamics modelling

This dissertation aims at proposing a comprehensive and flexible new approach towards the management and design of forests and buildings as a coupled CAS. This coupled approach towards the design and management of forests and buildings will better prepare our forests and built environments to face future challenges under rapidly changing global environmental and socio-economic conditions. An approach that stewards forests' resilience to global changes while also achieving the multi-functionality required for the building industry (i.e., the availability of timber for the construction industry). Researchers suggest the synchronization of forestry and building shows a promising means to address the ecological challenges of using wood buildings for carbon sequestration(Oliver C.D. et al. 2014). A preliminary investigation into the combined carbon sequestration of forests and buildings draws particular attention to the drivers under the control of each sector and how assessing carbon sequestration in forests and buildings alone is may be counterproductive(Osborne 2022). Instead, as illustrated in Figure 25 building practices and policies should be tuned to forests' regeneration cycles. The study results suggest that total carbon storage would be greatest when forests and building practices are synchronized, where the harvest is at the point of max biomass growth (i.e. long harvest rotations), the harvest rate is a relatively small portion of total stand biomass(<20%) and building lifespan is longest. In addition, these preliminary findings suggest that the shift towards high wood use techniques such as mass timber may sequester more carbon if the lifespan of a building is longer than the regrowth of the forest after harvest.  These findings suggest a combined CAS approach can be used to develop and evaluate more suitable forestry and construction policies and practices that are more environmentally and socially acceptable.

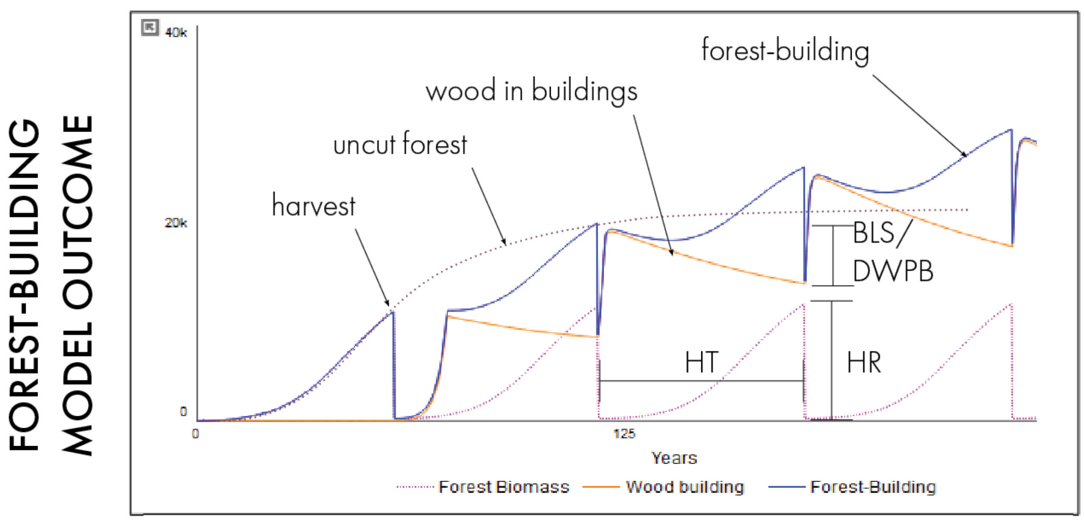



*Figure 25 – Combined forest-building system dynamics model showing the carbon sequestered(tons Carbon) for a theoretical 100ha forest unit and possible building carbon poo, and the primary influence of each driver: Harvest Threshold(HT), Harvest Rate(HR), Desired Wood Per Building(DWPS) and Building Lifespan(BLS). Reproduced from Osborne (2022).*

# 3 Overview of impact assessments and indicators

The Forest-Building design-space being proposed can be associated with a family of impact assessment frameworks, indicators, methods and tools. While the literature is inconsistent in its use of terms, I adopt the terminology in Sala et al. (2013) throughout this dissertation to acknowledge a hierarchically different role for each element. I use the framework as the rationale and structure for the integration of concepts, methodologies and tools. The methodology describes a collection of unique characterization methods addressing environmental, economic and social effects and impacts. Methods are a set of models used for the evaluation of indicators for a particular impact category. Tools are a set of software, databases, or applications supporting the analysis done by adopting a specific method and related models. Moreover, an indicator is a measurable (quantitively or qualitatively) parameter that describes a specific process or aggregation of processes. Many sustainability assessment researchers argue that the goal of sustainability assessment is to provide decision-makers and stakeholders with indicators, tools and methods to evaluate the socio-ecological systems (SES) across multiple scales of space and time to determine which actions should or should not be taken to build a more resilient and adaptable society (Devuyst et al. 2001; Kates et al. 2001; Ness et al. 2007; Karvonen et al. 2017; Sala, Farioli, and Zamagni 2013; Sala, Ciuffo, and Nijkamp 2015). These methods fall under various forms depending on the social, ecological, economic or integrated focus and the different scalar, temporal, and industry-related boundaries to the questions at hand.

For this background review—an assessment of assessments—over 100 assessment criteria, tools, and methods have been categorized according to CAS framework in Figure 53. This assessment inventory is based on literature from a wide array of sources and disciplines. The material used consists of literature describing each method, tool, and criteria and material related to applying each of the assessment approaches. This review is not to provide an exhaustive list of all the methods, criteria and tools available for sustainability assessment but rather to highlight and connect those most essential for assessing the complex system dynamics of forests and buildings found in the literature today. Extant methods include but are not limited to Sustainability Impact Assessment, Environmental Impact Assessment, Ecological/Economic/Social Impact Assessments, Life-cycle assessment, Life cycle costing, Environmental footprinting, Ecosystem science assessment, Environmental Impact Assessment, and Strategic Environmental Assessment, Input-Output and Environmentally Extended Input-Output, Material/Substance Flow Analysis, Energy/Exergy/Emergy Analysis, Cost-benefit analysis, Uncertainty/vulnerability/risk analysis, and Multicriteria Analysis. Nevertheless, authors agree that extant impact assessments pay little attention to forests' services and functions, including a wide range of ecological, political, economic, social, and cultural systems and processes that are necessary for building. Therefore a new nexus design-space is needed to bring together these multiple disciplines.

Of particular interest for this dissertation is the inclusion of ecological impacts — understood as feedback loops from the framework of CAS — between forestry and building. The focus on carbon emissions alone, while extremely important, has been increasingly myopic and has blinded stakeholders to the complexities of spatio-temporal dynamics of forest ecologies— such as soil compaction and quality, water and air, biodiversity, land-use change and forest stand regeneration capacity in the face of global climate change(Schweier et al. 2019). In addition, the disciplinary divisions of forestry and construction make it difficult to assess the impacts changes in building practices have on forest ecosystems and vice versa. In order to better understand these impacts, I reflect on the following question:

- How can today's tools for monitoring and reporting on environmental and ecological conditions be integrated within a Forest-Building design-space to provide more useful guidance for designers to design and build with wood?

This question stresses the need for the extension and integration of ecological and building assessment, monitoring, and planning necessary for Forest-Building. It is clear that the purpose of sustainability assessment is to provide decision-makers with an evaluation of global to local integrated nature-society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable. Therefore, with the stated objectives of Forest-Building assessment, and integrated sustainability assessment more generally in mind, the challenges to future assessments call for:

- The adoption of a holistic approach for understanding the dynamic relationships, vulnerability, and resilience of the complex social-ecological systems of forests and buildings;
- Moving from multidisciplinary to transdisciplinary design, characterized as: the functional integration of different methods and worldviews; the co-production of knowledge through collaboration between disciplines; engagement with the specific characteristics of the local and regional settings; and the inclusion of stakeholder values and perceptions in the identification of design solutions (Lang et al. 2012).
- The capability to provide direction through visions and goals.

- The promotion of social learning and mutual feedback though stakeholder engagement leading to the co-production of knowledge and design solutions with all actors. It is essential to acknowledge that forestry and building have a disproportionately large effect on rural and indigenous communities where the majority of the effects are located (Kates et al. 2001; S. Bunker 2005; Alvarez and Rubio 2016).
- The ability to account for uncertainty by adopting resiliency based approach for assessment scenarios.

But to which degree do the current sustainability assessment frameworks and methodologies fulfill these promises of these objectives? And which criteria, tools, and methods best integrate the complex nature-society systems to address the multi-scale, multi-temporal dimensions required for a next-generation Forest-Building assessment? Unfortunately, according to many authors these characteristics are rarely found in examples of forestry related sustainability assessments (Pope, Annandale, and Morrison-Saunders 2004; Sala, Ciuffo, and Nijkamp 2015; Karvonen et al. 2017), and even fewer enter assessments of the built environment.

A general understanding of the current assessment frameworks and to which degree they can incorporate the complex social, ecological, and economic system dynamics is necessary for an integrated Forest-Building assessment today. Further, this chapter presents a categorization of sustainability assessment tools and methods with a presentation of each group of tools and its area of applicability for Forest-Building. This categorization is based first on their approaches and focus area, then evaluated according to the principles of complex adaptive systems. Recognizing the value of Forest-Building as an approach based on complex adaptive systems may help shift the focus of sustainability assessment from doing ‘less bad’ towards one who believes humans, through forestry and building, can contribute to making our natural world more adaptive and resilient to the increasing speed of change and disturbances through careful, designed, and scientifically sound interventions. By focusing on the exchanges of forests and buildings, we can ask how building cycles can impact the natural, synergistic, and emergent properties of forests.

## 3.1 Assessing Complex Adaptive Systems

To evaluate the various sustainability assessment indicators and tools needed for a Forest-Building framework, we need to evaluate them according to the principles of complex adaptive systems. To the earlier discussion:

- Forest systems provide the biophysical surroundings and flows of energy, materials, and information that are required by the self-organizing processes of the building system.
- Building systems can alter the structures in forest systems. Changes in the forest structure can then, in return, alter the context for the building systems themselves.
- Building systems can alter the context for the self-organizing processes of forest systems. Changes in ecological processes can alter ecological structure and consequently they context of the societal system. For example, clear cutting and plantation of monoculture forests will alter the underlying complexity of the forest ecosystem.

Understanding forests and buildings as integrated complex adaptive systems will require foresters, land managers, architects and builders to assess how their practices affect all properties of complexity science described above. Preiser et al. (2018) describe the key implications of using the principles of complex adaptive systems for choosing potential methods and approaches to sustainability assessment. They argue the impact of such changes include a greater emphasis on multiple temporal, spatial and hierarchical scales; more explicitly considering interactions among numerous biotic and abiotic components of forests; understanding and expecting nonlinear responses; and planning for greater uncertainty in future conditions. Therefore, the goal of using the principles of complex adaptive systems to evaluate sustainability indicators and tools is to transcend the subject-object, society-nature, relationship of traditional reductionist practices and introduce a relational component as the object of study, in which the complex spatio-temporal dimensions and the contextual environment for that relationship are addressed.

### 3.1.1 Criteria and Indicators

To assess forests and buildings, multidimensional impact assessments for decision making are needed. Earlier overviews and evaluation of sustainability assessment tools are based on numerous factors and dimensions are presented in Table 9 (Baumann 1999; Wrisberg et al. 2002; Finnveden and Moberg 2005; Kates et al. 2001; Ness et al. 2007; Gasparatos, El-Haram, and Horner 2008; Mayer 2008; Thabrew, Wiek, and Ries 2009; Kissinger, Rees, and Timmer 2011; Jeswani et al. 2010; Patterson, McDonald, and Hardy 2017; Villeneuve et al. 2017; Waas et al. 2014; Cinelli, Coles, and Kirwan 2014; Schweier et al. 2019; Ananda and Herath 2009). The sustainability assessment tool framework developed by Ness et al. (2007) is organized into three general categories; 1) indicators and indices, which include both non-integrated and integrated criteria; 2) product-related assessment tools which focus on the material and/or energy flows of a product or service from a life cycle perspective; and 3) integrated assessment, which is a collection of tools focused on policy change or project implementation.  Noting that forests and wood products will play an essential role in efforts to decrease the use of hydrocarbon fuels and to transition towards a low-carbon society, Karvonen et al. (2017) assessed the current state of the art sustainability indicators, methods, and tools used in the assessment of forest bioeconomies. The authors propose that evaluating indicators and tools for their interlinked economic, ecological, and social sustainability impacts of forestry is critical to understand how a change in one dimension is reflected in other dimensions. They organized indicators and tools into the three dimensions of sustainability (environmental, economic, and social) as well as identifying the integrated relationships between each indicator or tool. In their paper on the concept of forest operation sustainability, Marchi et al. (2018) proposed a more detailed approach towards what they refer to as Sustainable Forest Operations (SFO). They define SFO as "a complex system of relationships that encompasses a set of technologies, methods, systems and practices applied in forest operations planning, implementation, monitoring and improvements." The authors base SFO on the concepts of complex systems and include five performance areas: economic, ergonomic, environmental, environment, quality optimization, and people and society. The inclusion of ergonomic and quality optimization brings more consideration to the anthropogenic activities of humans as an interactive element in the system. Specifically, understanding the ergonomics of forest operations is necessary as forestry cannot be considered sustainable if forest workers—historically one of the most dangerous and under-paid sectors of human labor—are not safeguarded and protected from undue risks. Furthermore, in their review of state of the art Sustainability Impact Assessments of forest operations, Schweier et al. (2019) included an umbrella category for soil compaction caused by forest operations. The inclusion of soils as a specific category brings greater emphasis to the role soils play in the context of forest ecosystems. Finally, structure-strengthening criteria have been found in various studies related to the locating of urban forests (Van Elegem et al. 2002; Gül, Gezer, and Kane 2006). In their study, Van Elegem et al. (2002) use structure-strengthening targets to give weight criteria that reinforce multiple other criteria such as forests fulfilling acoustic and visual buffers or the role forest play as natural borders to a city area.

On the basis of the above review, the evaluation by Sala et al. (2015) most fully represent the meta-criteria necessary for assessing the capabilities of indicators, methods, and tools for addressing the complex dynamics of Forest-Building. The criteria are:

- **boundary-orientatedness** — starting from no reference adopted, up to combining science-based and policy-based thresholds
- **comprehensiveness** — from covering one pillar up to three or more pillars such as environment, economic, social and any sub-categories such as soil
- **integratedness** — from a mono-disciplinary, sectorial approach up to a trans-disciplinary, inter-sectorial and participated approach
- **stakeholders' involvement** — from mere communication, up to close interaction in all phases of the assessment
- **scalability** — from local, specific and with limited time frame approaches, up to methods capable to deal with multi temporal and multiscale aspects
- **strategicness** — from mere accounting methods, up to methods that already integrated sustainability principles – e.g. life cycle thinking – and true solution orientated/change orientated methods
- **transparency** — from closed model to open model in which values are also transparently reported

The various criteria categories described above represent the basis of what many authors would deem necessary for any assessment method of complex adaptive systems, such as Forest-Building. Decisions made using assessments of each indicator category in terms of quality and quantity will affect many aspects of forests and strongly influence the quality and quantity of the other categories. Moreover, it is important to understand that these categories will affect and be affected by specific regional factors, the scale of assessment, and temporal dynamics inherent in any complex adaptive system. As such, each performance criterion represents an overarching category in which case specific metrics can be further developed through an iterative process, ideally through stakeholder engagement. The criteria which may be considered are:

**Environment**: The environmental impacts due to forest operations at the local, regional, and global scales. The key aspects are:

- **Energy Consumption**: energy, fossil fuels, and oils consumed and the proportion of renewable energy used.
- **Air**: direct and indirect emissions due to the use of forest machinery such as greenhouse gas emissions (GHG).
- **Water**: effects on quality and quantity of sedimentation, pollution, temperature change, and hydrogeological modifications due to the changes in water flows.
- **Remaining stand and regeneration capacity**: damage to residual trees and their reproduction capacity.
- **Biodiversity**: disturbance of flora and fauna causing negative effects to forest populations and communities.
- **Land use change**: caused through harvesting practices and infrastructure such as roads.
- **Soil**: The impacts of ground-based mechanized and non-mechanized forest operations. The key aspects include:
- **Soil compaction**: such as increases in soil bulk density.
- **Soil displacement or rutting**: lateral and longitudinal displacement of soil cause by the forestry operations.
- **Soil quality**: including nutrients, eutrophication and acidification.

**Economic**: Forest operations should be profitable in order to maintain a healthy forest sector and improve the forest management process. Applicable indicators are:

- **Productivity**: the quantity and quality of timber produced
- **Costs**: fixed and variable costs associated with forestry operations
- **Total amount of wood harvested**
- **Gross and local value-added**
- **Trade**
- **Labor/compensation**

**Quality optimization**: Forest operations should strive towards improving utilization rates of harvested trees, the reduction of waste material, and product quality control. The key elements may include:

**Utilization Rate**: applying the 'best' harvesting system in relation to local conditions. Consideration should be given to the logging residues as they relate to local ecosystem functioning, nutrient cycling, and the protection of soil and water resources.

**Waste reduction**: minimization of damage to timber during harvesting and extraction.

**Quality and value**: increasing product quality and value through wood quality assessment, and consideration of uses in the timber market.  Higher consideration should be given to long-lived harvest wood products such as buildings, which can contribute to the sequestration of carbon and the substitution for products with substantial environmental and social impacts(reference needed).

**Social**: the services and functions provided by forests include a wide range of ecological, political, economic, social, and cultural systems and processes that are necessary for society(La Notte, 2017). The main aspects include:

**Employment** and rural development: to support the local economy and the development of steady job opportunities in rural areas with equitable pay and earning.

**Cultural services and functions**: to maintain the cultural services and functions that effect livelihoods and wellbeing of local communities and the rights of indigenous peoples, while avoiding landscape aesthetic and amenity value.

**Provisioning of services and functions**: to ensure the sustainability of future yields of wood and non-wood forest products needed by society.

The indicators described above are widely applicable within many forestry and building contexts. Generally, the criteria selected for any Forest-Building assessment should promote socially acceptable and responsible forestry and building practices that support community values and wellness, enhance ecosystem resilience, and enhance public understanding of the synergistic relations between forestry and the built environment.

## 3.2 Product, Project-Related and Integrated Assessment

Beyond sustainability criteria and indicators, product-related, and integrated assessments should be included in forestry and building sustainability assessments. Product-related tools focus primarily on evaluating the flows of material and/or energy in relation to specific products or services. They assess resource use, social, environmental, and economic impacts along the production chain for the life-cycle of a product. As such, they are inherently less complex modes of assessment. Product-related assessments identify particular risks and inefficiencies in a product's life-cycle to support decision-making regarding the design of products and production systems. Most product-related assessment tools focus on the environment and are not considered to integrate nature-society systems (Ness et al. 2007).

Examples of product-related assessments come from Industrial Ecology and Ecosystems Science. They include Life Cycle Assessment (LCA), Social Life Cycle Assessment (SLCA), and Life Cycle Costing (LCC), which measure the environmental, social, and economic impacts of a given product or process. Furthermore, tools such as Material Flow Analysis (MFA), Substance Flow Analysis (SFA), and various forms of product energy analysis such as Emergy and Exergy analysis are also often used for the assessment of a single product as well as whole industries (Odum 1996; Brown 2002).

Integrated or project related assessment tools differ from product-related tools as they can be used for supporting decisions related to local, national, or global policies as well as for the assessment of specific projects. As integrated assessment tools are used for decision making regarding the future, they are often carried out using scenarios. The most commonly used integrated assessment tools include Cost-benefit analysis (CBA), input-output (IO) and environmentally extended input-output (EEIO) analysis, and multicriteria analysis (MCA). Input-output and environmentally extended input-output analysis are tools where an input resource is converted into an output product, and the system-wide interdependencies are assessed for their impact on all sectors of the national economy (Leontief 1970; 1986). For example, the input of wood from a sawmill resulting in wood products for buildings is a direct part of the forestry and building sector. However, it utilizes inputs from other sectors for energy, transportation, etc. and may result in the decline in sectors such as concrete (Oliver C.D. et al. 2014). IO and EEIO benefit from the ready availability of national market data and the linear impact market responses between demand and production without any thresholds. However, as discussed above, forests act as complex systems where national data will not represent local conditions, and the linear market is not often representative of reality.

In their review of Sustainability Assessment methodologies, Sala et al. (2015) outlined three approaches commonly used in the identification and selection or suitable methodologies which can be applied in a specific case/context:

- **reductionistic approach** - in which the results of several models and tools are combined, covering the three pillars;
- **holistic approach** - in which methods and models specifically developed for sustainability assessments are chosen, in order to assess the emergent properties of the complex adaptive socio-ecological system affecting the problem/issue being evaluated;
- **combined approach** - in which in the framework of the holistic approach to the evaluation, the reductionistic model and methods are used to delve into some specific theme/issue within the assessment.

Therefore, a combination of product, project and integrated methods, representing the reductionist, holistic methodologies would provide the most comprehensive form of assessment yet would be extremely complex to both perform and interpret. Similarly, Karvonen et al. (2017) concluded that while there is no issue with data measurement for product and integrated assessment tools (reductionist and/or holistic approaches), their practical application is currently limited by their complex interconnected relations and incommensurability between indicators. Furthermore, Karvonen et al. (2017) note the main challenge for sustainability assessment is the combination of hierarchically different tools covering economic, ecological, and social indicators is not always possible as the measurements often do not share the same characteristics such as system boundary and temporal characteristics. For Karvonen et al. (2017), the assessment task is a continually evolving set of practices, a mix of different methods, as well as different sustainability approaches that are necessary to support and improve the decision-making for forest bioeconomies. Therefore, there is no single assessment method to which can adequately describe the complex nature of Forest-Building.

### 3.2.1 Multicriteria Assessment

For any sustainability impact assessment related to forestry and building, problems with multiple dimensions, including uncertainty of the relationships between indicators, thresholds, and multiple scales, are among the most challenging as uncertainty lies in both the indicators as well as the method of analysis. For example, Martin-Fernandez (2016) found that when comparing the sustainability of pairs of forest locations, individual preferences varied according to criteria. One tool which authors find useful in this scenario is multicriteria analysis (MCA). A unique aspect of multicriteria analysis is the ability to use results from any impact assessment method, including criteria, indicators, product, project, and integrated assessment. Furthermore, MCA is capable of assessing social, ecological, and economic impacts without aggregation using stakeholder preferences that often prioritize some dimensions over others (Sheppard and Meitner 2005; Ananda and Herath 2009; Nordström, Eriksson, and Öhman 2010; Jalilova, Khadka, and Vacik 2012; Martin-Fernandez and Martinez-Falero 2018). For this reason, a number of multicriteria analysis (MCA) methods have been developed.

MCA has been used extensively to evaluate sustainability and a general grouping of has emerged which distinguished three underlying theories: utility function, outranking relation and, sets of decision rules (Munda 2005; Huang, Keisler, and Linkov 2011; Cinelli, Coles, and Kirwan 2014; Kangas, Kangas, and Kurttila 2008). The utility-based theory describes methods that aggregate or synthesize the information into a unique parameter. Examples of utility-based approaches are Multi-attribute utility theory (MAUT) and Analytical hierarchy process (AHP). The outranking relation theory involves methods that compare pairs of options to conclude whether "alternative

A is at least as good as alternative B" according to each category, criteria, or indicator. Examples of this method are Elimination and choice expressing the reality (ELECTRE) and Preference ranking organization method for enrichment of evaluations (PROMETHEE). The decision rule theory derives a preference model through the use of classification or comparison of decision examples and includes dominance-based rough set approach (DRSA).

Cinelli at al. (2014) argue the selection of a certain MCA method has to be based on an appropriate knowledge of the basics of the approach and the evaluation to be performed as well. This implies the recognition that some aspects can be covered only by certain methods and not by others, so that the adoption of the approach is tailored to the decision-making situation at stake and not vice versa. To support the MCA method selection, five methods described above were evaluated according to sustainability-related indicators. The factors of relevance for this discussion include the ability to use qualitative and quantitative data, a life-cycle perspective, whether they allow trade-off or substitution rates, the inclusion of thresholds in the method, and the treatment of uncertainty. While the comparison criteria are not exhaustive, it was found that the utility theory-based models performed much worse as they do not enforce a strong sustainability approach, allow for trade-offs and compensation among criteria, and are incapable of including thresholds and uncertainty in their analysis.

Understanding the variety of criteria, tools, and indicators used to describe the integrated ecological, economic and social nature of forests, it can be seen that tools such as multicriteria analysis provide a set of methods that can be used to support the project, policy and decision making processes regarding the future forests at the local, regional and national scales.

### 3.2.2 Towards a Forest-Building Assessment

Through this review of critical indicators, tools, and methods for sustainability assessment used in forestry and wood building, the synergies between complex adaptive systems thinking and multicriteria decision analysis begin to emerge as suitable for Forest-Building assessments and practice. The selection of specific sustainability indicators, assessment tools, and multicriteria analysis methods must be based on the particular assessment being considered. Increased activity in Forest-Building to substitute fossil fuel raw material, for example, creates various positive and negative impacts at many spatio-temporal scales. Any practical Forest-Building assessment will combine a wide range of stakeholder preferences, values, and many factors that remain unknown. This implies that some aspects can only be covered by specific tools and methods and not by others. For Forest-Building, the inclusion of indicators and methods that describe social, ecological, economic, and integrated-emergent relationships are desired. Each indicator and method should be further specified by considering case-specific impacts ideally developed through the stakeholder participation process. Through this constant feedback between general, expertly developed, and case-specific, stakeholder-developed indicators and methods, the concepts of complex adaptive systems can be applied toward Forest-Building. Through engagement with Forest-Building as an integrated complex adaptive system, this methodology will guide the selection of case specific best practices for forestry related to building, and vice versa. In principle, the best possible Forest-Building system would minimize environmental damage, maximize economic productivity, and achieve broad social acceptance with consideration of workers' rights, and product quality. Yet, it is unlikely that these characteristics would even be possible, and more likely they will be viewed from multiple different perspective for all stakeholders and mean drastically different things when looked at from multiple spatio-temporal lenses.

Recognising the value of Forest-Building as an approach based on complex adaptive systems may also help shift the focus of sustainability assessment from doing 'less bad' towards one which believes humans, through forestry and building, can contribute to making our natural world more adaptive and resilient to the increasing speed of change and disturbances through careful, designed, and scientifically sound interventions.  By focusing on the exchanges of forests and buildings, we can begin to ask how building cycles can have impacts on the direct, synergistic, and emergent properties of forests. Thus, Forest-Building, as a new nexus assessment method and practice, will synchronize the intergenerational carbon pulsing of forests, carbon sequestration in the timber building industry, and patterns of urbanization, which can together changing how architects, engineers and foresters will source, design, and build our decarbonized futures.

# 4 A Trait-Based Approach to Both Forestry and Timber Building Can Synchronize Forest Harvest and Resilience

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# 4.1 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

# 4.2 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 (Churkina et al. 2020; Craig et al. 2020). Forests have historically been shaped by anthropogenic forces and managed to meet society's current and future needs (Klaus J. Puettmann, Coates, and Messier 2009). 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.

While a multitude of approaches to forest management exist and are applied worldwide (C. Messier et al. 2015; Klaus J. Puettmann, Coates, and Messier 2009), 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 (Klaus J. Puettmann, Coates, and Messier 2009). 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 (Holling and Meffe 1996). 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 (Brunet-Navarro, Jochheim, and Muys 2016; Alvarez and Rubio 2016). 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 (Ibañez, Hutton, and Moe 2020). Such pressure towards homogenizing forest structures and species composition across large landscapes negatively affects species diversity putting forest ecosystems at greater risk of climate change and natural disturbances 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 (Jactel et al. 2017) 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 systems 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 (Christian Messier, Puettmann, and Coates 2013). 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 (Christian Messier, Puettmann, and Coates 2013; Seidl et al. 2016). 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.

However, this needs to be accompanied by a similar increase in the flexibility of wood-based industries/markets. 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 (Petchey and Gaston 2006; Violle et al. 2007). 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 (Suding et al. 2008).

Plant functional trait-based methods have been proposed to guide forest management practices focused on ecosystem services and functions (Cadotte, Carscadden, and Mirotchnick 2011) to better foster forest ecosystems' adaptive capacity (Lindner et al. 2010). Messier et al. (2019) 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. (Aquilué et al. 2020), who first clustered tree species into functionally similar groups to compare the outcomes of favoring or planting functionally rare species in a south eastern Canadian forest landscape. The functional complex network approach has also been compared to traditional forest management approaches across a study region by Mina et al. (Mina et al. 2022) and was shown to increase ecological resilience to unexpected global change stressors and increase net primary productivity and aboveground forest biomass. 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 re-organize 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 (Laughlin 2014; Mina et al. 2020). To do so, we first need to better understand the viability of currently un- and under-utilized 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.

## 4.3 The forest-building approach

We introduce the Forest-Building framework as a trait-based approach that couples plant and wood-building traits (Figure 26). We expand a plant trait-based approach to include building traits to 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 (Christian Messier et al. 2019; Aubin et al. 2016) 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 (Mina et al. 2022; Aquilué et al. 2020; 2021a). Through an analysis of forest- and building-related indicators, one can characterize the 'push' — the impact climate change, natural disturbances 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 (Oliver C.D. et al. 2014).

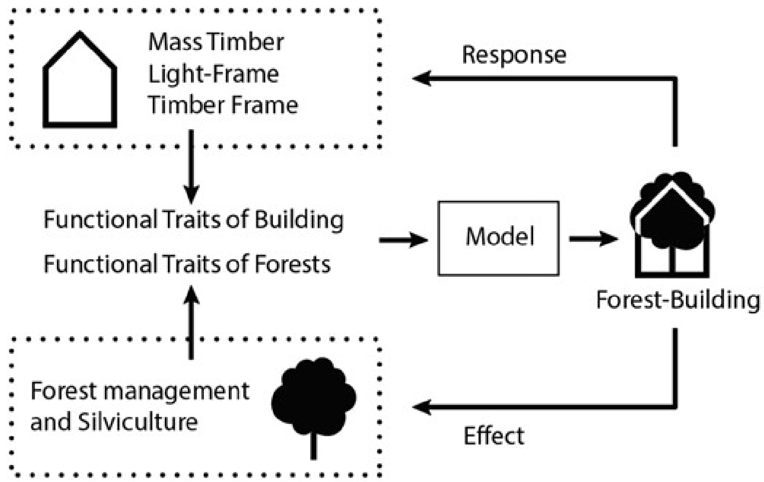


*Figure 26 - Conceptual diagram of the Forest-Building approach. Reproduced from Osborne et al. (2023).*

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 2, Section 8.2.2). 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 (Table 3). 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 (Figure 27). 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 (Núñez-Florez, Pérez-Gómez, and Fernández-Méndez 2019; Gérard, Jean et al. 2011), 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 (Diaz-Balteiro and Romero 2008; Díaz et al. 2016), 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 southeastern Canada previously studied in (Mina et al. 2022). Using the process-based forest landscape model LANDIS-II (Scheller et al. 2007), 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 to increase ecological resilience.

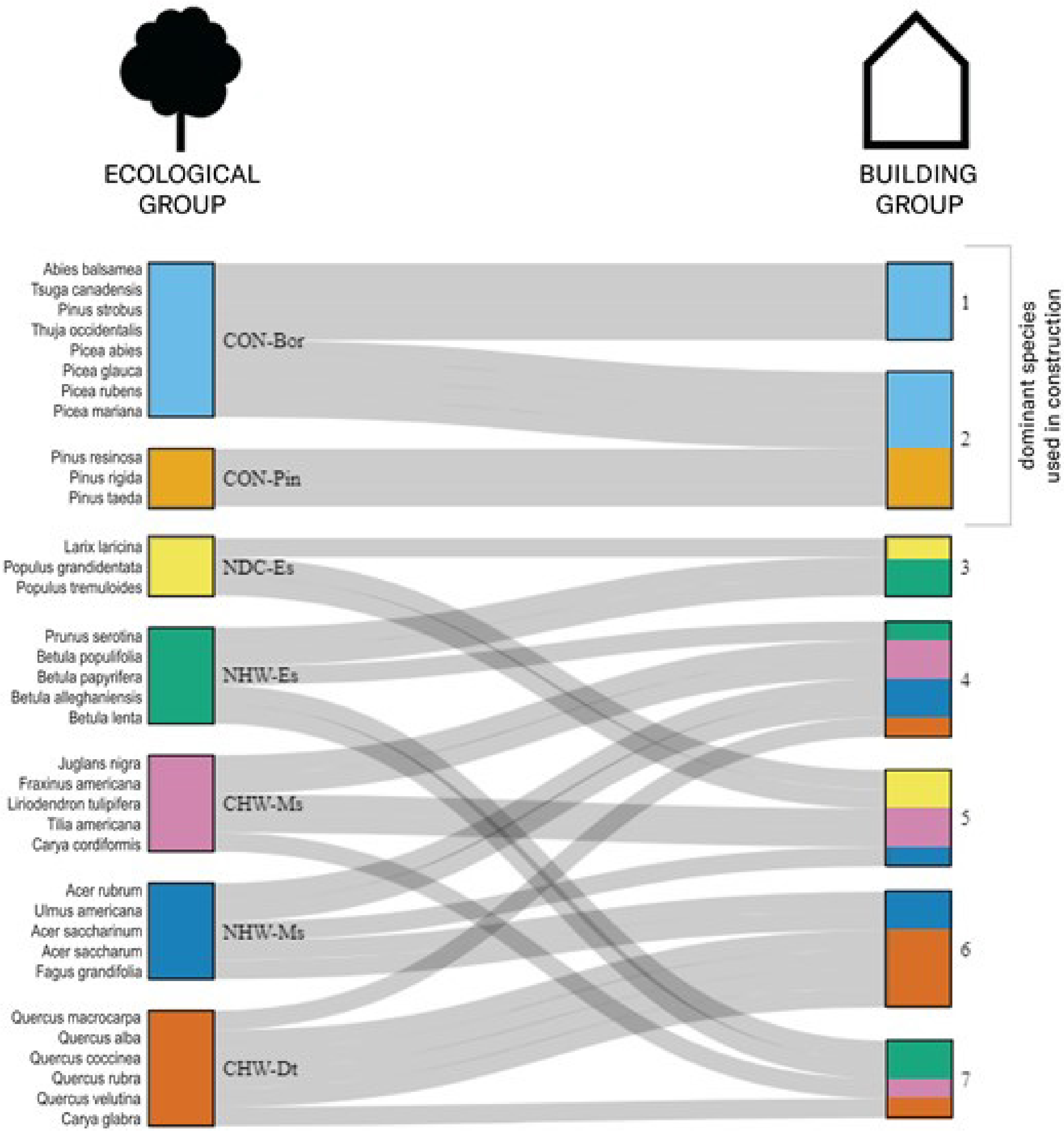


*Figure 27 - The interaction between ecological and building groups. By clustering tree species into groups with similar building traits, builders and architects can specify wood from within a particular group that has utility in building and simultaneously support the goals of maximizing the ecological resilience and adaptability of the forests. See Tables 2 and 3 for species and key characteristics of building and ecological groups. For further information on the trait selection and clustering methods, see supplementary material Section 7.1.1. Reproduced from Osborne et al. (2023).*

*Table 2 - 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. Reproduced from Osborne et al. (2023).*

| 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. |

*Table 3 - 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. Reproduced from Osborne et al. (2023).*

| **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* |

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.

# 4.4 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.

## 4.4.1 Forest-Building trait interaction

Figure 27 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 3). 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).

### 4.4.2 Changing forest harvest output and functional composition

Experiments were conducted by comparing the harvest output and harvested species composition for management treatments under selected climate change scenarios. This approach allowed for the exploration of harvest output of each species and building group under increasing levels of climate-induced stress at the landscape level. Fig. 4 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 to 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 (Supporting Information 8.3 and Table 10). The FDN15 scenario shows an increase in total harvest output of between 20%-35% when compared to CCA, depending on the severity of the climate change scenario. Furthermore, increasing the harvest rate of the FDN approach from 15% to 25% over five years (FDN15 and FDN25, respectively) was previously shown to improve functional diversity and network connectivity (Mina et al. 2022), and the results demonstrate that such approaches will also increase harvest output across the study region by 20% across all climate scenarios.

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. The 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 Acer 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).

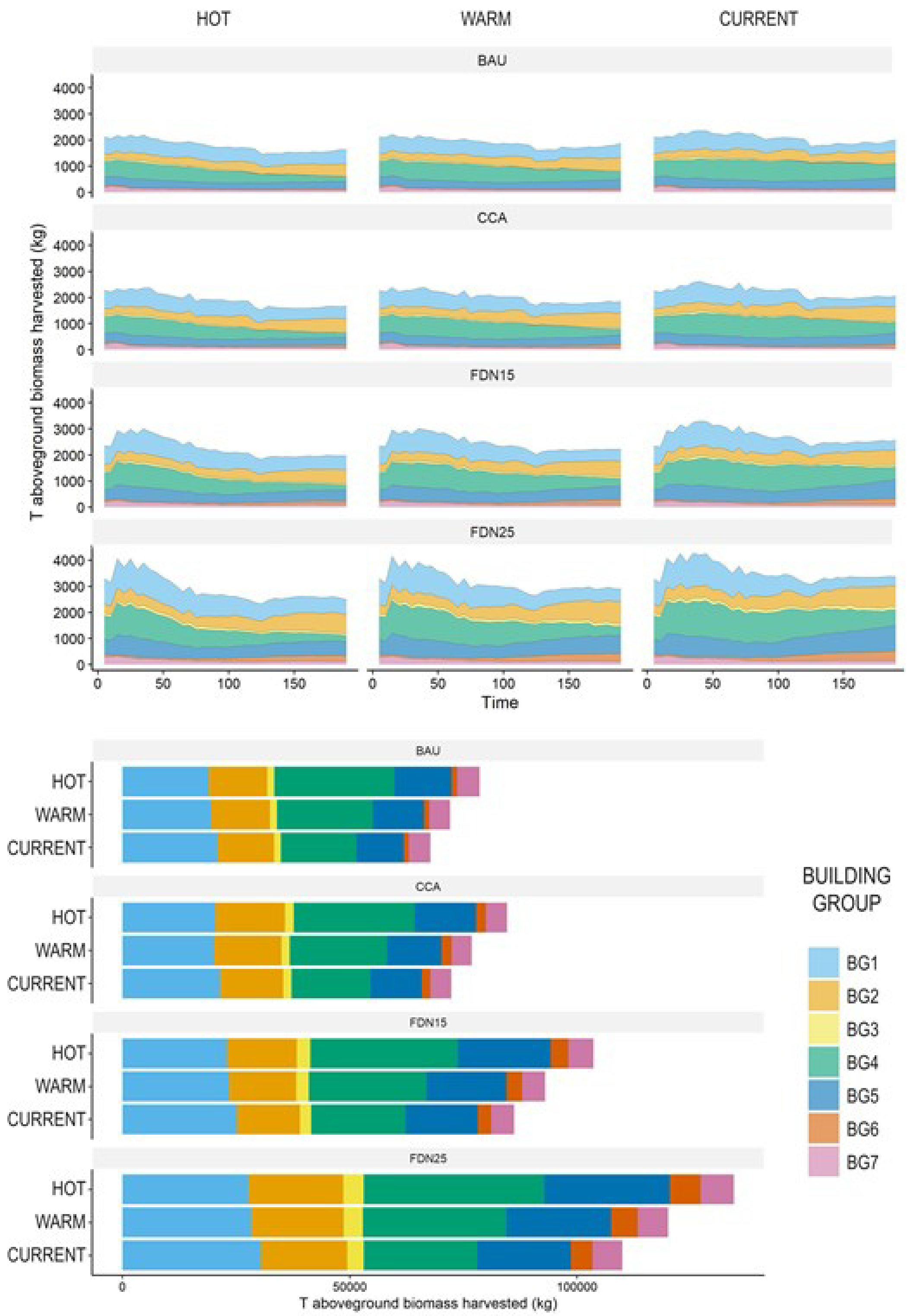


*Figure 28 - Above: aboveground biomass harvested (kg*$10^3$) by species building functional group (Table 2) under the different scenarios (columns, climate; rows, management treatment). Below: Total harvested biomass (kg*$10^3$) for the study period (190 years) organized by building groups. Reproduced from Osborne et al. (2023).*

# 4.5 Discussion

Studying and managing buildings and forests as a coupled human and natural complex system (Liu et al. 2007) contrasts past and current closed-system methods of today's forestry and building industries, evident in both foresters' and builders' tools and techniques (Oliver C.D. 2014). 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 conservationists would argue forests are critical terrestrial systems for carbon sequestration and climate change mitigation (Ni et al. 2016). Each group's response is framed by tools and methods which reinforce not only 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 (Oliver C.D. et al. 2014). 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 (Figure 28). Species used in wood construction must be diversified to increase the ecological

resilience of forests and plantations and the socio-economic 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 (Figure 28). 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 (Odum 2002). 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, 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 (1) a more dynamic and flexible approach to wood utilization and (2) 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. 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 (Nygaard et al. 2019). 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 (Oliver C.D. et al. 2014; Himes and Busby 2020). 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 cross-laminated timber panels, wood fibre 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 (C. X. Chen, Pierobon, and Ganguly 2019; Muszynski et al. 2022; Kaboli, Clouston, and Lawrence 2020). 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

(Oliver C.D. et al. 2014). 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.

### 4.5.1 Implications of Forest-Building system management and future perspectives

We have shown that future global changes impacting forested landscapes' ecological adaptability and resilience 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 forest to 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 (Holling and Meffe 1996). 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. Recent work into the utilization of restoration pine in California shows a promising direction for further research (Figure 29b). 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.

*Figure 29 - 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 (Muszynski et al. 2022) . Popular industry CLT panel manufactured with black spruce (90% by volume) and other common building spies (spruce, pine, and fir; typically known as SPF). Reproduced from Osborne et al. (2023).*

# 4.6 Materials and Methods

## 4.6.1 Study Area

We conducted our study in the Central Quebec region of southeastern Canada (Figure 30). 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(Danneyrolles et al. 2019). Currently, the most abundant tree species are maples (*Acer rubrum* and *Acer saccharum*), balsam fir (*Abies balsamea*), and yellow birch (*Betula alleghaniensis*).

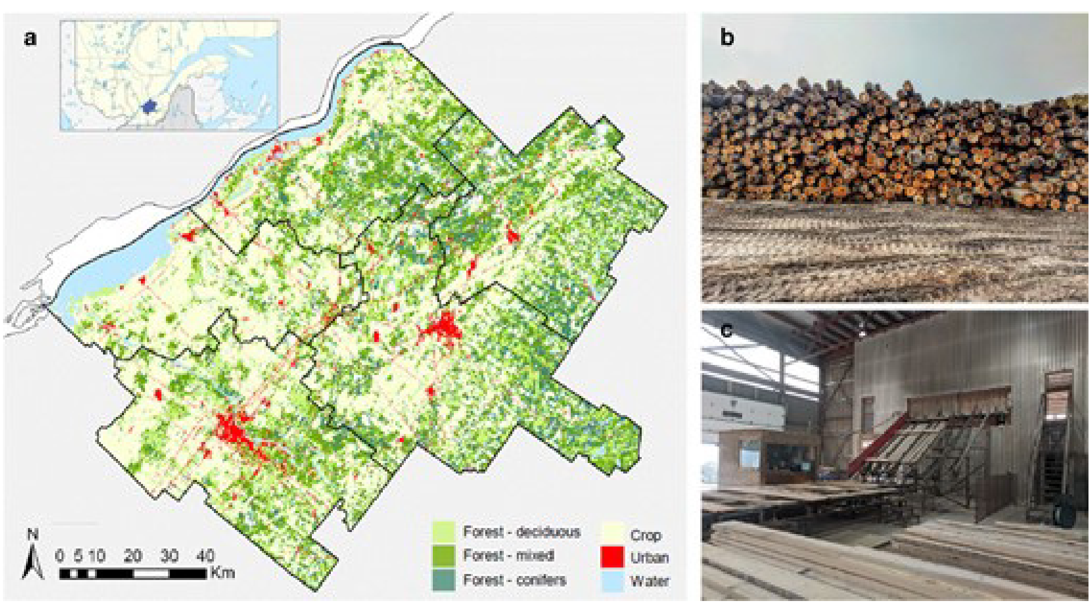


*Figure 30 - a) Central Quebec study area in SE Canada. b) Spruce, pine, and fir logs aging before (c) typical softwood milling seen throughout the region (photos: author). Reproduced from Osborne et al. (2023).*

### 4.6.2 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 (Mina et al. 2022) – 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). Further details on ecological traits can be found in the Supplemental Information Section 8.2.1.

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. We selected ten 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 Information Section 8.2.

We clustered all 77 species into two 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 (Aquilué et al. 2020; 2021a) clustered the 77 tree species into seven ecological on the one hand and seven building groups on the other hand (BG1-7) (Table 2, Table 3, Figure 27). 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 2). 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 (Figure 27). The three most abundant groups were soft conifers (BG1 and BG2, predominantly pine and fir) and medium-hard deciduous species (BG4, maples and birches).

### 4.6.3 Model Description and Experimental Design

We used LANDIS-II, a spatially explicit, process-based forest landscape model to simulate t future forest development and evaluate potential harvest outputs (Scheller et al. 2007). 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 (Boulanger et al. 2019; Creutzburg et al. 2017; Duveneck et al. 2017). 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 (40). 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 (27), and the design and implementation of the management and climate scenarios are given in the Supplementary Information, with further details also given in (Aquilué et al. 2021a; Mina et al. 2022).

#### 4.6.3.1 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 (Mina et al. 2022). 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; (Arora and Boer 2010)). We compared a scenario of current climate, representing the continuation of normal climate conditions (1961–2000), with two hypothetical future climates: (1) 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 (2) high emissions (RCP 8.5: approximately +8.5°C, slight increase of annual precipitation, and drastic increase of $CO_2$ levels; Hot). See Supporting Information, section 2, for details about preparing climate scenarios and choosing the climate model and emission projections.

#### 4.6.3.2 Management Scenarios

The effect of forest management treatments—harvesting and planting— in LANDIS-II was implemented using the Biomass-Harvest extension v4.3 (Gustafson et al. 2000). 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 (de Bruijn et al. 2014). Four management strategies were considered in our simulation experiment: business-as-usual (BAU), climate change adaptation (CCA), and two variants of the functional diversification network 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 (Christian Messier et al. 2019). 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 (approximately 15% of the forest landscape was made allowable for harvesting every five years). For FDN25, we increased the management intensity to reflect harvest levels necessary for the enrichment planting of an additional ten species with functional traits absent in our landscape but present in neighbouring bioregions (25% allowable harvesting every five 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 the Supporting Information 8.3 and Table 10.

## 4.7 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 prescription called "background disturbance," in which some cells are randomly disturbed to emulate disturbances typical to the region (e.g., small windthrow events, small scale mortality) and to add some variability to the model runs (Mina et al. 2022; 2020). 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 building and requires 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 (Bartlett, Hadden, and Bisby 2019). 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.

# 4.8 References

Alvarez, Sergio, and Agustín Rubio. "Wood Use and Forest Management for Carbon Sequestration in Community Forestry in Sierra Juárez, Mexico." Small-Scale Forestry 15, no. 3 (2016): 357–74. https://doi.org/10.1007/s11842-016-9325-2.

Aquilué, Núria, Élise Filotas, Dylan Craven, Marie-Josée Fortin, Lluís Brotons, and Christian Messier. "Evaluating Forest Resilience to Global Threats Using Functional Response Traits and Network Properties." Ecological Applications 30, no. 5 (2020): e02095. https://doi.org/10.1002/eap.2095.

Aquilué, Núria, Christian Messier, Kyle T. Martins, Véronique Dumais-Lalonde, and Marco Mina. "A Simple-to-Use Management Approach to Boost Adaptive Capacity of Forests to Global Uncertainty." Forest Ecology and Management 481 (February 2021): 118692. https://doi.org/10.1016/j.foreco.2020.118692.

Arora, V. K., and G. J. Boer. "Uncertainties in the 20th Century Carbon Budget Associated with Land Use Change." Global Change Biology 16, no. 12 (2010): 3327–48. https://doi.org/10.1111/j.1365-2486.2010.02202.x.

Aubin, I., A.D. Munson, F. Cardou, P.J. Burton, N. Isabel, J.H. Pedlar, A. Paquette, et al. "Traits to Stay, Traits to Move: A Review of Functional Traits to Assess Sensitivity and Adaptive Capacity of Temperate and Boreal Trees to Climate Change." Environmental Reviews 24, no. 2 (June 2016): 164–86. https://doi.org/10.1139/er-2015-0072.

Bartlett, Alastair I., Rory M. Hadden, and Luke A. Bisby. "A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction." Fire Technology 55, no. 1 (January 2019): 1–49. https://doi.org/10.1007/s10694-018-0787-y.

Boulanger, Yan, Dominique Arseneault, Yan Boucher, Sylvie Gauthier, Dominic Cyr, Anthony R. Taylor, David T. Price, and Sébastien Dupuis. "Climate Change Will Affect the Ability of Forest Management to Reduce Gaps between Current and Presettlement Forest Composition in Southeastern Canada." Landscape Ecology 34, no. 1 (January 1, 2019): 159–74. https://doi.org/10.1007/s10980-018-0761-6.

Bruijn, Arjan de, Eric J. Gustafson, Brian R. Sturtevant, Jane R. Foster, Brian R. Miranda, Nathanael I. Lichti, and Douglass F. Jacobs. "Toward More Robust Projections of Forest Landscape Dynamics under Novel Environmental Conditions: Embedding PnET within LANDIS-II." Ecological Modelling 287 (September 10, 2014): 44–57. https://doi.org/10.1016/j.ecolmodel.2014.05.004.

Brunet-Navarro, Pau, Hubert Jochheim, and Bart Muys. "Modelling Carbon Stocks and Fluxes in the Wood Product Sector: A Comparative Review." Global Change Biology 22, no. 7 (2016): 2555–69. https://doi.org/10.1111/gcb.13235.

Cadotte, Marc W., Kelly Carscadden, and Nicholas Mirotchnick. "Beyond Species: Functional Diversity and the Maintenance of Ecological Processes and Services." Journal of Applied Ecology 48, no. 5 (2011): 1079–87. https://doi.org/10.1111/j.1365-2664.2011.02048.x.

Chen, Cindy X, Francesca Pierobon, and Indroneil Ganguly. "Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) Produced in Western Washington: The Role of Logistics and Wood Species Mix," 2019, 17.

Churkina, Galina, Alan Organschi, Christopher P. O. Reyer, Andrew Ruff, Kira Vinke, Zhu Liu, Barbara K. Reck, T. E. Graedel, and Hans Joachim Schellnhuber. "Buildings as a Global Carbon Sink." Nature Sustainability 3, no. 4 (April 2020): 269–76. https://doi.org/10.1038/s41893-019-0462-4.

Craig, Salmaan, Anna Halepaska, Jacob Elbrecht, Katherine Ferguson, Preston Rains, Andrew Freear, David Kennedy, and Kiel Moe. "Buildings as a Global Carbon Sink? The Design of Mass Timber Panels as Heat-Exchangers (Dynamic Insulation)," August 12, 2020. https://doi.org/10.20944/preprints202008.0278.v1.

Creutzburg, Megan K., Robert M. Scheller, Melissa S. Lucash, Stephen D. LeDuc, and Mark G. Johnson. "Forest Management Scenarios in a Changing Climate: Trade-Offs between Carbon, Timber, and Old Forest." Ecological Applications 27, no. 2 (2017): 503–18. https://doi.org/10.1002/eap.1460.

Danneyrolles, Victor, Sébastien Dupuis, Gabriel Fortin, Marie Leroyer, André de Römer, Raphaële Terrail, Mark Vellend, et al. "Stronger Influence of Anthropogenic Disturbance than Climate Change on Century-Scale Compositional Changes in Northern Forests." Nature Communications 10, no. 1 (March 20, 2019): 1265. https://doi.org/10.1038/s41467-019-09265-z.

Díaz, Sandra, Jens Kattge, Johannes H. C. Cornelissen, Ian J. Wright, Sandra Lavorel, Stéphane Dray, Björn Reu, et al. "The Global Spectrum of Plant Form and Function." Nature 529, no. 7585 (January 2016): 167–71. https://doi.org/10.1038/nature16489.

Diaz-Balteiro, Luis, and Carlos Romero. "Making Forestry Decisions with Multiple Criteria: A Review and an Assessment." Forest Ecology and Management 255, no. 8 (May 15, 2008): 3222–41. https://doi.org/10.1016/j.foreco.2008.01.038.

Duveneck, Matthew J., Jonathan R. Thompson, Eric J. Gustafson, Yu Liang, and Arjan M. G. de Bruijn. "Recovery Dynamics and Climate Change Effects to Future New England Forests." Landscape Ecology 32, no. 7 (July 1, 2017): 1385–97. https://doi.org/10.1007/s10980-016-0415-5.

Gérard, Jean, Guibal, Daniel, Paradis, Sébastien, Vernay, Michel, Beauchêne, Jacques, Brancheriau, Loïc, Châlon, Isabelle, et al. "Tropix 7." Application/x-msdownload. CIRAD, 2011. https://doi.org/10.18167/74726F706978.

Gustafson, Eric J, Stephen R Shifley, David J Mladenoff, Kevin K Nimerfro, and Hong S He. "Spatial Simulation of Forest Succession and Timber Harvesting Using LANDIS." Canadian Journal of Forest Research 30, no. 1 (February 2000): 32–43. https://doi.org/10.1139/x99-188.

Himes, Austin, and Gwen Busby. "Wood Buildings as a Climate Solution." Developments in the Built Environment 4 (November 1, 2020): 100030. https://doi.org/10.1016/j.dibe.2020.100030.

Holling, C. S., and Gary K. Meffe. "Command and Control and the Pathology of Natural Resource Management." Conservation Biology 10, no. 2 (1996): 328–37. https://doi.org/10.1046/j.1523-1739.1996.10020328.x.

Ibañez, Daniel, Jane Hutton, and Kiel Moe, eds. Wood Urbanism: From the Molecular to the Territorial. English edition. New York ; Barcelona: Actar, 2020.

Jactel, Hervé, Jürgen Bauhus, Johanna Boberg, Damien Bonal, Bastien Castagneyrol, Barry Gardiner, Jose Ramon Gonzalez-Olabarria, Julia Koricheva, Nicolas Meurisse, and Eckehard G. Brockerhoff. "Tree Diversity Drives Forest Stand Resistance to Natural Disturbances." Current Forestry Reports 3, no. 3 (September 1, 2017): 223–43. https://doi.org/10.1007/s40725-017-0064-1.

Kaboli, Hamid, Peggi L. Clouston, and Seth Lawrence. "Feasibility of Two Northeastern Species in Three-Layer ANSI-Approved Cross-Laminated Timber." Journal of Materials in Civil Engineering 32, no. 3 (March 1, 2020): 04020006. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003058.

Laughlin, Daniel C. "Applying Trait-Based Models to Achieve Functional Targets for Theory-Driven Ecological Restoration." Ecology Letters 17, no. 7 (2014): 771–84. https://doi.org/10.1111/ele.12288.

Lindner, Marcus, Michael Maroschek, Sigrid Netherer, Antoine Kremer, Anna Barbati, Jordi Garcia-Gonzalo, Rupert Seidl, et al. "Climate Change Impacts, Adaptive Capacity, and Vulnerability of European Forest Ecosystems." Forest Ecology and Management, Adaptation of Forests and Forest Management to Changing Climate, 259, no. 4 (February 5, 2010): 698–709. https://doi.org/10.1016/j.foreco.2009.09.023.

Liu, J., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, et al. "Complexity of Coupled Human and Natural Systems." Science 317, no. 5844 (September 14, 2007): 1513–16. https://doi.org/10.1126/science.1144004.

Messier, C., K. Puettmann, R. Chazdon, K. P. Andersson, V. A. Angers, L. Brotons, E. Filotas, R. Tittler, L. Parrott, and S. A. Levin. "From Management to Stewardship: Viewing Forests As Complex Adaptive Systems in an Uncertain World." Conservation Letters 8, no. 5 (2015): 368–77. https://doi.org/10.1111/conl.12156.

Messier, Christian, Jürgen Bauhus, Frederik Doyon, Fanny Maure, Rita Sousa-Silva, Philippe Nolet, Marco Mina, Núria Aquilué, Marie-Josée Fortin, and Klaus Puettmann. "The Functional Complex Network Approach to Foster Forest Resilience to Global Changes."

Forest Ecosystems 6, no. 1 (April 9, 2019): 21. https://doi.org/10.1186/s40663-019-0166-2.
Messier, Christian, Klaus J. Puettmann, and K. David Coates. Managing Forests as Complex Adaptive Systems: Building Resilience to the Challenge of Global Change. Routledge, 2013.
Mina, Marco, Christian Messier, Matthew Duveneck, Marie-Josée Fortin, and Núria Aquilué. “Network Analysis Can Guide Resilience-Based Management in Forest Landscapes under Global Change.” Ecological Applications n/a, no. n/a (2020): e2221. https://doi.org/10.1002/eap.2221.
Mina, Marco, Christian Messier, Matthew J. Duveneck, Marie-Josée Fortin, and Núria Aquilué. “Managing for the Unexpected: Building Resilient Forest Landscapes to Cope with Global Change.” Global Change Biology n/a, no. n/a (March 2022). https://doi.org/10.1111/gcb.16197.
Muszynski, Lech, Mariapaola Riggio, Rakesh Gupta, and Jeff Morrell. “Defining Custom CLT Grade Utilizing Low-Value Ponderosa Pine.” TallWood Design Institute, 2022. https://tallwoodinstitute.org/defining-custom-clt-grade-utilizing-low-value-ponderosa-pine/.
Ni, Yuanming, Gunnar S. Eskeland, Jarl Giske, and Jan-Petter Hansen. “The Global Potential for Carbon Capture and Storage from Forestry.” Carbon Balance and Management 11, no. 1 (2016): 1–8. https://doi.org/10.1186/s13021-016-0044-y.
Núñez-Florez, Rafael, Uriel Pérez-Gómez, and Fernando Fernández-Méndez. “Functional Diversity Criteria for Selecting Urban Trees.” Urban Forestry & Urban Greening 38 (February 1, 2019): 251–66. https://doi.org/10.1016/j.ufug.2019.01.005.
Nygaard, Marius, Isaak Elias Skjeseth Bashevkin, Ute Groba, and Catherine Sunter. “Increased Use of Timber in New Buildings in Oslo and Akershus: Potentials and GHG Emission Effects.” Frontiers in Built Environment 5 (2019). https://www.frontiersin.org/articles/10.3389/fbuil.2019.00131.
Odum, Howard T. “Material Circulation, Energy Hierarchy, and Building Construction.” In Construction Ecology: Nature as the Basis for Green Buildings, edited by Charles J. Kibert, Jan Sendzimir, and G. Bradley Guy, 37–71. Taylor & Francis, 2002.
Oliver C.D. “Functional Restoration of Social-Forestry Systems Across Spatial and Temporal Scales.” Journal of Sustainable Forestry 33, no. SUP1 (2014): S123–48. https://doi.org/10.1080/10549811.2014.884003.
Oliver C.D., Nassar N.T., Lippke B.R., and McCarter J.B. “Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests.” Journal of Sustainable Forestry 33, no. 3 (2014): 248–75. https://doi.org/10.1080/10549811.2013.839386.
Osborne, Peter, Núria Aquilué, Marco Mina, Kiel Moe, Michael Jemtrud, and Christian Messier. “A Trait-Based Approach to Both Forestry and Timber Building Can Synchronize Forest Harvest and Resilience.” PNAS Nexus 2, no. 8 (August 1, 2023): pgad254. https://doi.org/10.1093/pnasnexus/pgad254.
Petchey, Owen L., and Kevin J. Gaston. “Functional Diversity: Back to Basics and Looking Forward.” Ecology Letters 9, no. 6 (2006): 741–58. https://doi.org/10.1111/j.1461-0248.2006.00924.x.
Puettmann, Klaus J., K. Dave. Coates, and Christian C. Messier. A Critique of Silviculture: Managing for Complexity. 1 online resource (xvi, 189 pages) : illustrations vols.

Washington, DC: Island Press, 2009. http://public.eblib.com/choice/publicfullrecord.aspx?p=3317551.

Scheller, Robert M., James B. Domingo, Brian R. Sturtevant, Jeremy S. Williams, Arnold Rudy, Eric J. Gustafson, and David J. Mladenoff. "Design, Development, and Application of LANDIS-II, a Spatial Landscape Simulation Model with Flexible Temporal and Spatial Resolution." Ecological Modelling 201, no. 3 (March 10, 2007): 409–19. https://doi.org/10.1016/j.ecolmodel.2006.10.009.

Seidl, Rupert, Thomas A. Spies, David L. Peterson, Scott L. Stephens, and Jeffrey A. Hicke. "REVIEW: Searching for Resilience: Addressing the Impacts of Changing Disturbance Regimes on Forest Ecosystem Services." Journal of Applied Ecology 53, no. 1 (2016): 120–29. https://doi.org/10.1111/1365-2664.12511.

Suding, Katharine N., Sandra Lavorel, F. S. Chapin, Johannes H. C. Cornelissen, Sandra Díaz, Eric Garnier, Deborah Goldberg, David U. Hooper, Stephen T. Jackson, and Marie-Laure Navas. "Scaling Environmental Change through the Community-Level: A Trait-Based Response-and-Effect Framework for Plants." Global Change Biology 14, no. 5 (2008): 1125–40. https://doi.org/10.1111/j.1365-2486.2008.01557.x.

Violle, Cyrille, Marie-Laure Navas, Denis Vile, Elena Kazakou, Claire Fortunel, Irène Hummel, and Eric Garnier. "Let the Concept of Trait Be Functional!" Oikos 116, no. 5 (2007): 882–92. https://doi.org/10.1111/j.0030-1299.2007.15559.x.

## 4.9 Bridging Text

Chapter 4 introduced the functional building traits concept and provides the foundation of Forest-Building approach and its use at the core of a plant-trait based approach to wood construction. We demonstrated 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.

Chapter 5 provides the next step needed to assess the functional resilience of wood construction approaches. This study outlines the tools and indicators needed to assess the functional resilience and adaptability of existing and novel harvested wood products and wood construction approaches using the plant-trait based approach established in Chapter 4.

# 5 Wood in transition: diversifying wood construction to cope with forest change

This manuscript is in preparation for submission.

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## 5.1 Abstract

This study demonstrates how to design and assess the resilience and adaptability of wood buildings using a plant-to-building functional trait-based approach and explores the performance of three 'generic' wood building construction techniques—mass timber, timber-frame, and light frame wood construction— and their resultant forest management strategies in shaping the *functional resilience and adaptability* of managed forested ecosystems. The results demonstrates the functional traits of each wood construction approach; the functional traits of the forestry practices inherent to each method; and finally, a multi-scale indicator of wood construction resilience based on species functional traits. This study provides a new indicator and benchmark for future wood products and construction approaches.

Keywords: functional traits, resilience, wood construction, indicators

## 5.2 Context

With the decarbonization of construction becoming crucial to national and global GHG emissions policies(Geng et al. 2017; Churkina et al. 2020; Pomponi et al. 2020), architects and builders are turning to wood construction systems and techniques to offset industry emissions through the carbon storage potential of wood(Churkina et al. 2020). More wood buildings will, prevailing claims suggest, store more carbon. Yet, current wood construction approaches select a narrow range of species, strongly encouraging the homogenizing of forests and plantations across large landscapes(Osborne et al. 2023). This homogenization of forest composition and structures leads to decreased biodiversity, resilience and adaptability to the impacts of natural and anthropogenic disturbances(Jactel et al. 2017; Christian Messier et al. 2019; K. J. Puettmann, Coates, and Messier 2009). It also impacts the carbon dynamics of forests and buildings. There is a need for architects and designers to recognize how current wood construction practices, focusing on high volume mass timber wood constructions that utilize a few short rotation commercial species are contributing to diversity loss, decreasing resilience and adaptability to disturbances like changing climates, and restricting the combined GHG emission potential of both forestry and construction sectors combined(Soto-Navarro et al. 2020; Schlotzhauer et al. 2019). Here, a new approach is presented to design and evaluate the resilience of HWPs and wood buildings by (a) categorizing and benchmarking extant wood construction approaches according to indicators of ecological diversity, (b) assessing their adaptability to changes in forest management approach and increasing climate change by quantifying wood product resilience, and (c) determining what regional wood construction approaches are better suited to steward long-term forest resilience and adaptation to global change. Combining insights from forest ecology and wood construction, a promising approach to synchronize forest and timber-building practices is posited.

### 5.2.1 Wood use and characterization in construction

Wood species used in construction are predominantly organized as either softwood (gymnosperm) or hardwood (angiosperm) and sold commercially under an individual species (e.g., Eastern White Pine, Western Red Cedar) or commercial group (e.g. Spruce-Pine-Fir). Softwood trees (not to be confused with softwood) represent the majority of current wood construction. The contemporary use of softwood in construction has been favored over hardwood because the physical and mechanical traits are relatively predictable, easy to process, and variations within and between the different softwood species are relatively small. Softwood tree species are favored in construction due to their height, relatively uniform stems that exhibit minimal tapering, predictable physical and mechanical characteristics, and sparsely scattered small knots. Furthermore, softwood species generally grow faster than hardwoods and therefore have shorter rotation periods. Softwood grows much quicker, sometimes in as little as 25 years. In contrast, hardwoods are slow slow-growing and take up to 100 years to fully mature, which is a reason for the dense timber. The impact of rotation period on ecological and building traits is critical. In a study on the impact of rotation period on merchantable Sitka Spruce, Moore et al. (2012) found that mean modulus of elasticity and bending strength of timber from the outermost radial position were 51% and 41% greater, respectively, than for timber from adjacent to the pith. In addition, wood density differed by 9% between these positions. These differences in building traits resulted in increased distortion (spring, twist and bow) in timber cut from adjacent to the pith. Therefore, longer forestry rotations resulted in timber with improved mechanical properties and less distortion.

For the ease of specification, application, and standardization in construction, softwood varieties that share comparable strength properties and are commonly cultivated within the same geographical area are grouped together into commercial categories. Designing and building with a smaller number of species combinations simplifies the specification of appropriate wood species and standardizes installation and inspection during manufacturing or construction. For example, the Spruce-Pine-Fir (S-P-F) species group grows abundantly throughout Canada, making up the largest proportion of dimensional lumber production. In contrast, hardwoods are characterized by complex branching and a much lower percentage of useable stem wood for lumber. The ratio of roundwood yield has been estimated to be 85% for softwoods and 55% for hardwoods (Krackler et al. 2011; See Figure 31). Hardwoods and softwoods also differ according to anatomical structures and functional traits influencing their physical and mechanical properties, durability, workability and bonding capacity. For a detailed description of the building related traits, building trait clustering and building groups see Osborne et al. (2023)/Chapter 4 and Supplementary Information Section 8.2. For example, the structure of hardwoods is more differentiated because of the types of cells required to fulfill specific tasks including stabilization, water transportation and storage. Therefore, it is typical for hardwoods like beech, oak, and ash to have higher density, increased stiffness, and strength but a lower dimensional stability due to increased swelling and shrinkage, complicating the drying and bonding. While research and applications of hardwoods and other low-value and underutilized species remain limited, various studies have demonstrated their suitability for use and the technical feasibility of production (Das et al. 2023; Purba et al. 2022; Li and Ren 2022; Brunetti et al. 2020; Jahedi et al. 2019).

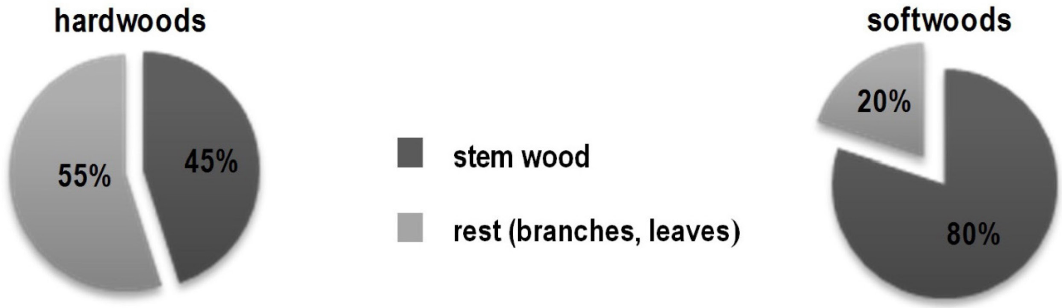


*Figure 31 - Useable percentage of stem wood (Krackler et al. 2011)*

### 5.2.2 Regional use of wood products in construction

It is necessary to understand forest and wood product flows at the regional scale as an important guide for decision makers in the local building and forest product industries.  For example, wood is one of Canada and Quebec's, most important natural resources and construction products. For non-residential buildings, surveys have estimated that approximately 28% of buildings below four stories use wood structures, but the volume and type of wood construction approach remains unknown (Cordier et al. 2019).  For single-family homes, light-frame softwood construction represents approximately 90% of new construction.  Furthermore, recent building code changes have increased the possible height of wood buildings to 12 stories using cross laminated timber (CLT) in the region further increasing the demand for construction timber on regional forests. While the feasibility of wood-based structures for these low-rise and high-rise constructions may represent a technical reality, the high volume of wood required will impact wood resource availability, their impact on regional forest resilience, and climate-induced changes forest structures and species composition (Osborne et al. 2023).

### 5.2.3 The impact of changing forest management on wood construction

In Osborne et al. (2023), we proposed a whole system trait-based approach, an important aspect of what we called Forest-Building, for the wood construction industry to better characterize the relationship between wood utilization in buildings and forest ecosystem biodiversity, resilience and adaptability. By grouping wood species according to functional ecological and building-related traits, Forest-Building facilitates the specification of a broader range of wood species, is adaptable to multiple forestry management and silvicultural approaches, and can help identify suitable species substitutions and adaptation in existing wood building practices. This study aims to address the next steps towards an integrated Forest-Building approach to inform practical design, policy-making and industry actions. To do so, this study used the plant-trait based approach to building set-out in Osborne et al. (2023)/Chapter 4 to assess the functional resilience and adaptability of existing and novel harvested wood products (dimensional lumber, wood panels, mass timber, and structural composite lumber) and wood construction approaches (light frame, timber frame and mass timber). Specifically, this study utilized ecological indicators of resilience, species richness, functional diversity and redundancy alongside indicators of wood utilization/demand further illustrate how a changing forest composition and structure will change the wood building composition of the built environment.

## 5.3 Methodology

### 5.3.1 Study Site

Following previous work by the author, this study was performed in the Central Quebec region of southeastern Canada (Osborne et al. 2023) (Figure 30). The study site was chosen due to its location on a transition from northern hardwoods to mixed wood with southern boreal conifers.

The study region is currently dominated by northern deciduous tree species with patches of monoculture conifer stands resulting from past anthropogenic disturbances, including harvesting (Danneyrolles et al. 2019). Currently, the most abundant tree species are maples (*Acer rubrum* and *Acer saccharum*), balsam fir (*Abies balsamea*), and yellow birch (*Betula alleghaniensis*).

### 5.3.2 Wood species, commercial groups and ecological groups

Of the 35 species present in the study region, 14 species from 4 commercial groups were present: the Eastern Hemlock Group (Hem-Tam), the Northern Species Group (N. Species), the Spruce-Pine-Fir Group (S-P-F), and Northern Aspen Group (N. Aspen). Additionally, this study utilizes the same ecological groups describe previously Osborne et al. (2023) (Table 3). The clustering of species into functional groups according to their ecological traits, was previously shown to offer a simple and meaningful way to categorize species that share similar sets of traits and to guide decisions toward more ecologically diverse forest communities. In addition to the 35 tree species currently present in the Centre-du-Quebec, this study included 42 other tree species found in biogeographical regions surrounding the study area (e.g. the Mixedwood Plains ecozone in Canada and Northern Lakes and Forests ecoregion in the United States). This was done to cover a more extensive array of traits and functions from species that could potentially grow in the study area and may likely proliferate northward in the coming years, thus obtaining a larger representation of each ecological group and novel wood for construction.

### 5.3.3 Wood construction approaches

Each species present in the study region was assessed for its current use in wood construction as well as various projected uses through innovations in low-value wood utilization. Wood construction approaches were organized according to the categories of wood products used in construction (Table 4). This includes dimensional lumber, structural mass timber, structural composite lumber, wood-based panels, and other wood-based products not covered in the other categories, including solid-sawn heavy timber and hardwoods.

### 5.3.4 Study Scenarios

Three structural wood construction approaches were assessed in this study, light frame, timber frame(adaptive) and mass timber. The range of wood products used within these approaches represents existing and novel wood construction practices selected from Table 4. For each scenario, a four-story 'typical' commercial construction for each approach was designed in order to calculate product material quantities (Figure 32). Wood subassemblies for each scenario were selected to represent extremes of functional diversity (low, medium and high) as well volume utilization (low, medium, high). Additional combinations are possible using the subassemblies as well as novel approaches not covered within this study. Although wood products are often used for finishes, millwork, insulation and various other products described above, they were not included in the scenario analysis and were assumed to be identical for each approach.

*Table 4 - Scenario and subassembly wood product by category, species, commercial groups, and functional groups present within this study.*

| | | | | | | Lumber | | | | Structural mass timber products (CLT) | | | | Structural composite lumber | | | | Wood-based panels | | Other | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Botanical Name | Commercial Name | Ecological Group | Building Group | Commercial Species ID | Species Commercial Group | DL: S-P-F | DL: N. Species | DL: Hem-Tam | DL: N. Aspen | MT: Black Spruce | MT: Commercial Group (SPF) | MT: Commercial Group (Hem-Tam) | MT: Hardwoods | SCL: Laminated veneer lumber | SCL: Laminated strand lumber | SCL: Oriented strand lumber | SCL: Parallel strand lumber | WP: Oriented strandboard | WP: Plywood | Hardwoods | Solid-sawn heavy timber |
| Abies balsamea | Fir, Balsam | Con-Bor | 1 | B Fir (N) | SPF | 1 | | | | | 1 | | | | | | | | 1 | | |
| Acer rubrum | Maple, Red | NHW-Es | 4 | | | | | | | | | | 1 | | | | | | | 1 | |
| Acer saccharinum | Maple, Silver | NHW-Es | 5 | | | | | | | | | | 1 | | | | | | | 1 | |
| Acer saccharum | Maple, Sugar | NHW-Es | 6 | | | | | | | | | | 1 | | | | | | | 1 | |
| Betula alleghaniensis | Birch, Yellow | NDC-Es | 7 | | | | | | | | | | 1 | | | | | | | | |
| Betula lenta | Birch, Sweet | NDC-Es | 7 | | | | | | | | | | 1 | | | | | | | | |
| Betula papyrifera | Birch, Paper | NDC-Es | 4 | W Birch | N. Species | | 1 | | 1 | | | | 1 | | | | | | 1 | | |
| Betula populifolia | Birch, Gray | NDC-Es | 3 | | | | | | | | | | 1 | | | | | | | | |
| Carya cordiformis | Hickory, pecan, Bitternut | NHW-Ms | 7 | | | | | | | | | | | | | | | | | | |
| Carya glabra | Hickory, true, Pignut | CHN-Dt | 7 | | | | | | | | | | | | | | | | | | |
| Fagus grandifolia | Beech, American | NHW-Es | 6 | | | | | | | | | | 1 | | | | | | | | |
| Fraxinus americana | Ash, White | NHW-Ms | 4 | | | | | | | | | | | | | | | | | | |
| Juglans nigra | Walnut, black | NHW-Ms | 4 | | | | | | | | | | | | | | | | | 1 | |
| Larix laricina | Tamarack | CHW-Ms | 3 | Tam (N) | Hem-Tam | | | 1 | | | | 1 | | 1 | | | | | 1 | | 1 |
| Liriodendron tulipifera | Yellow-poplar | NHW-Ms | 5 | | | | | | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | |
| Picea abies | Spruce, Norway | Con-Bor | 2 | N Spr (N) | N. Species | | 1 | 1 | | | | | | | | | | | 1 | | |
| Picea glauca | Spruce, White | Con-Bor | 2 | W Spr (N) | SPF | 1 | | | | | 1 | | | | | | | | 1 | | |
| Picea mariana | Spruce, Black | Con-Bor | 2 | B Spr (N) | SPF | 1 | | | | 1 | 1 | | | | | | | | 1 | | |
| Picea rubens | Spruce, Red | Con-Bor | 2 | R Spr (N) | SPF | 1 | | | | | 1 | | | | | | | | 1 | | |
| Pinus resinosa | Pine, Red | Con-Pin | 2 | R. Pine | N. Species | | 1 | | | | 1 | | | | | | | | 1 | | |
| Pinus rigida | Pine, Pitch | Con-Pin | 2 | | | | | | | | | | | | | | | | 1 | | |
| Pinus strobus | Pine, Eastern white | Con-Bor | 1 | EW Pine (N) | N. Species | | 1 | | | | | | | | | | | | 1 | | |
| Pinus taeda | Pine, Loblolly | Con-Pin | 2 | | South | | | | | | 1 | | | 1 | | | | | 1 | | |
| Populus grandidentata | Aspen, Bigtooth | CHW-Ms | 5 | Aspen (N) | N. Aspen | | | | 1 | | | | | 1 | 1 | 1 | 1 | 1 | 1 | | |
| Populus tremuloides | Aspen, Quaking | CHW-Ms | 5 | Aspen (N) | N. Aspen | | | | 1 | | | | | 1 | 1 | 1 | 1 | 1 | 1 | | |
| Prunus serotina | Cherry, black | NDC-Es | 3 | | | | | | | | | | | | | | | | | 1 | |
| Quercus alba | Oak, white, White | CHN-Dt | 6 | | | | | | | | | | 1 | | | | | | | 1 | |
| Quercus coccinea | Oak, red, Scarlet | CHN-Dt | 6 | | | | | | | | | | 1 | | | | | | | 1 | |
| Quercus macrocarpa | Oak, white, Bur | CHN-Dt | 4 | | | | | | | | | | 1 | | | | | | | 1 | |
| Quercus rubra | Oak, red, Northern red | CHN-Dt | 6 | | | | | | | | | | 1 | | | | | | | 1 | |
| Quercus velutina | Oak, red, Black | CHN-Dt | 6 | | | | | | | | | | 1 | | | | | | | 1 | |
| Thuja occidentalis | Cedar, Northern white | Con-Bor | 1 | EW Cedar (N) | N. Species | | 1 | | | | | | | | | | | | 1 | | |
| Tilia americana | Basswood, American | NHW-Ms | 5 | | | | | | | | | | | | | | | | | | |
| Tsuga canadensis | Hemlock, Eastern | Con-Bor | 1 | E Hem (N) | Hem-Tam | | | 1 | | | | 1 | | | | | | | 1 | | 1 |
| Ulmus americana | Elm, American | NHW-Es | 4 | | | | | | | | | | | | | | | | | | |

Table 4 (con't) - Scenario and subassembly wood product by category, species, commercial groups, and functional groups present within this study

| | | | | | | Scenario 1a: Light Frame (S-P-F) | | | Scenario 1b: Light Frame (All commercial groups) | | | Scenario 2: Mass Timber (Single Species) | | | Scenario 3: Post and beam | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Botanical Name | Commercial Name | Ecological Group | Building Group | Commercial Species ID | Species Commercial Group | Commercial Group (SPF) | Sheating (OSB) | Scenario 1A: LF SPF Combined | Dimensional Lumber (All comercial groups) | Sheating (Plywood) | Scenario 1B: LF All CGs Combined | Single Species Black Spruce | Scenario 2a: MT Black Spruce | Scenario 2b: MT Balsam Fir | Solid-sawn heavy timber (hardwood + softwood) | Built-Up (all commercial groups | Built-Up (SCL) | Glulam (SPF) | Scenario 3: TF Combined | Light Frame Infill (all commercial groups | Scenario 3 Combined |
| Abies balsamea | Fir, Balsam | Con-Bor | 1 | B Fir (N) | SPF | 1 | | 1 | 1 | 1 | 1 | | | 1 | | 1 | | 1 | 1 | 1 | 1 |
| Acer rubrum | Maple, Red | NHW-Es | 4 | | | | | | | | | | | | 1 | | | | 1 | | 1 |
| Acer saccharinum | Maple, Silver | NHW-Es | 5 | | | | | | | | | | | | 1 | | | | 1 | | 1 |
| Acer saccharum | Maple, Sugar | NHW-Es | 6 | | | | | | | | | | | | 1 | | | | 1 | | 1 |
| Betula alleghaniensis | Birch, Yellow | NDC-Es | 7 | | | | | | | | | | | | | | | | | | |
| Betula lenta | Birch, Sweet | NDC-Es | 7 | | | | | | | | | | | | | | | | | | |
| Betula papyrifera | Birch, Paper | NDC-Es | 4 | W Birch | N. Species | | | | 1 | 1 | 1 | | | | | 1 | | | 1 | 1 | 1 |
| Betula populifolia | Birch, Gray | NDC-Es | 3 | | | | | | | | | | | | | | | | | | |
| Carya cordiformis | Hickory, pecan, Bitternut | NHW-Ms | 7 | | | | | | | | | | | | | | | | | | |
| Carya glabra | Hickory, true, Pignut | CHN-Dt | 7 | | | | | | | | | | | | | | | | | | |
| Fagus grandifolia | Beech, American | NHW-Es | 6 | | | | | | | | | | | | | | | | | | |
| Fraxinus americana | Ash, White | NHW-Ms | 4 | | | | | | | | | | | | | | | | | | |
| Juglans nigra | Walnut, black | NHW-Ms | 4 | | | | | | | | | | | | 1 | | | | 1 | | 1 |
| Larix laricina | Tamarack | CHW-Ms | 3 | Tam (N) | Hem-Tam | | | | 1 | 1 | 1 | | | | 1 | 1 | 1 | | 1 | 1 | 1 |
| Liriodendron tulipifera | Yellow-poplar | NHW-Ms | 5 | | | | 1 | 1 | | 1 | 1 | | | | | | 1 | | 1 | | 1 |
| Picea abies | Spruce, Norway | Con-Bor | 2 | N Spr (N) | N. Species | | | | 1 | 1 | 1 | | | | | 1 | | | 1 | 1 | 1 |
| Picea glauca | Spruce, White | Con-Bor | 2 | W Spr (N) | SPF | 1 | | 1 | 1 | 1 | 1 | | | | | 1 | | 1 | 1 | 1 | 1 |
| Picea mariana | Spruce, Black | Con-Bor | 2 | B Spr (N) | SPF | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | | | 1 | | 1 | 1 | 1 | 1 |
| Picea rubens | Spruce, Red | Con-Bor | 2 | R Spr (N) | SPF | 1 | | 1 | 1 | 1 | 1 | | | | | 1 | | 1 | 1 | 1 | 1 |
| Pinus resinosa | Pine, Red | Con-Pin | 2 | R. Pine | N. Species | | | | 1 | 1 | 1 | | | | | 1 | | 1 | 1 | 1 | 1 |
| Pinus rigida | Pine, Pitch | Con-Pin | 2 | | | | | | | 1 | 1 | | | | | | | | | | |
| Pinus strobus | Pine, Eastern white | Con-Bor | 1 | EW Pine (N) | N. Species | | | | | 1 | 1 | | | | | 1 | | | 1 | 1 | 1 |
| Pinus taeda | Pine, Loblolly | Con-Pin | 2 | | South | | | | 1 | 1 | 1 | | | | | | 1 | 1 | 1 | | 1 |
| Populus grandidentata | Aspen, Bigtooth | CHW-Ms | 5 | Aspen (N) | N. Aspen | | 1 | 1 | 1 | 1 | 1 | | | | | 1 | 1 | | 1 | 1 | 1 |
| Populus tremuloides | Aspen, Quaking | CHW-Ms | 5 | Aspen (N) | N. Aspen | | 1 | 1 | 1 | 1 | 1 | | | | | 1 | 1 | | 1 | 1 | 1 |
| Prunus serotina | Cherry, black | NDC-Es | 3 | | | | | | | | | | | | 1 | | | | 1 | | 1 |
| Quercus alba | Oak, white, White | CHN-Dt | 6 | | | | | | | | | | | | 1 | | | | 1 | | 1 |
| Quercus coccinea | Oak, red, Scarlet | CHN-Dt | 6 | | | | | | | | | | | | 1 | | | | 1 | | 1 |
| Quercus macrocarpa | Oak, white, Bur | CHN-Dt | 4 | | | | | | | | | | | | 1 | | | | 1 | | 1 |
| Quercus rubra | Oak, red, Northern red | CHN-Dt | 6 | | | | | | | | | | | | 1 | | | | 1 | | 1 |
| Quercus velutina | Oak, red, Black | CHN-Dt | 6 | | | | | | | | | | | | 1 | | | | 1 | | 1 |
| Thuja occidentalis | Cedar, Northern white | Con-Bor | 1 | EW Cedar (N) | N. Species | | | | | 1 | 1 | | | | | 1 | | | 1 | 1 | 1 |
| Tilia americana | Basswood, American | NHW-Ms | 5 | | | | | | | | | | | | | | | | | | |
| Tsuga canadensis | Hemlock, Eastern | Con-Bor | 1 | E Hem (N) | Hem-Tam | | | | 1 | 1 | 1 | | | | 1 | 1 | | | 1 | 1 | 1 |
| Ulmus americana | Elm, American | NHW-Es | 4 | | | | | | | | | | | | | | | | | | |

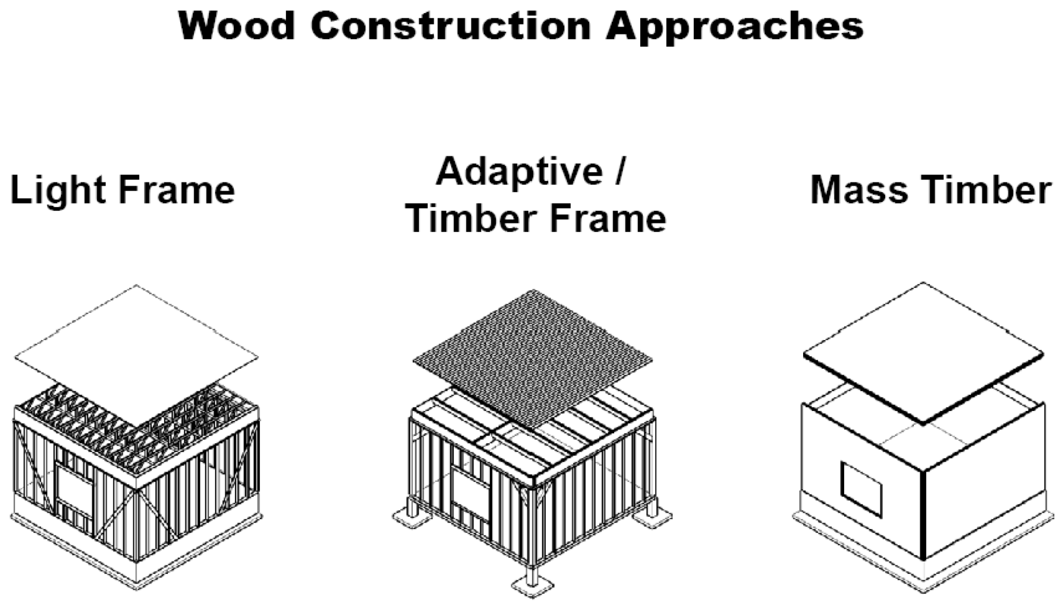


*Figure 32 Axonometric section of different wood construction scenarios.*

*Table 5 - Wood construction approaches used in this study.*

| Scenario | Functional Diversity | Wood Utilization | Wood Subassemblies |
|---|---|---|---|
| 1a Light Frame | Low | Low (100%) | DL – SPF, WP – OSB |
| 1b Light Frame | Medium | Low (100%) | DL – All, WP – OSB/Plywood |
| 2 Mass Timber (CLT) | Low | High (550%) | MT – CLT Single Species (a:black spruce, b: balsam fir) |
| 3 Timber Frame | High | Medium (245%) | TF – DL – All, SCL – All, Hardwood, Solid-Sawn Timber |

### 5.3.5 Measurement of functional resilience of wood products

This study quantifies three major properties likely to influence wood construction resilience using the following indicators. Species richness by ecological group (SR) was measured as the total number of species by ecological group available within the study region suitable for each wood product or construction approach. Wood product or approach functional redundancy (FR) was calculated as proposed by Ricotta et al. and applied in previous studies of landscape resilience using the FD package in R. Functional redundancy quantifies the overlap of functional traits within each wood construction approach. To see its application in biological communities, see (Ricotta et al. 2016; Laliberté and Legendre 2010). The functional diversity (FD) of each wood product and construction approach was computed as the exponent of the Shannon diversity index (Jost 2006; Aquilué et al. 2020) and applied to the relative utilization of species functional groups for each construction approach and calculated as follows:

$$fdiv_k = \exp\left(-\sum_{i=1}^{n} p_i \cdot \ln(p_i)\right),$$

where n is the total number of functional groups utilized according to each construction approach k and $p_i$ is the relative volume utilized of functional group i within construction approach k. The functional redundancy and diversity of each wood approach ranged from 1 to n. To facilitate interpretation it was linearly rescaled it to [0,1] representing minimum to maximum functional redundancy and diversity of each approach, respectively.

### 5.3.6 Measurement of harvest resource availability and Forest-Building synchronization

To explore spatial and temporal suitability of each wood construction approach for the landscape, three indicators were analyzed. Harvest Resource Availability (HRA) indicates the quantity of wood resources useable by each wood approach for a site as a function of tree species composition from the site. To better understand the suitability of each wood construction approach to the site context Harvested Resource Index (HRI), and the Forest-Building Index (FBI) were assessed. HRI is calculated as the ratio of useable wood to total harvested wood and is calculated as follows:

**HRIwc = HRAwc/Total Harvested Output,**

where wc is the wood construction approach. Approaches with a high HRI are able to more fully utilize the total harvested volume, diverting it away from short-lived wood products such as paper and biofuels. Finally, FBI (unitless) is calculated by dividing the HRI by the relative wood volume utilization of each wood construction scenario found in Table 5.

**FBIwc = HRIwc/Wood demand of construction approach**

The translation from HRA to FBI is a critical step to understand the societal benefits of following a specific wood construction approach. While HRA is a measure of wood utilization efficiency, by normalizing this measure using each construction approach's wood demand, FBI can act as an indicator of the relative number of products or buildings possible under each scenario. Together HRA, HRI and FBI can be used to assess regional synchronization between the wood construction approach and the harvest output species composition that ultimately dictates the Forest-Building suitability of the wood construction approach in a given region.

### 5.3.7 Model description and experimental design

This study uses LANDIS-II, a spatially explicit, process-based forest landscape model to simulate future forest development and evaluate potential harvest outputs (Scheller et al. 2007). Three management strategies of increasing resilience and adaptability to climate change were considered in this experiment: business-as-usual (BAU), climate change adaptation (CCA) and two variants of the functional diversification network approach (FDN15 and FDN25). The design allowed us to explore the connection between forest ecological and construction system resilience indicators of various wood construction approaches under an increasing level of unexpected stress at the landscape level while maintaining a reasonable number of scenarios (Table 6). Further details can be found in the Supplemental Information 8.3.

*Table 6 - Combination of climate, management scenarios and wood construction approaches analyzed. Scenarios are ordered by increasing level of change and climatic/disturbance stress. All three wood construction approaches were simulated for each climate and management scenario. See Supplemental Information for inputs parameterization and details of each scenario.*

| Climate | Management | Wood Approach |
|---|---|---|
| Present (Current) | BAU/CCA/FDN15/FDN25 | LF/MT/TF |
| Warm (RCP 4.5) | BAU/CCA/FDN15/FDN25 | LF/MT/TF |
| Hot (RCP 8.5) | BAU/CCA/FDN15/FDN25 | LF/MT/TF |

# 5.4 Results & Discussion

## 5.4.1 Benchmarking functional resilience of wood construction

Despite the relatively large quantity and diversity of wood construction approaches, current wood building scenarios utilize fewer than four species growing or planted in the study region (Figure 33). The construction industry is dominated by commercially available dimensional lumber and single species approaches using primarily cold-adapted softwood species (mostly S-P-F) with only a few approaches utilizing hardwoods. Notable exceptions include structural composite lumber and wood panels such as plywood, which can utilize hardwoods with or without softwood species. All seven ecological groups were represented in at least one approach within the study, yet the early to mid-successional hardwood species (NHW-MS & CHW-Dt) were exclusive to hardwood approaches. Wood construction approaches utilizing species from one or two ecological groups represent 75% of all extant wood construction approaches. Five of seven ecological groups were represented within the existing commercial groups sold in Canada. Late successional, drought intolerant softwood species (Con-Bor) were represented in seven approaches across three categories, yet early successional and drought tolerant softwoods (Con-Pin) were rarely represented.  Hardwood species were represented in eleven approaches across all five categories.

The mean functional diversity for all wood construction approaches was 0.19 while the mean functional redundancy was 0.8 (Figure 34). The mean ecological diversity/redundancy for each f the wood product categories was 0.14/0.94 for dimensional lumber, 0.17/.93 for structural composite lumber, 0 for structural mass timber, 0.30/0.92 for wood panels, and 0.27/0.91 for hardwood and solid-sawn heavy timber. The approaches with the highest ecological diversities of 0.46 and 0.95 were plywood and hardwoods respectively.  Single species approaches that utilize wood from a single ecological group stand out with the lowest ecological diversity and redundancy within the study of 0 for both indicators. The mean functional diversity and redundancy of the scenarios, excluding mass timber, was 0.52/0.90. The ecological diversity for each approach, from lowest to highest, was 0 for single species mass timber (both), 0.27 for light frame construction using S-P-F and OSB, 0.46 for light frame construction using all commercial groups and plywood, and 0.84 for timber frame construction.

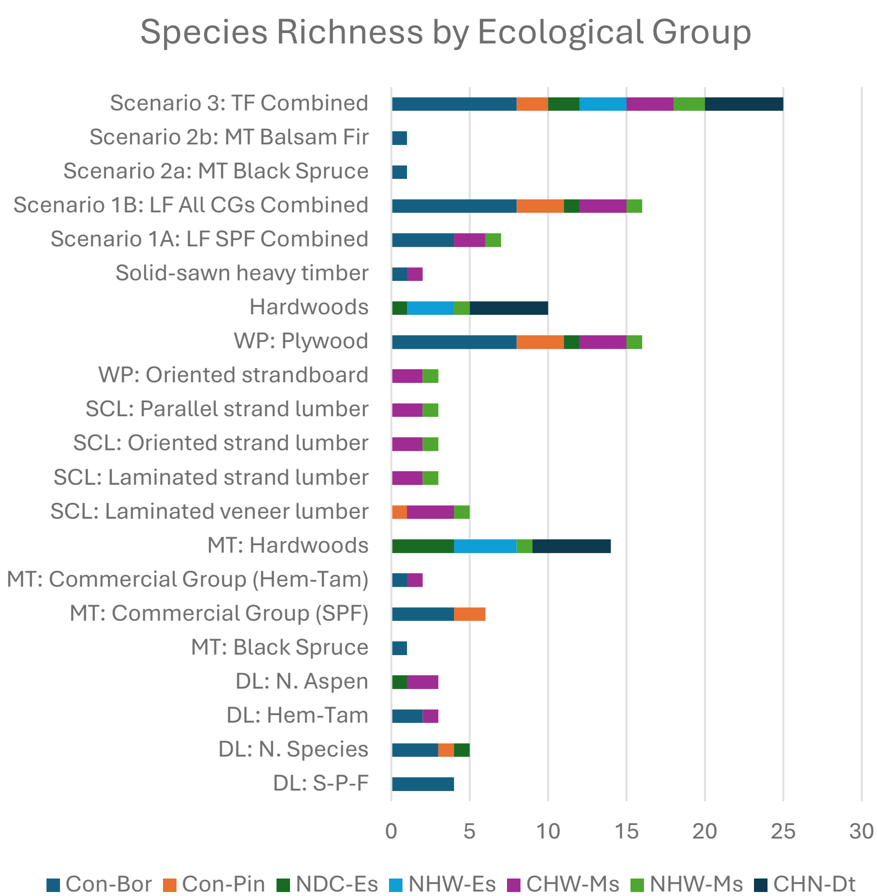


*Figure 33 - Wood products and scenarios species richness by ecological group. Higher species richness and number of ecological groups represented are indicators of wood product resilience. Plywoods, hardwoods, Northern species dimensional lumber, and laminated veneer lumber are all able to utilize species from with 3 or greater ecological groups. By combining these products into a single building, such as an adaptive timber frame approach, designers and builders can maximize the resilience of this construction approach to changes in forest composition and climate change.*

# BENCHMARK

RESILIENCY AND ADAPTABILITY OF WOOD PRODUCT CATEGORIES AND CONSTRUCTION APPROACHES

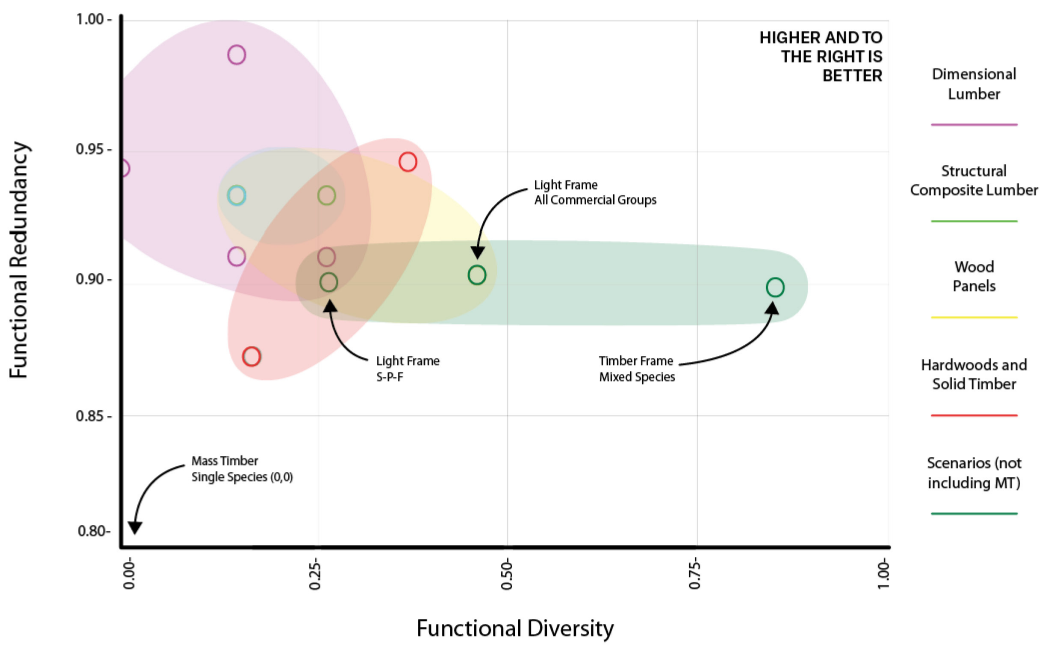


*Figure 34 Functional redundancy and diversity of wood construction approaches and scenarios in the study. The higher and to the right the shape the greater the resilience. Single species approaches (Mass Timber) with FD and FR of 0 are not shown. While dimensional lumber has high functional redundancy, they have low functional diversity. This puts manufacturers, sawmills, and wood construction approaches relying on a single commercial lumber group at risk as all species will react in a similar manner to future known and unknown disturbances. In contrast, wood panels and hardwood/solid timber approaches have slightly higher functional diversity, yet lower functional redundancy. Designers are able to increase the resiliency of their wood building approach by combining these products together – moving from Light Frame SPF, to Light Frame All Commercial Groups, and finally to an Adaptive Timber Frame.*

### 5.4.2 Regional suitability of wood construction approaches

Changes in HRA, HRI and FBI due to climate change and forest management are shown in Figure 35, Figure 36, and Figure 37 respectively. The quantity of wood utilization by each construction approach differed more among management scenarios than climate scenarios. Under all management and climate change scenarios, our study region was found to be most suitable for low to medium volume wood construction approaches with high species richness and functional diversity (mixed species timber frame and light frame construction using all commercial groups). The relative increase in HRA/HRI for timber frame was higher under CCA and FDN treatments. Climate driven impacts to harvest output were smallest for mixed species approaches and increased for less ecologically diverse construction approaches. The HRI was the highest for the mixed species timber frame approach with a consistently high overall landscape value of 0.6 to 0.8 over time across all management and climate change scenarios. The light frame wood construction approach using all commercial groups was also found to have a relatively high HRI (0.45-0.6). Compared to timber frame and light frame construction, single species mass timber approaches show limited suitability for the study region in terms of harvest resource availability at the landscape scale. When considering wood volume requirements of each approach, the FBI for light frame wood construction approach using all commercial species was found to have the highest relative value. This implies that even though the HRA/HRI were lower when compared to the timber frame scenario, the low volume utilization for light-frame construction would yield a greater number of buildings for study region. In contrast, wood construction approaches which rely exclusively on a single species or commercial group were found to be vulnerable to changes in forest management and climate.

# MEASURE

## HARVEST RESOURCE AVAILABILITY AND DIVERSION POTENTIAL OF WOOD CONSTRUCTION APPROACHES

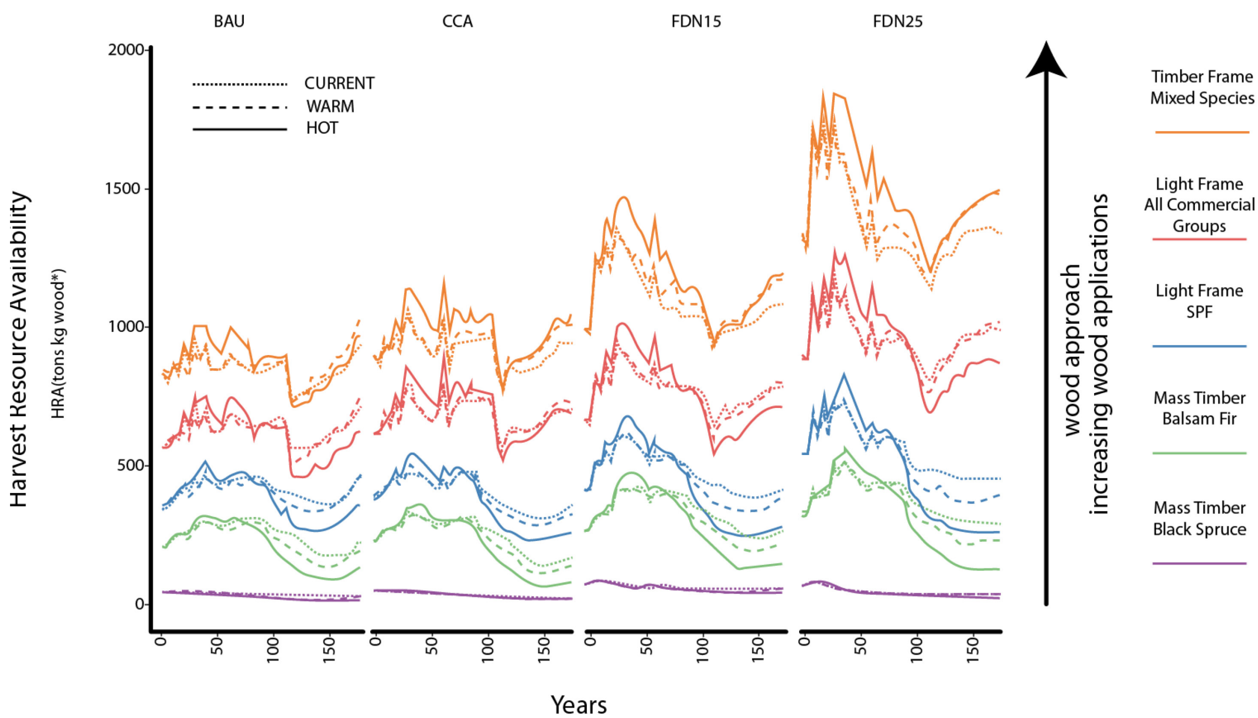


*Figure 35 Temporal development of HRA for the Centre du Quebec study region expressing overall resource availability for each wood construction and forest management approach for the study period (2010-2200).*

# ASSESS

## HARVEST RESOURCE INDEX AND DIVERSION RATIO

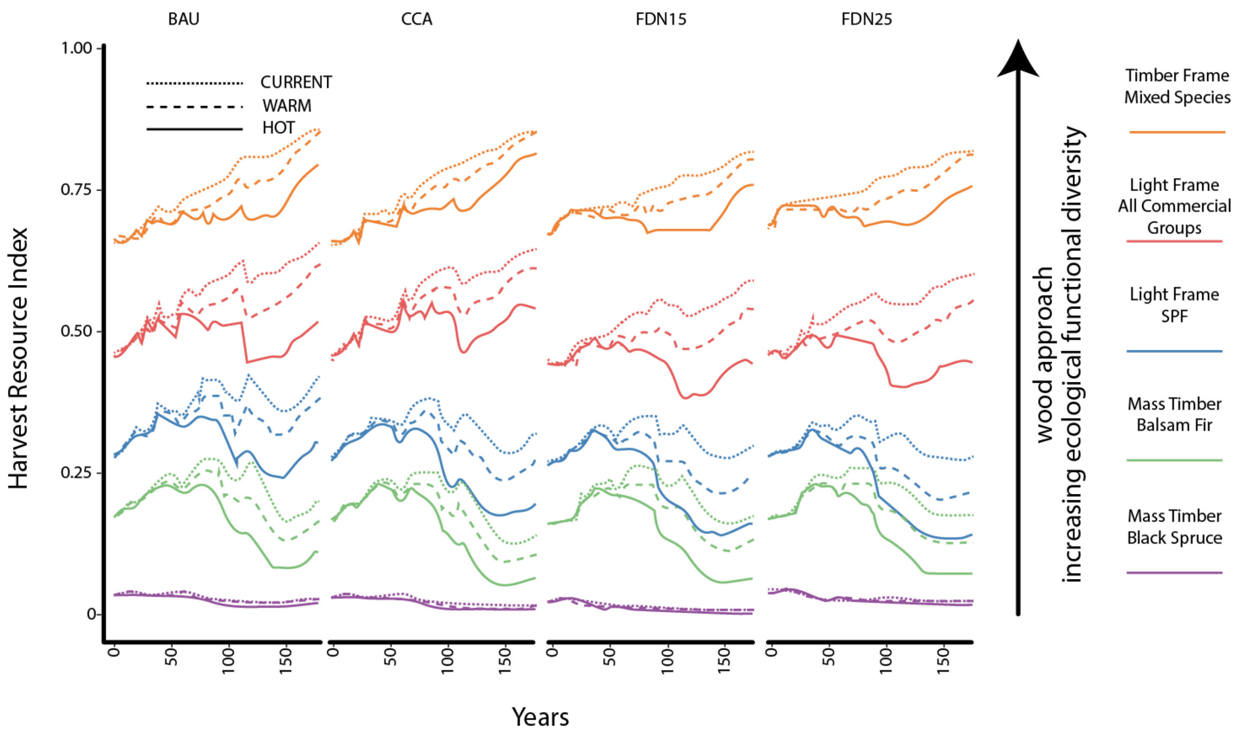


*Figure 36 Temporal development of HRI for the Centre du Quebec study region expressing overall resource utilization potential (0 low, 1 full) for each wood construction and forest management approach for the study period (2010-2200). Wood construction approaches with highest functional diversity and redundancy show the highest wood utilization potential and are impacted the least by forest composition change with the ability to substitute alternative species. The decline in wood utilization potential after year 50 of the simulation for both mass timber approaches illustrate the risk of relying on a single species(FR 0; FD0 0).*

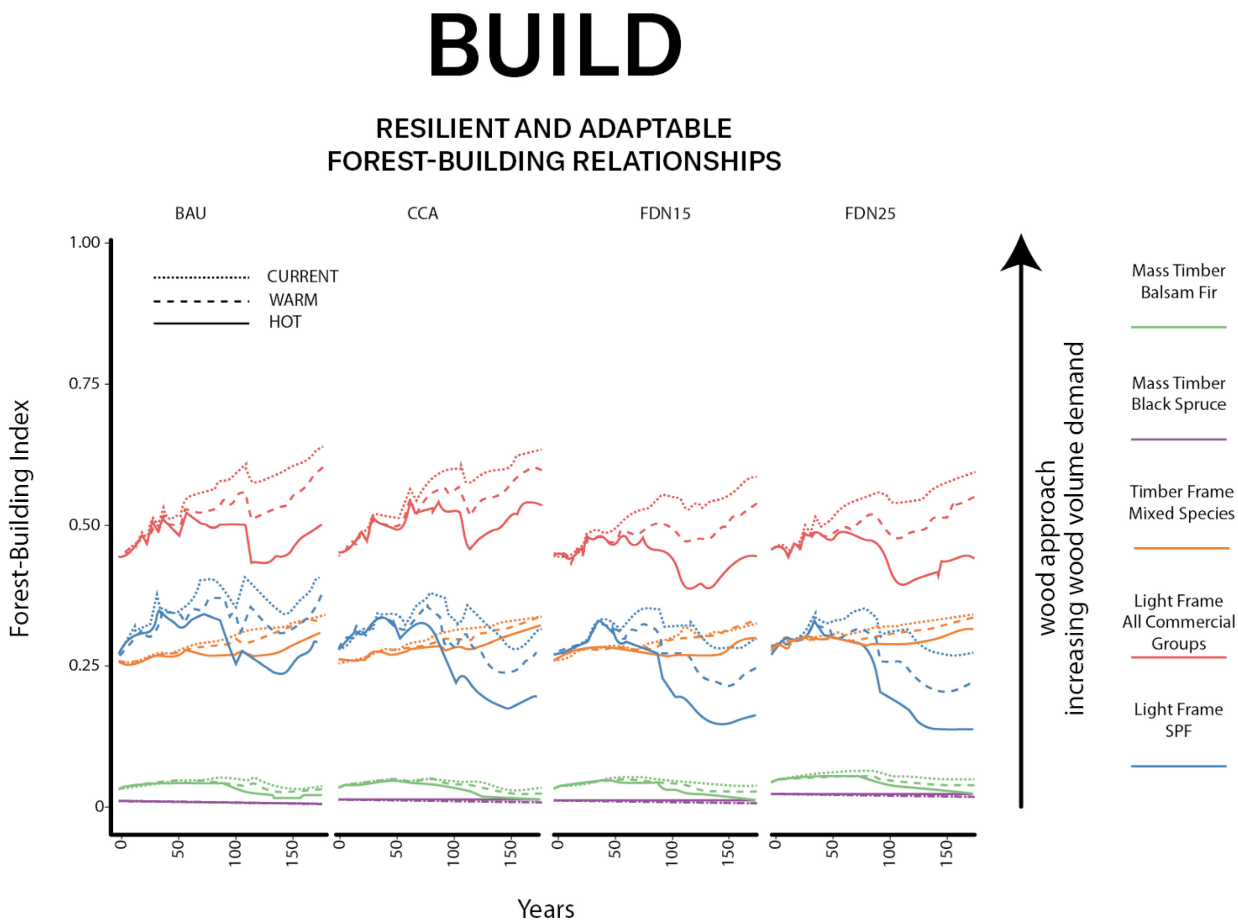


*Figure 37 - Temporal development of Forest-Building Index for the Centre du Quebec study region expressing overall resource utilization potential (0 low, 1 full) for each wood construction and forest management approach for the study period (2010-2200). FBI illustrates the relative quantity possible for of each construction approach. Here, wood construction approaches with lower volume demands, such as light frame, have a higher relative FBI. Where in Figure 36, the Timber Frame approach had the highest HRA, or greatest diversion of wood to wood construction, the greater wood quantity demands (see Table 5) reduces the construction potential of this wood. In other words, while selecting approaches which divert more wood species towards buildings using approaches with high functional diversity and redundancy, it is also critical to assess how many products, buildings etc. can be constructed.*

# 5.5 Conclusion

## 5.5.1 Implications for wood construction and planning

This study shows how expected and possible unexpected climate change and forest management approaches could impact the ongoing provisioning of wood for the construction industry and demonstrates the potential of using a synchronized ecological trait-based wood construction approach, what Osborne et al. (2023) called Forest-Building, to boost long-term ecological and construction resilience. This study found that the dominant approaches being used to offset construction industry emissions (such as single species CLT) are not resilient to climate change and alternative forest management approaches and may only be suitable in very limited regions. Diversifying the wood construction industry with key ecological traits could bring important benefits in terms of social and ecological adaptation. Given that wood harvest resources are spatially and temporally limited, adopting an synchronized landscape-scale perspective by planning regionally specific wood harvest and construction approaches—intervening in ways that maximize their ecological impact—and adopting a functional trait-based approach to diversify wood products to maximize the response range to unknown disturbances and harvest output—offers an effective approach for enhancing wood construction and forest resilience under rapid global change. This landscape-scale approach should also be merged with regional-scale assessment of biogenic carbon and other ecosystem service, as well as construction demand assessment to consider all aspects of this Forest-Building system.

For the study region, encouraging the introduction and early adoption of low volume, functionally resilient and adaptive wood construction approaches should be considered a priority in construction policies. In the context of this study, both the mixed species timber frame and light-frame all commercial group approaches had the highest species richness, functional diversity and adaptability (FD & FR), and diverted the highest quantities of harvested to long lived wood products (HRA & HRI). The higher wood quantity requirements of the timber frame approach reduced the building capacity of this approach when compared to the light frame approach. This relationship between how much harvested wood can be diverted to wood construction and the wood construction potential - or how many buildings can be built with the wood - is an important consideration and will be regionally and temporally specific according to stakeholder needs.

A functionally adaptive approach to wood construction—which adapts building design and specification to preferred forest futures—is well suited to highly flexible approaches such as light frame and timber frame which have relatively low infrastructure and fixed investments needed. In contrast, approaches such as CLT and mass timber manufacturing require large, centralized capital investments and their narrow stock parameters require a stable supply of nearly identical timber to ensure manufacturing quality control. In certain regions, a positive interaction between forest management and climate change might support high volume utilization approaches such as CLT. Yet, the regional forest composition of that region would require significant diversification of mass timber wood products towards currently underutilized and low value wood species(Thomas and Buehlmann 2017). Therefore, coordinated policy adaptations aimed at the increased utilization of wood at the regional scale should be implemented in parallel with monitoring and forecasting (e.g., modeling tools) the potential changes to harvest output, species composition, and specifying wood species that can be adapted to changing forests.

Finally, this study also highlights the need to extend the impact assessment of wood construction beyond carbon and traditional life cycle assessment approaches. Assessing the resilience of regional wood construction using multiple indicators that take into consideration several properties such as ecological resilience, species richness, resource availability, harvest diversion potential, and construction yield are critical to the combined health of forested and built environments. Ecologically diverse, species rich wood construction approaches such as mixed species timber frame, and the light frame approach using combined commercial groups with moderate ecological diversity were found to be most resilient to changes in climate and forest management approach. Approaches with high functional diversity and redundancy were able to mitigate changes in harvested volume and species composition by substituting similar species from within the same commercial group, or adapting their construction approach towards alternative wood products. Finally, construction approaches based on high functional diversification and redundancy were found to divert higher volumes of wood biomass towards construction and away from short lived products, such as biofuels and paper (Desrochers et al. 2022).

# 5.6 References


Aquilué, Núria, Élise Filotas, Dylan Craven, Marie-Josée Fortin, Lluís Brotons, and Christian Messier. "Evaluating Forest Resilience to Global Threats Using Functional Response Traits and Network Properties." Ecological Applications 30, no. 5 (2020): e02095. https://doi.org/10.1002/eap.2095.

Brunetti, Michele, Michela Nocetti, Benedetto Pizzo, Francesco Negro, Giovanni Aminti, Paolo Burato, Corrado Cremonini, and Roberto Zanuttini. "Comparison of Different Bonding Parameters in the Production of Beech and Combined Beech-Spruce CLT by Standard and Optimized Tests Methods." Construction and Building Materials 265 (December 2020): 120168. https://doi.org/10.1016/j.conbuildmat.2020.120168.

Churkina, Galina, Alan Organschi, Christopher P. O. Reyer, Andrew Ruff, Kira Vinke, Zhu Liu, Barbara K. Reck, T. E. Graedel, and Hans Joachim Schellnhuber. "Buildings as a Global Carbon Sink." Nature Sustainability 3, no. 4 (April 2020): 269–76. https://doi.org/10.1038/s41893-019-0462-4.

Cordier, Sylvain, François Robichaud, Pierre Blanchet, and Ben Amor. "Exploring the Regional-Scale Potential of the Use of Wood Products in Non-Residential Buildings: A Building

Permits-Based Quantitative Approach." BioResources 15, no. 1 (December 11, 2019): 787–813. https://doi.org/10.15376/biores.15.1.787-813.
Danneyrolles, Victor, Sébastien Dupuis, Gabriel Fortin, Marie Leroyer, André de Römer, Raphaële Terrail, Mark Vellend, et al. "Stronger Influence of Anthropogenic Disturbance than Climate Change on Century-Scale Compositional Changes in Northern Forests." Nature Communications 10, no. 1 (March 20, 2019): 1265. https://doi.org/10.1038/s41467-019-09265-z.
Das, Sumanta, Miroslav Gašparík, Anil Kumar Sethy, Tomáš Kytka, Gourav Kamboj, and Fatemeh Rezaei. "Bonding Performance of Mixed Species Cross Laminated Timber from Poplar (Populus Nigra L.) and Maple (Acer Platanoides L.) Glued with Melamine and PUR Adhesive." Journal of Building Engineering 68 (June 1, 2023): 106159. https://doi.org/10.1016/j.jobe.2023.106159.
Desrochers, Michaël, Jennifer Pinna, Angela Fahdi, and Julien Beaulieu. "Forest Sector in Quebec – Circularity Assessment and Market Opportunities." CENTRE DE TRANSFERT TECHNOLOGIQUE EN ÉCOLOGIE INDUSTRIELLE, 2022.
Geng, Aixin, Hongqiang Yang, Jiaxin Chen, and Yinxing Hong. "Review of Carbon Storage Function of Harvested Wood Products and the Potential of Wood Substitution in Greenhouse Gas Mitigation." Forest Policy and Economics 85 (December 1, 2017): 192–200. https://doi.org/10.1016/j.forpol.2017.08.007.
Jactel, Hervé, Jürgen Bauhus, Johanna Boberg, Damien Bonal, Bastien Castagneyrol, Barry Gardiner, Jose Ramon Gonzalez-Olabarria, Julia Koricheva, Nicolas Meurisse, and Eckehard G. Brockerhoff. "Tree Diversity Drives Forest Stand Resistance to Natural Disturbances." Current Forestry Reports 3, no. 3 (September 1, 2017): 223–43. https://doi.org/10.1007/s40725-017-0064-1.
Jahedi, Sina, Lech Muszynski, Mariapaola Riggio, and Rakesh Gupta. "Evaluation of Bond Integrity in Low-Value Blue-Stain Ponderosa Pine CLT." In Proceedings of the 62nd International Convention of Society of Wood Science and Technology. enaya Lodge, Yosemite, California USA, 2019.
Jost, Lou. "Entropy and Diversity." Oikos 113, no. 2 (2006): 363–75. https://doi.org/10.1111/j.2006.0030-1299.14714.x.
Krackler, Verena, Daniel Keunecke, Peter Niemz, and Andreas Hurst. "POSSIBLE FIELDS OF HARDWOOD APPLICATION." WOOD RESEARCH 56 (2011).
Laliberté, Etienne, and Pierre Legendre. "A Distance-Based Framework for Measuring Functional Diversity from Multiple Traits." Ecology 91, no. 1 (2010): 299–305. https://doi.org/10.1890/08-2244.1.
Li, Mingyue, and Haiqing Ren. "Study on the Interlaminar Shear Properties of Hybrid Cross-Laminated Timber (HCLT) Prepared with Larch, Poplar and OSB." Industrial Crops and Products 189 (December 2022): 115756. https://doi.org/10.1016/j.indcrop.2022.115756.
Messier, Christian, Jürgen Bauhus, Frederik Doyon, Fanny Maure, Rita Sousa-Silva, Philippe Nolet, Marco Mina, Núria Aquilué, Marie-Josée Fortin, and Klaus Puettmann. "The Functional Complex Network Approach to Foster Forest Resilience to Global Changes." Forest Ecosystems 6, no. 1 (April 9, 2019): 21. https://doi.org/10.1186/s40663-019-0166-2.
Moore, John R., Andrew J. Lyon, and Stefan Lehneke. "Effects of Rotation Length on the Grade Recovery and Wood Properties of Sitka Spruce Structural Timber Grown in Great

Britain." Annals of Forest Science 69, no. 3 (April 2012): 353–62. https://doi.org/10.1007/s13595-011-0168-x.

Osborne, Peter, Núria Aquilué, Marco Mina, Kiel Moe, Michael Jemtrud, and Christian Messier. "A Trait-Based Approach to Both Forestry and Timber Building Can Synchronize Forest Harvest and Resilience." PNAS Nexus 2, no. 8 (August 1, 2023): pgad254. https://doi.org/10.1093/pnasnexus/pgad254.

Pomponi, Francesco, Jim Hart, Jay H. Arehart, and Bernardino D'Amico. "Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits." One Earth 3, no. 2 (August 21, 2020): 157–61. https://doi.org/10.1016/j.oneear.2020.07.018.

Puettmann, K. J., K. D. Coates, and C. Messier. A Critique of Silviculture: Managing for Complexity. Washington: Island Press, 2009.

Purba, Citra Yanto Ciki, Guillaume Pot, Robert Collet, Myriam Chaplain, and Jean-Luc Coureau. "Assessment of Bonding Durability of CLT and Glulam Made from Oak and Mixed Poplar-Oak According to Bonding Pressure and Glue Type." Construction and Building Materials 335 (June 2022): 127345. https://doi.org/10.1016/j.conbuildmat.2022.127345.

Ricotta, Carlo, Francesco de Bello, Marco Moretti, Marco Caccianiga, Bruno E. L. Cerabolini, and Sandrine Pavoine. "Measuring the Functional Redundancy of Biological Communities: A Quantitative Guide." Methods in Ecology and Evolution 7, no. 11 (2016): 1386–95. https://doi.org/10.1111/2041-210X.12604.

Scheller, Robert M., James B. Domingo, Brian R. Sturtevant, Jeremy S. Williams, Arnold Rudy, Eric J. Gustafson, and David J. Mladenoff. "Design, Development, and Application of LANDIS-II, a Spatial Landscape Simulation Model with Flexible Temporal and Spatial Resolution." Ecological Modelling 201, no. 3 (March 10, 2007): 409–19. https://doi.org/10.1016/j.ecolmodel.2006.10.009.

Schlotzhauer, Philipp, Andriy Kovryga, Lukas Emmerich, Susanne Bollmus, Jan-Willem Van de Kuilen, and Holger Militz. "Analysis of Economic Feasibility of Ash and Maple Lamella Production for Glued Laminated Timber." Forests 10, no. 7 (July 2019): 529. https://doi.org/10.3390/f10070529.

Soto-Navarro, C., C. Ravilious, A. Arnell, X. de Lamo, M. Harfoot, S. L. L. Hill, O. R. Wearn, et al. "Mapping Co-Benefits for Carbon Storage and Biodiversity to Inform Conservation Policy and Action." Philosophical Transactions of the Royal Society B: Biological Sciences 375, no. 1794 (January 27, 2020): 20190128. https://doi.org/10.1098/rstb.2019.0128.

Thomas, R. Edward, and Urs Buehlmann. "Using Low-Grade Hardwoods for CLT Production: A Yield Analysis." In: Möttönen, V.; Heinonen, E., Eds. Proceedings of the 6th International Scientific Conference on Hardwood Processing; 2017 September 25-28; Lahti, Finland. Helsinki, Findland: Natural Resources Institute of Finland: 199-206., 2017, 199–206.

## 5.7 Bridging Text

Chapter 5 investigated the potential of the building-traits concept established in Chapter 4 and outlines how to apply this plant-trait based approach to assess the resilience of existing wood construction approaches. Chapter 5 further developed and explored the 'functional traits' of harvested wood products, the species richness, functional diversity and redundancy and how different wood construction approaches respond to various forest management strategies. The results demonstrated that functionally adaptive wood construction approaches – with high species richness, high functional diversity and redundancy – are the most resilient and adaptive to changes in forest management and climate and result in the highest wood utilization in all scenarios. Indicators of resource utilization (HRA, HRI, and FBI) point towards the increased wood building potential of the functionally adaptive wood construction and provided the case studies for Chapter 6.

Chapter 6 addresses the final goal of this dissertation – to investigate the carbon pooling potential of functionally adaptive wood construction. This study assesses the land-based carbon sink of three wood building approaches with increasing functional resilience and adaptability, established in the Chapter 5, and demonstrate the increased carbon pooling potential of a synchronized Forest-Building approach.

# 6 Enhancing forest carbon sinks through functionally adaptive wood construction

This manuscript is in preparation for submission.

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## 6.1 Abstract

Globally, efforts to increase the carbon pooling potential of buildings to decarbonize the built environment through the use of wood buildings are being perused. Yet, the resilience and adaptability of wood products to global change has a large impact on the land-based carbon pooling potential of harvested wood products and wood building. Carbon emissions/pooling assessment of wood construction approaches therefore need to include resiliency and adaptation to forests and climate change to evaluate possible future wood construction approaches. This study assesses the land-based carbon pooling potential of seven harvested wood products and three wood construction approaches and demonstrates the increased carbon pooling potential of a synchronized Forest-Building approach. The study results suggest that functionally adaptive wood construction approaches can better adapt to what the forests can give and stand to increase the land-based carbon sink of buildings by 105-295% for the study region. Additionally, the impacts become greater with increasing forest diversity and climate warming.
Keyword: Carbon sequestration, adaptive wood construction, climate change mitigation, forest resilience

# 6.2 Introduction

Forest land use, resilience and species composition significantly impact forest productivity, harvest and the potential Forest-Building carbon sink. The forestry, harvested wood products (HWP), and wood construction industries have the potential to mitigate or exacerbate the impacts of climate change on the forest carbon sink through the species selected for planting, harvest, and construction (Simard et al. 2020; Smyth et al. 2018; Oliver C.D. et al. 2014; Thompson 2009; Lecina-Diaz et al. 2018). Wood construction approaches capable of adapting to what species forests can provide may dramatically increase the land-based building carbon sink potential of forest landscapes.  This study presents an innovative dynamic species-level HWP carbon model, which assesses the potential of resilient and adaptable wood construction approaches to increase the Forest-Building carbon sink.

## 6.2.1 The state of Canada's forest carbon sink

The carbon sink in Canada's forests is vulnerable to deforestation, degradation, and disturbances triggered or intensified by climate change. A quick look at Canadian-managed forests shows they were approximately carbon neutral in the 1990s and became small sources in the 2000s and 2010s (Pan et al. 2024). Outbreaks of insects and wildfires in the 2000s caused a much-increased carbon source from living biomass (−55 Tg C yr−1) (W. Kurz et al. 2013). In the 2010s, living biomass, dead wood, and litter pools became carbon sources, and soil sinks were reduced by 35%, reflecting increased impacts of disturbances, warming, and droughts (W. Kurz et al. 2013). Canada's boreal forests have experienced significant impacts from climate change, including greater increases in temperature and variability than in the other regions (IPCC 2014). Climate change has disrupted the carbon dynamics in vegetation and soils and has exacerbated disturbances caused by wildfires, insect outbreaks and droughts. The high carbon stock and sink in boreal forest necromass (non-living organic matter in standing and lying dead wood, litter and soil) are impacted by increasing decomposition rates and wildfires resulting from dry conditions (Phillips et al. 2022). These impacts make Canadian forests a carbon source (W. Kurz et al. 2013). Future threats to forest carbon dynamics also include the northward shifting of bioclimatic zones, which will influence the growth potential of existing species. This movement of bioclimatic zones causes permafrost thawing, triggering forest fires such as those across Canada in 2020–22, increased risk of large-scale pest outbreaks, and increased rates of illegal logging, all of which release methane and $CO_2$.

Additionally, for Canada's highly managed temperate forests, climate change has caused increases in the frequency and intensity of natural disturbances, triggering intensified outbreaks of bark beetles after droughts across Canadian forests (C. Messier, Puettmann, and Coates 2013). All these factors impact growth, mortality and forest stocks. Therefore, future changes will affect the persistence and strength of Canada's forest carbon sink (Puhlick et al. 2020) and may dramatically change the future species composition.

### 6.2.2 The contribution of wood products to the sink

In addition to living and dead biomass, HWPs are included as part of Canada's forest carbon sink. The carbon contribution of HWPs is related to the amount of timber harvested and the portion that remains in use or solid waste-disposal sites. Globally, HWPs account for roughly 10% of the carbon in harvested timber. This small amount is because typically half of the wood harvested is used for fuel, and much of the rest is lost during processing into wood products, followed by losses when the products are discarded and decomposed (IPCC 2019). Compared with short-lived HWPs, such as pulp and paper, with a half-life of 2 years, the average half-life for sawn-wood products, such as those used in buildings, is 35 years (IPCC 2019). Currently, HWP contributes on average 6% of the global forest carbon sink, with 7%, 13% and 4% in boreal, temperate and tropical forests, respectively (Pan et al. 2024). This chapter focuses on ways to increase the wood building contribution to the global forest carbon sink through the Forest-Building approach.

It is crucial to understand how changes in climate and forest management, such as planting and harvesting a more diversified set of species to promote forest resilience to wildfire, pest and other disturbances, will affect the carbon dynamics of HWPs and buildings. Understanding the impact of forest management, HWP specification and future land-use choices in a heavily forested and heavily populated region, such as the Centre-du-Quebec, can help guide future policy and wood construction guidelines toward increasing the region's forest carbon sink. However, anticipating the future conditions of regional ecosystems where small private landowners dominate is challenging. Ninety-three percent (93%) of the Centre-du-Quebec's forests are privately owned, and many ecosystem services are dependent on tree communities (e.g., timber, maple syrup production, biodiversity, and recreation), each making land-use decisions based on their individual priorities. These choices significantly impact the carbon sink potential of Quebec's forests and wood buildings. Given that predicting the future of these socio-ecological systems is impossible, analyzing alternative forest management and construction scenarios offers another way to design future forests and building practices.

The subsequent analysis evaluates the consequences of climate change, forest management, and wood construction approaches on the building biogenic carbon sink of a coupled Forest-Building system. The scenarios studied represent a spectrum of resilient and adaptable forestry and wood construction approaches outlined in Osborne et al. (2023) and Chapter 5(BAU-FDN15; mass timber, light frame, mixed species). The forest management scenarios are highly divergent regarding the types, intensities, and spatial allocation of silvicultural prescriptions and thus represent a wide range of potential futures for the region's forests and the species they provide. The wood construction approaches utilize a range of products with increasing species adaptability and demonstrate the suitability of each wood product and construction approach for the region's harvested timber.

### 6.2.3 Assessing Biogenic Carbon in Harvested Wood Products and Buildings

A challenge within carbon accounting and LCA is the modelling of biogenic carbon (Levasseur et al. 2013; Breton et al. 2018; Hoxha et al. 2020). Biogenic carbon is emitted to the atmosphere ($CO_2$, CO or $CH_4$) through biomass transformation or degradation (e.g. combustion, digestion, composting, landfilling). Biogenic carbon can also be captured as $CO_2$ from the atmosphere through photosynthesis during biomass growth, a process commonly referred to as sequestration. Bio-based products, such as wood, hemp and straw, contain approximately 50% carbon by dry mass (Pittau et al. 2018), creating an opportunity to store carbon in HWP and buildings constructed with these materials (Churkina et al. 2020; Craig et al. 2020; Oliver C.D. et al. 2014). Forestry, wood products, and building researchers have been considering the biogenic carbon of HWPs throughout their life cycles for a few decades (Lucey et al. 2024). HWP models have been used to either estimate and evaluate the fate of biogenic carbon in different HWP classes, such as this study, or to estimate the carbon emissions from wood product use and end-of-life for LCA (Brunet-Navarro, Jochheim, and Muys 2016). In either case, HWP models typically track carbon, including co-products, consider time and can handle various end-of-life treatment options.

When calculating regional or national forest, HWP, and building pools, HWP models can be used alongside forest growth models to determine the aggregate carbon sink and evaluate the climate mitigation potential of forest management and regional suitability of HWPs and construction approaches. The carbon accounting team at the Canadian Forest Service (CFS) have developed various HWP carbon models using the Abstract Network Simulation Engine (ANSE, formerly known as the Carbon Budget Model Framework for Harvested Wood Products (CBM-FHWP) (N. R. Canada 2023). The most prominent models using ANSE are the National Forest Carbon Monitoring, Accounting, and Reporting System for Harvested Wood Products (NFCMARS-HWP) model and the Carbon Budget Model for Harvested Wood Products (CBM-HWP) model.  The NFCMARS-HWP is the central component of Canada's NFCMARS, and it complements the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) modelling framework used for international reporting of the forest carbon balance of Canada's managed forests (W. A. Kurz et al. 2009; Kull et al. 2019). Several additional ANSE-compatible HWP models have been developed by external parties, including MitigAna (Xie, Kurz, and McFarlane 2021; 2023; Xie et al. 2024) and the British Columbia Harvested Wood Products, version 1 model (BC-HWPv1) (Dymond 2012).  The MitigAna HWP carbon model is designed for users to undertake mitigation analyses for different HWP scenarios. MitigAna includes modules that can calculate substitution benefits and cascading uses.  The BC-HWPv1 is an HWP carbon model similar to the CBM-HWP model designed explicitly for the province of British Columbia and can be used to estimate wood carbon retention and emissions over time for the American and Canadian wood markets.

### 6.2.4 The uncertainty of regrowth

While at the landscape level, annual regrowth may balance harvest losses; in the case of a single stand, regrowth may require decades to centuries, if at all (Head et al. 2021). The assumption that trees will regrow after harvesting is an assumption made across most HWP and LCA approaches (see Section 2.5.2). However, there are several ways in which the carbon transferred from forests to wood buildings and other long-lived harvested products is not fully accounted for or replaced by equal carbon sequestration in forest biomass regrowth. Differences in climate, forest management, species growth rates, harvest rotation periods and other factors impact biomass regrowth and are not considered in traditional HWP models and LCAs. Head et al. (2019) addressed these issues by explicitly modelling carbon fluxes as a function of tree species, growing conditions and forest management practices. They used this to determine the ecosystem carbon costs of the harvest activity for 12 commercial species and noted that the mean time to ecosystem cost neutrality for each species ranged from 16 to 60 years.

However, LCA and HWP carbon model researchers have yet to consider how forest management approaches coupled with climate change will alter forest species composition, harvest output utilization, suitable wood construction approaches, and ultimately, the contributions of HWPs and wood buildings to forests' land-based carbon sink potential. These assumptions make planning for future forestry, HWP manufacturing and wood construction increasingly uncertain and may significantly change the HWP and wood construction industries. This chapter aims to model these changes in the carbon sinks as a function of tree species, climate change, forest management and construction approaches. More specifically, this study quantifies the impact of adopting more resilient and adaptive construction approaches in Quebec on the HWP portion of the carbon sink. This was achieved by calculating changes in HWP carbon pools over time for the study region covering a range of climate change and forest management scenarios and using construction approaches that promote underutilized tree species. Therefore, this final chapter focuses on creating a species-level Forest-Building Carbon Model to assess the contribution of functionally adaptive wood buildings to the combined Forest-Building carbon sink. As such, the outputs of this work can be subsequently used to assess the regional suitability of HWP and wood construction approaches and adapted in later studies for use in life-cycle inventories.

# 6.3 Methods

## 6.3.1 Wood construction approach model

The Forest-Building carbon model used in this study was developed using ANSE (N. R. Canada 2023). ANSE allows for the design, validation, simulation and analysis of various wood product systems that describe and quantify the temporally dynamic flow of carbon from harvested logs to wood products and buildings. The ANSE framework requires users to design all aspects of the model definition, including the definition of space (i.e. the origin of harvest and wood utilization throughout its lifecycle), the quantity and species of harvested wood, the carbon stocks, the physical state of carbon at various stages within the model (i.e. roundwood, bark, CLT, etc.), as well as the end-of-life of the carbon. The Canadian Forest Service (CFS) most extensively uses ANSE to calculate the contribution of harvested wood products to Canada's greenhouse gas emissions for the national inventory reports submitted to the United Nations Framework Convention on Climate Change (UNFCCC) each year. More recently, researchers have begun to use the CBM-FHWP/ANSE model to focus on individual wood products throughout their life cycles (Head et al. 2021). The specific perspective of this dissertation, focusing on adapting the wood construction industry to the changing species composition of our forests in response to changes in management and increasing global change, will be a new application of the modelling framework.

### 6.3.2 Model scope and system boundaries

Seven wood product models and three construction approaches corresponding to the primary wood products or wood construction approaches used for wood buildings in Canada were designed and simulated for this study. Upstream forest management and climate change scenarios were simulated using LANDIS-II and published in a previous study (Mina et al. 2022), and downstream processes from product manufacture to use in the building were simulated using ANSE. Each model tracks the carbon from living aboveground biomass harvested in the forest, the removal of leaves and branches to produce roundwood, the selection of suitable species for use in each product, the allocation of logs into construction products and relevant co-products, the use of the co-products (use in bioenergy, external manufacturing, or disposal in landfill), the long-term storage of wood carbon over the lifecycle of the building and product, and the end-of-life processing including recycling, incineration and landfilling (see Figure 38). Research has shown that storing and processing co-products at the end of their life can lead to substantial greenhouse gas emissions. While these emissions are considered part of the co-product life cycles for LCA emissions calculations and would be outside the boundary of the HWPs, the goal of this study is to understand the fate of all carbon harvested from forests and was therefore tracked for this study. Each model was simulated for 190 years for six different climate and management scenarios (2 climate x 3 management scenarios) for each product and construction approach. The model is exclusively focused on the biogenic carbon contained in roundwood log input for a given species, product and wood construction approach. Product lifecycle emissions, such as glues, preservatives, manufacturing and others, are already included in life cycle inventory databases and, therefore, are not considered in this study.

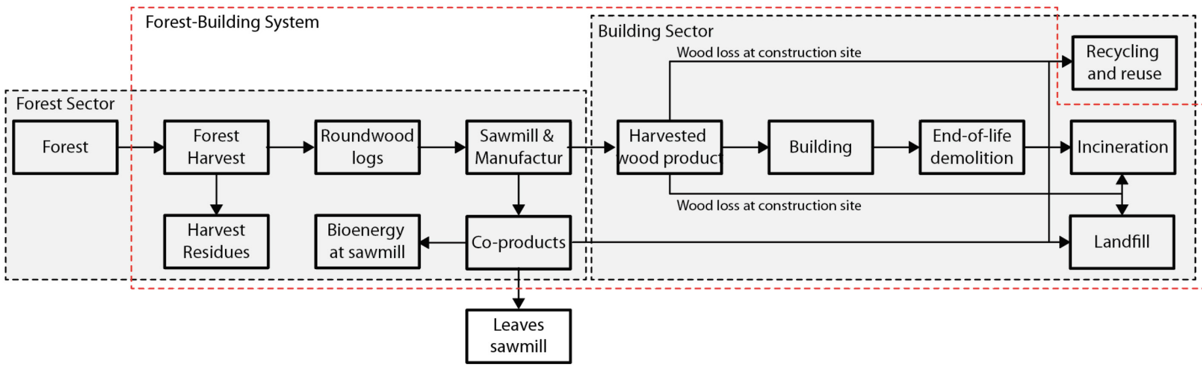


*Figure 38 - System boundaries for wood product carbon flows. The processes contained within the red dotted line describe the combined forest-building system and are tracked in the model. The forest ecosystem and upstream forest harvest activities are developed in a previous study (Mina et al. 2022). The implementation of the model treats the "Leaves sawmill" and "Recycling and reuse" processes as being outside the system scope but we have tracked the carbon pools throughout the study.. The figure only includes the biogenic carbon contained within the wood*

### 6.3.3 ANSE model description and parameter definition

This study focuses on modelling the downstream processes of the species-level HWP carbon model. The ANSE provides a set of generic modelling building blocks and rules used to define and arrange these various model components. A user can create a new model with the ANSE by defining lifecycle flow networks, parameters, names, spatial and temporal references, and inputs that satisfy the scope of their data and research needs. Pools and events are defined so carbon can move through each life-cycle stage, co-product and end-of-life stage in succession. The partitioning of species, products, construction approaches, co-products and end-of-life at each event is done as a mass balance.

Models were developed for the three construction approaches. Each of the models begins with harvested biomass per species from the LANDIS-II upstream forest management and harvest model(Osborne et al. 2023), but has different partitioning for leaves and branches and roundwood, product species partitioning, co-product outputs and fates at the manufacturing phase, construction approach product utilization, and fates of wood products following building demolition. The partitioning of harvested biomass into roundwood, leaves, and branches is summarized in Figure 31 and ranged between 50-80% for hardwoods and softwoods, respectively (Krackler et al. 2011). The mass balances of the wood products were obtained from Athena Sustainable Materials Institute product reports (ASMI 2012a-d; 2013a-c; 2018a-c) and have been used in previous studies (Head et al. 2021). The mass balances provided determine the proportion of all carbon pool flows in and out of an event (see Table 7; Figure 39).

*Table 7 - Co-product outputs for seven wood product types studied (% mass flows)*

| | **Lumber** | **CLT** | **Glulam** | **I-Joist** | **LVL** | **OSB** | **Plywood** |
|---|---|---|---|---|---|---|---|
| Main Product | 43.1% | 54.0% | 50.3% | 55.0% | 47.3% | 79.3% | 49.8% |
| Bark | 8.9% | 9.0% | 8.7% | 6.7% | 11.3% | | |
| Planar shavings | 6.3% | | 2.9% | 2.1% | | | |
| Sawdust | 5.6% | 4.4% | 4.8% | 1.9% | | | |
| Pulp chips | 34.5% | 32.5% | 32.5% | 21.1% | 28.7% | | 19.4% |
| Trim ends | 0.6% | | 0.3% | 0.2% | | | |
| Chipper fines | 0.2% | 0.2% | 0.2% | 0.1% | | | |
| Wood waste | 0.7% | | 0.3% | 0.3% | | 0.3% | |
| Off-spec | | | | 2.4% | 2.6% | | |
| Peeler cores | | | | 3.4% | 10.1% | 17.4% | 9% |
| Wood for hog fuel | | | | 5.8% | | 2.9% | 21.5% |
| By-products | | | | 1.0% | | | |
| Veneer | | | | | | | 0.3% |
| Total roundwood % | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |

CLT cross-laminated timber, glulam glue laminated timber, I-joist engineered wood joist, LVL laminated veneer lumber, OSB oriented strand board, off-spec off-specification, by-products unspecified co-products, Total (log) total roundwood log mass by Source: Athena Reports (ASMI 2012a-d; 2013a-c; 2018a-c)

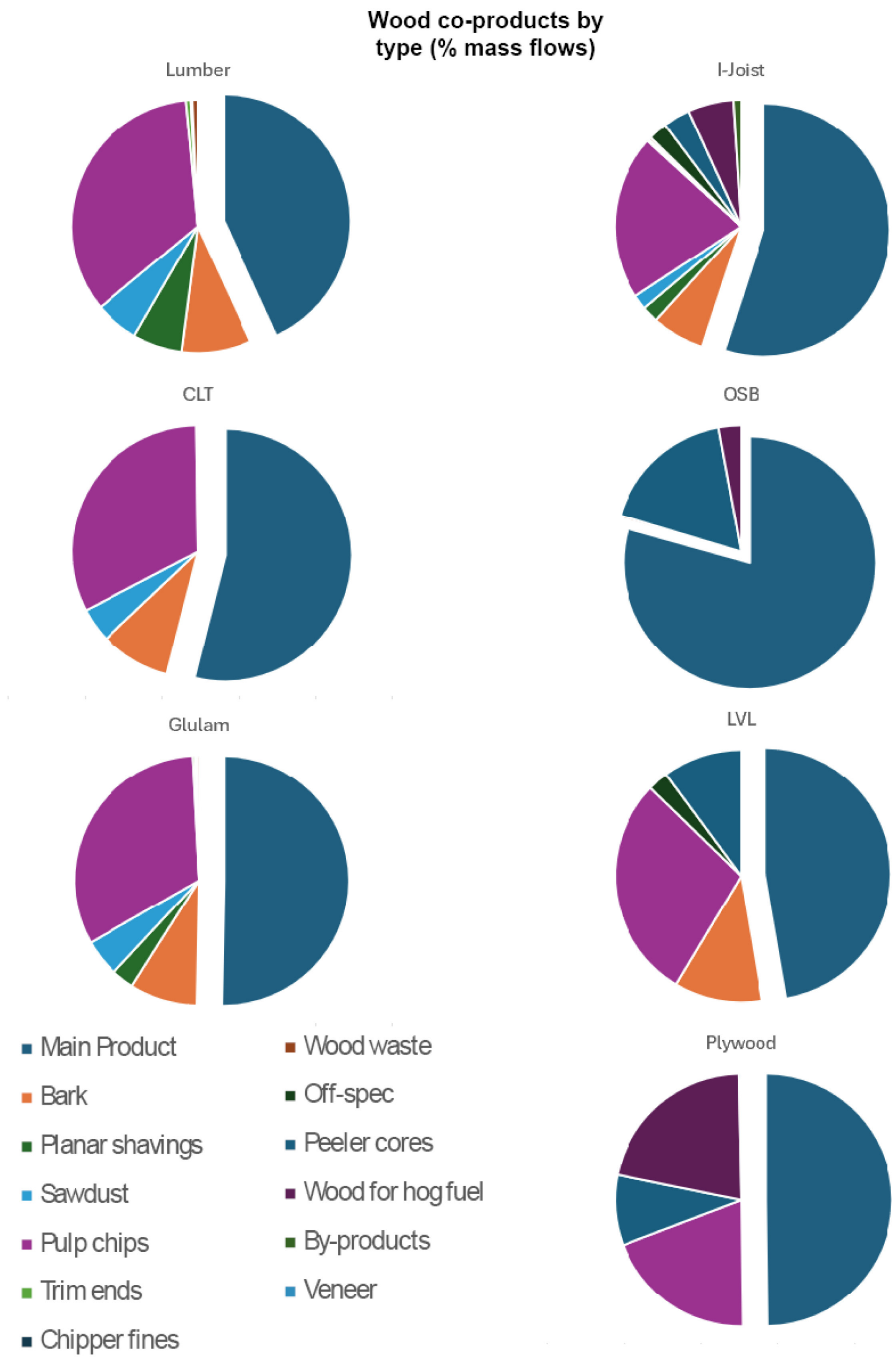


*Figure 39 - Co-product outputs for seven wood product types studied (% mass flows). Oriented Strand Board (OSB) stands out from the other wood products by having 79.3% of wood inputs directed towards the primary product In contrast, dimensional lumber has the lowest quantity of wood directed towards the main products. See Table 7 for detailed information. Source: Athena Reports (ASMI 2012a-d; 2013a-c; 2018a-c)*

Following the manufacturing phase, wood products flowed into three wood building types: light-frame wood construction, mass timber construction, and a mixed timber frame construction approach adaptive to changes in product availability. For details of each wood product and the selection of species suitable for use in building see Table 4. During construction, the lumber or wood products are divided into two pools; wood-in-building and waste. The amount of waste occurring during construction is taken from Wang et al. (2013) as a waste factor of 10% in North America, and the remaining carbon (90%) is assumed to remain in the building. The carbon stored in wood-in-buildings is modelled as 100% up until the building demolition, at this point, all carbon is moved to end-of-life fates.

Product manufacturing, construction site waste, and building demolition waste are all treated with the same three end-of-life treatments: landfilling, incineration and recycling. Regardless of policies and incentives to limit the landfilling of wood in Canada, only a small portion of construction waste is recycled. The proportion of wood waste from manufacturing, construction and demolition was based on an Environment Canada report on construction waste (Perry and VanderPol 2014). For Canada, the proportion of wood landfilled, incinerated, and recycled varies, with 10% going to recycling in our study region of Quebec.

### 6.3.4 Wood coproduct and system outputs

The variety of different co-products modelled as outputs at the manufacturing stage of this study include bark, shavings, sawdust, pulp chips, trim ends, chipper fines, peeler cores, and off-specification products. The proportions of each co-product that is going to end-of-life fate is provided in Table 12. The Athena Reports determined the end uses of all of these co-products in a Canadian context and have summarized them into three different fates:

Leaves system: This refers to co-products that are sold to other facilities to be used as raw materials. Since these co-products and their carbon content are used by third parties, the carbon in the co-product is allocated to other systems (separate from the main product system) and shares the burden of the upstream processes with the main product.

Landfilling: The landfill fate is modeled as a Quebec landfill. The specific treatment of landfills will be described along with other end-of-life options for the wood from building demolition. The carbon released from landfilling sawmill co-products is allocated to the main wood product.

Bioenergy: The co-products can also be used for bioenergy at the sawmills. The bioenergy transforms the carbon embedded in the co-product into $CO_2$ and $CH_4$ (negligible) emitted from the combustion of the material. Carbon emitted through the combustion of co-products for bioenergy at the sawmill is allocated to the other wood co-products.

### 6.3.5 Wood utilization scenarios

Three wood construction approaches previously described in Section 5.3.3 are also used for this study. The three wood construction approaches represent extremes in resilience: single species CLT or Mass Timber approach, an SPF and Hem-Tam based Light Frame approach representing the business as usual for the region, and the mixed species or Adaptive wood construction approach. Wood product flows were obtained for each building type by 3d modelling the structure of three typical wood construction approaches (Figure 32).

### 6.3.6 End-of-life and waste management

**Landfilling**

Approximately 4 million tonnes of annual construction, renovation, and demolition waste was generated in Canada (according to Statistics Canada estimate), and wood accounts for approximately 7% of all unrecovered waste sent to landfills in Canada (Perry and VanderPol 2014; Service Canada 2024). Within Canada, landfill conditions are predominately anaerobic due to their design, preventing both moisture and precipitation from entering the landfill and exposure to air. While anaerobic decomposition of organic materials will emit greenhouse gases, several studies demonstrate that wood degraded very slowly in landfill sites (Larson et al. 2012; Wang et al. 2013; J. Chen et al. 2008). Prior research estimates that only 0-3% of carbon contained in wood is emitted at landfill sites (Skog et al. 2015). Wang et al. (2013) found for the United States that the degradation of wood in landfill is dependent upon the type of wood product. They found that for a period of 1.5-2.5 years 5-23% of engineered wood degraded, while only 0-9% of carbon in lumber degraded. Furthermore, Ximenes et al. (2015) found that over 16-44 years of temperate species in landfills only experienced 0-8% carbon loss. Considering the low degradation found in the literature for the study region, and the high variability of wood degradation by wood species, products type, and local climate conditions, we chose to use the landfill models supported and previously applied by the ANSE and CBM-FHWP. The CBM-FHWP models the degradation of carbon in landfills using the first order decay, the same method used by the IPCC:

$$DDOCm = DDOCm0 \cdot e - kt$$

where t is time (years), DDOCm is the mass of the degradable organic carbon that will decompose under anaerobic conditions in a landfill at time t, $DDOCm_0$ is the mass of DDOC at time 0, k is the decay rate constant ($years^{-1}$).

Climate, landfill engineering, and waste composition influence the decay rate constant, k. The fate of degradable organic carbon in landfills can be categorized into three possibilities: capturing methane ($CH_4$) without flaring for energy generation (16.8%), capturing methane with flaring and direct emission of carbon dioxide ($CO_2$) (17.2%), and direct release of landfill gas into the atmosphere (66%). When landfill gas is used for energy production through capture without flaring, the proportion of carbon emitted as $CO_2$ and $CH_4$ is modelled as 99.995% and 0.005%, respectively. Carbon emissions from capture with flaring consist of 99.7% $CO_2$ and 0.3% $CH_4$, while direct release of landfill gas results in 10% $CO_2$ and 90% $CH_4$ emissions.

**Recycling**

Recycling rates for wood construction depend on multiple factors, including location, product type, construction approach and age. When recycled or solid and untreated wood, it will have higher market values than engineered and treated woods that contain adhesives, paints, and preservatives (Perry and VanderPol 2014). For this study, the carbon content of the wood from manufacturing, construction and demolition sent to recycling is tracked, however the subsequent fate is not considered within the scope of this study. This approach was chosen primarily due to the fact that the actual state of the recycled material will differ substantially and its use across a multitude of purposes would introduce substantial complicatedness into the model results. Second, the subsequent product life-cycles and ultimate fate would be unknown. Third, the co-product carbon would become part of another product system, of which the impact assessment belongs to that product life cycle. Finally, since the objective of this study was to provide species and temporally differentiated carbon tracking for wood products and construction approaches, the inclusion of effects of subsequent product life cycles goes beyond the scope of this work.

**Incineration & Firewood**

Incineration from sawmills and waste streams have been combined into a single category for this model. Incineration accounts for a tiny proportion of waste management in Canada (Perry and VanderPol 2014), with almost none occurring in Quebec. Many jurisdictions in Quebec and Canada do not accept construction and demolition waste for incineration. Therefore, following previous studies on wood emissions from incineration in Canada, we have assumed that 0% of construction and demolition waste will be incinerated (Head et al. 2021). While incineration produces both $CO_2$ and methane, to simplify the results, the carbon emitted through incineration is modelled in this work to be $CO_2$ (100%). The heat generated by incinerators can also be used for energy purposes. Some incinerators produce usable electricity or heat, and burning firewood generates heat, which can replace other residential heat sources like electric, oil, or natural gas heating systems. The effects of substituting bioenergy and heat produced from incineration and firewood can be calculated separately from the model and are beyond the scope of this study.

### 6.3.7 Forest management model

For this study, a limited selection of climate change and forest management scenarios were chosen from Osborne et al. (2023). Specifically, we chose scenarios with the greatest changes and variations in species composition to illustrate the impact this will have on most wood products and construction approaches (see Table 8). Two management strategies at the extremes of resilience and adaptability to climate change were considered: business-as-usual (BAU), and two variants of the functional diversification network approach (FDN15 and FDN25). Furthermore, two climate scenarios, Current and RCP 8.5 were used in this study.  This design allowed us to explore the land-based carbon sink of various wood construction approaches.

*Table 8 - Combination of climate, management scenarios and wood construction approaches analyzed. Scenarios are ordered by increasing level of change and climatic/disturbance stress. All three wood construction approaches were simulated for each climate and management scenario. See Supplemental Information for input parameterization and details of each scenario.*

| Climate | Management | Wood Approach |
|---|---|---|
| Present (Current) | BAU /FDN15/FDN25 | Light Frame/ Mass Timber/ Adaptive Approach |
| Hot (RCP 8.5) | BAU /FDN15/FDN25 | Light Frame/ Mass Timber/ Adaptive Approach |

## 6.4 Results & Discussion

Tracking carbon as it moves through different carbon pools over its life cycle from tree to building and, ultimately, end-of-life can be complex. This complexity is especially true when evaluating multiple differing climate, forest management and construction approaches. This work represents a first attempt at modelling the species-level building carbon sequestration potential of forests in response to changes in climate, forest management and construction approaches.

### 6.4.1 Roundwood Carbon, Functional Groups and Utilization

Understanding the impacts of climate change and forest management on the production of useable roundwood is a critical first step towards a more complete understanding of the building carbon sink potential of the Forests-Building approach. The resiliency of the wood construction industry to changes in forest composition is especially important for those stakeholders most directly impacted by these changes, including foresters, sawmill operators, landowners, manufacturers and wood builders. Figure 40 illustrates the changes in roundwood carbon over the six climate change and forest management scenarios used within this chapter over the study period. As discussed in Section 4.4.2, forest management across the study region was the primary contributor to changes in roundwood carbon stocks across all scenarios. Using the Forest-Building Carbon Model, both functionally adaptive forest management approaches (FDN15 & FDN25) showed increased net roundwood biogenic carbon production over current practices (BAU). Furthermore, despite the widely divergent forest management scenarios, increasing temperatures and precipitation caused by climate change increased net roundwood carbon produced for all scenarios over the first 100 years of the simulation. These increases were driven by changes in forest management and silviculture practices and climate, with climate warming (RCP 8.5) enhancing growth more in the FDN15 and FDN25 forest management scenario when compared against the baseline (BAU). Such climate warming-induced growth can be attributed to increased diversity in species planted and harvested under the more resilient and adaptable forest management approaches. For the Centre-Du-Quebec study region, these results should be seen as a warning sign of future changes needed in the wood industry. Maintaining a focus on a few commercial species will not only reduce the resilience of forests, but it will also reduce the transfers of biogenic carbon to HWP and wood buildings. On the other hand, the model results are also reassuring for all Forest-Building stakeholders as they demonstrate that resilient forest-management approaches and climate change will not decrease the quantity of wood useable in long-lived wood products so long as they adapt their practices to the changes in compositions of the forests.

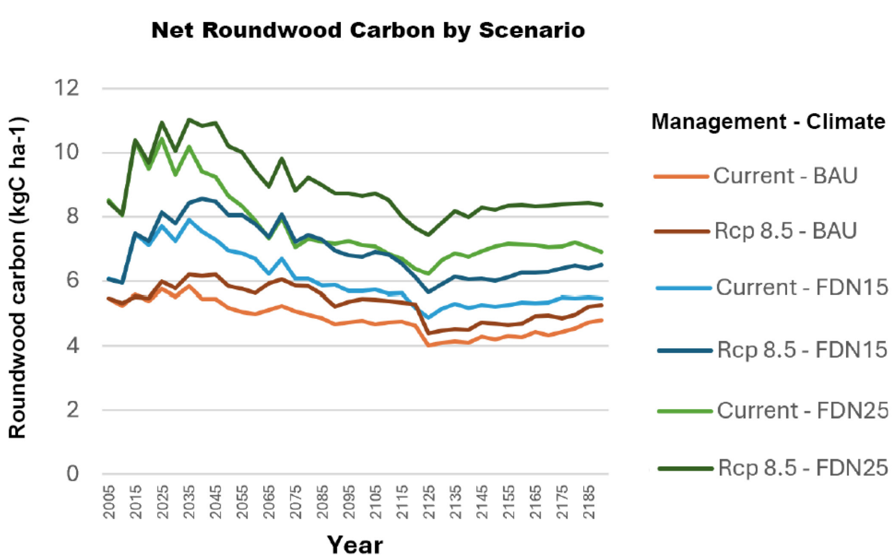


*Figure 40 – ANSE Forest Building Carbon Model results comparing net roundwood carbon(aboveground biomass less leaves and branches) fluxes per hectare (kg ha-1) under different climate change and forest management scenarios. More functionally adaptive approaches (FDN15 & FDN 25) with higher species diversity in planting and harvest increased net roundwood carbon and showed greater enhancement in response to increasing climate change (RCP 8.5).*

However, changes in roundwood carbon between the FDN and BAU scenarios also result in changes in forest composition. Assessing the impact of this change is where the novel aspect of the Forest-Building Carbon Model – the ability to track species, building and ecological group wood utilization – becomes most compelling. Using the Forest-Building approach, stakeholders can assess the contribution of each species, as well as ecological and building group contributions to their forest's building carbon sink potential. For the study region, the model results show that in both FDN15 and FDN25, roundwood carbon became increasingly diversified across more ecological and building groups compared to BAU throughout the simulation period (Figure 41 & Figure 42). The FDN scenarios show a significant increase in carbon fluxes for the first 50-100 years of the simulations due to harvesting abundant cold-adapted softwoods (Con-Bor) and early successional hardwoods (NHW-Es). This pulse of cold-adapted hard and softwoods was followed by an increase in warm-adapted softwood and mid-seral hardwoods (Con-Pin and NHW-Ms) reaching maturity during later successional stages of the forest regrowth. Such changes in ecological groups also result in similar changes in building groups throughout the simulation. For example, the results clearly show an association between the commercial softwood building groups (BG1 and BG2) with the two softwood ecological groups (CON-Bor & Con-Pin). Changes in Con-Bor and Con-Pin, result in similar changes in BG1 and BG2, respectively. In contrast, the changes in hardwood species ecological groups result in significant diversification of building groups later in the simulation. For example, changes in the northern hardwood groups from early to mid-seral species, from NHW-ES to NHW-Ms, throughout the simulation result in changes in all hardwood building groups (BG3-7).

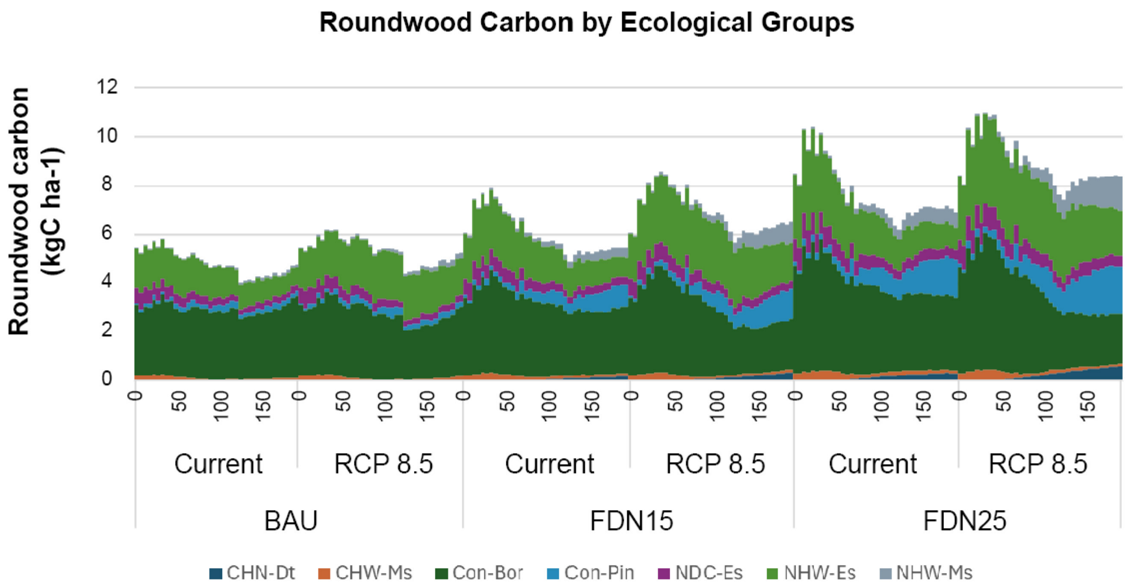


*Figure 41 – ANSE Forest Building Carbon Model results comparing net roundwood carbon fluxes per hectare(kg ha-1) by Ecological Group under different climate change and forest management scenarios. Early pulses found in the functionally adaptive approaches (FDN15 & FDN25) result from an increase in species harvest diversity with particular focus on abundant cold adapted species from the NHW-ES and Con-Bor ecological groups.*

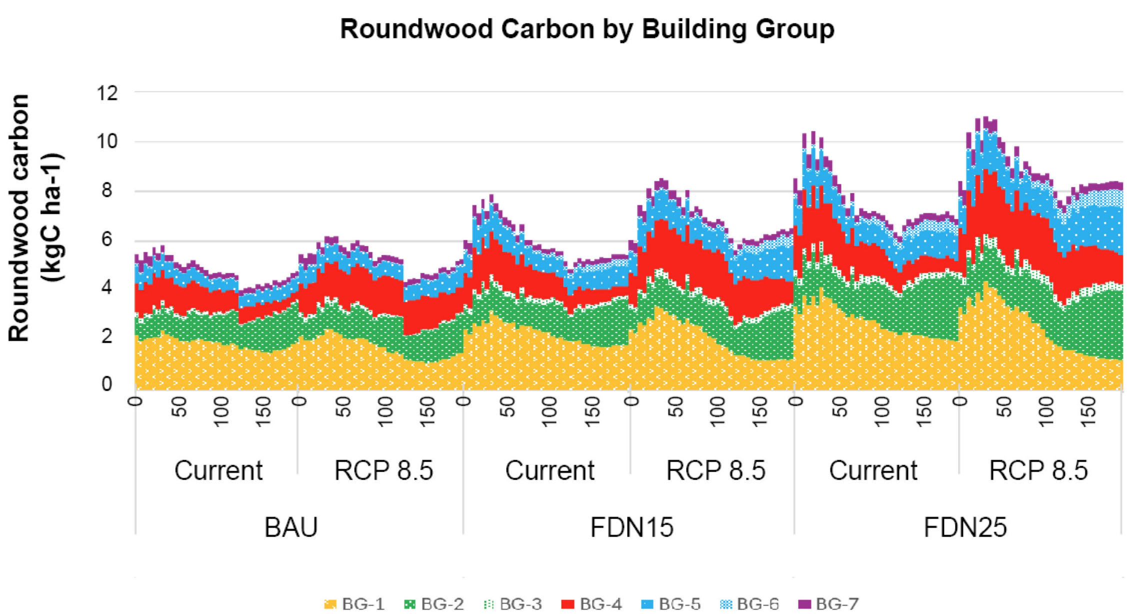


*Figure 42 - ANSE Forest Building Carbon Model results comparing net roundwood carbon fluxes per hectare (kg ha-1) by Building Group under different climate change and forest management scenarios. The functionally adaptive approaches (FDN15 & FDN 25) focus on replacing abundance cold-adapted species with more warm adapted species results in a large pulse of BG-1 and BG-4 for the first 100 years of the simulation followed by an increased roundwood from more warm adapted softwoods and hardwoods in BG-2 and BG-5.*

Finally, just as roundwood harvest potential increased with more functionally adaptive forest management approaches, so does the utilization potential of that roundwood increase with more functionally adaptive construction approaches. Figure 43 illustrates the different roundwood utilization percentages of mass timber, light frame, and adaptive wood construction approaches. For the light frame wood construction approach, 25-40% of the roundwood harvested was utilized depending on climate change and management scenarios. The impact of climate change reduced the roundwood utilization by roughly 8%, and more diversified forest management (FDN15 & FDN 25) further reduced the utilization by approximately 7%. In contrast, the adaptive wood construction approach stood out for its high and resilient roundwood utilization, ranging from roughly 82-85% across all scenarios. Finally, to no surprise, the single species mass timber approach had the lowest roundwood utilization in the study region, with less than 3% utilization across all climate and management scenarios.

This approach of tracking potential species, ecological and building group roundwood carbon and wood construction approach roundwood utilization allows for upstream (foresters and sawmill owners) as well as downstream (manufacturers and builders) stakeholders to assess their current practices' contribution to the building carbon sink as well as the resilience to possible changes in forest composition. The results show clearly the impact that both forest management and construction approaches can have on the land-based building carbon sink of forests and the significant contributions that a synchronized and functionally adaptive Forest-Building approach may have.

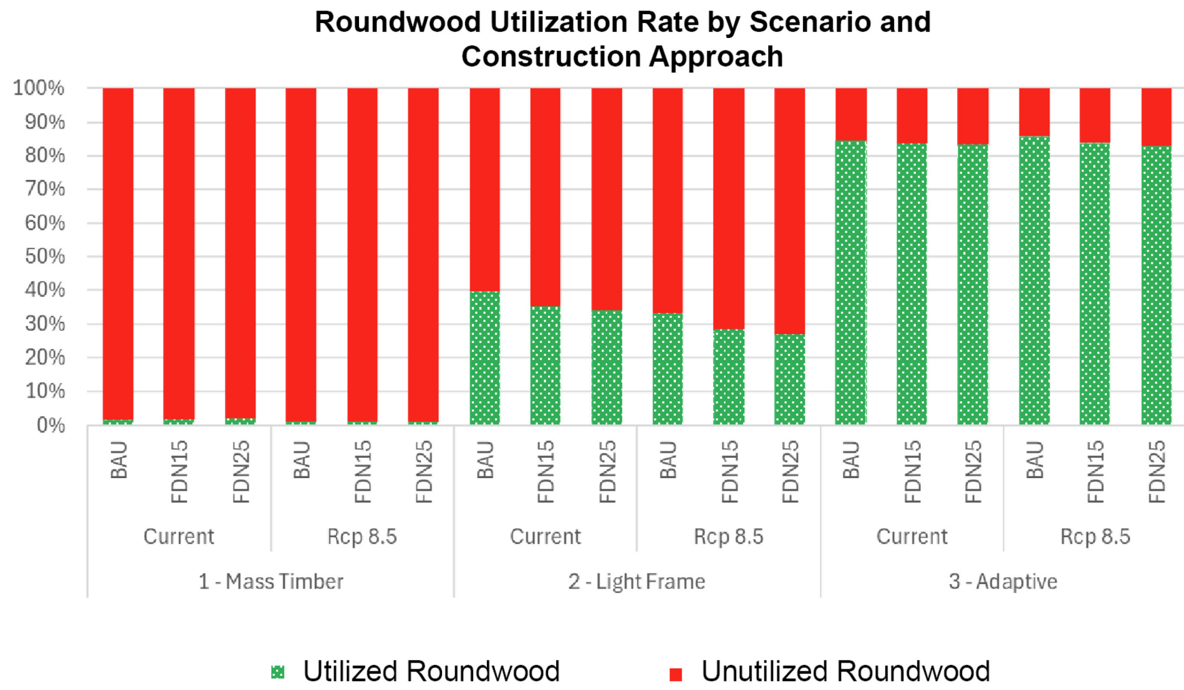


*Figure 43 – Comparing the percentage of roundwood utilization by construction approach. 1 – Mass timber showed < 3% wood utilization. 2 – Light frame approach with dimensional lumber and OSB utilized between 25-40%. 3 – The Adaptive approach utilized the most species and therefore had the highest utilization of 82-85% of roundwood. For more details on the construction approach and species, see Section 5.3.3.*

## 6.4.2 Species, Building and Ecological Group Utilization

By tracking the contributions of building and ecological groups to the wood-in-building carbon pool, stakeholders can assess their current practices' resilience to changes in forest species composition and also help them identify what species to use and when. For the scenarios simulated, each species' availability and utilization varied according to the complex interactions of climate, forest management approaches, and construction approaches. Figure 44 illustrates the total species, building and ecological group utilization of the construction approaches studied for the most extreme climate and forest management scenarios (BAU and FDN25) across the simulation period. Figure 45 describes the contribution each building and ecological group makes to the net building carbon sink (kg C/ha) at any given moment within the simulation period — or what designers and HWP manufacturers should be building with at any moment. Finally, Figure 46 describes the contribution of each building and ecological group toward the total land-based building carbon sink during the simulation.

The results show that following a functionally diverse and redundant construction approach is critical to maximizing the land-based building carbon sink potential of our forests. The mass timber approach underperforms in this regard by utilizing a single species across all scenarios. Without any redundant species to substitute or replace black spruce (BG2, Con-Bor), the mass timber approach is highly susceptible to management, climate change and other disturbances. Similarly, the light frame approach, a combination of both SPF lumber and OSB panels in its construction, had moderate functional redundancy and diversity across both BAU and FDN scenarios. With a total of five species spread across 3-4 ecological and building groups, the light frame approach could only utilize a single additional species — yellow-poplar from the BG5 and the NHW-Ms ecological group — when responding to the FDN25 forest management approach. Therefore, the light frame approaches reliance on a few building groups (BG1, BG2 & BG5) and ecological groups (Con-Bor, Con-Pin & NWH-Ms) present in the region limits the potential for significantly increasing wood utilization. In contrast, the adaptive approach stood out from the other two scenarios, increasing its species utilization by 10 new species when changing from current climate/BAU to the Rcp8.5/FDN25 scenarios. This change introduces species from six building groups and all seven ecological groups, dramatically increasing the combined forest-building system resilience to unexpected future changes. The flexibility of the adaptive approach to substitute multiple species within the same building and ecological groups, as well as adapting to HWPs which utilize different building and ecological groups throughout the simulation was key to its much higher building carbon sink potential.

The results demonstrate clearly that the carbon contained in wood buildings varies as a function of the wood construction approach's functional redundancy and adaptability to different species groups (Figure 34). Across all climate and forest management scenarios, wood construction approaches with high functional diversity and functional redundancy showed the greatest capacity to transfer carbon from forests to wood in building over the 190-year simulation (Figure 59). For example, the mass timber approach, which has low functional redundancy and diversity and utilizes a single species of wood, shows a constant decline. In contrast, the changes in harvest composition impacted the light frame and adaptive approaches less due to their ability to adapt to substitute the decline in white spruce (BG2/Con-Bor) with an increase in a balsam fir (BG1/Con-Bor). The adaptive approach, with the highest functional diversity and redundancy, stands out in terms of maintaining a relatively consistent carbon flux of wood in buildings across the entire simulation period due to a more ecologically diverse selection of tree species being useable within this approach.

Regarding the initial building and ecological groups utilized within the adaptive construction approach, the most carbon stored in in-use building pools comes from the BG1-Con-Bor, BG2-Con-Bor and BG4-NHW-Es groups (Figure 45Figure 45). Species from these groups are typically cold adapted. In contrast, later in the simulations, the building and ecological groups utilized within the adaptive approach are not as dominated by a single group, instead composed of a range of woods from all groups with BG2-Con-Pin(warm adapted softwoods) being the highest.

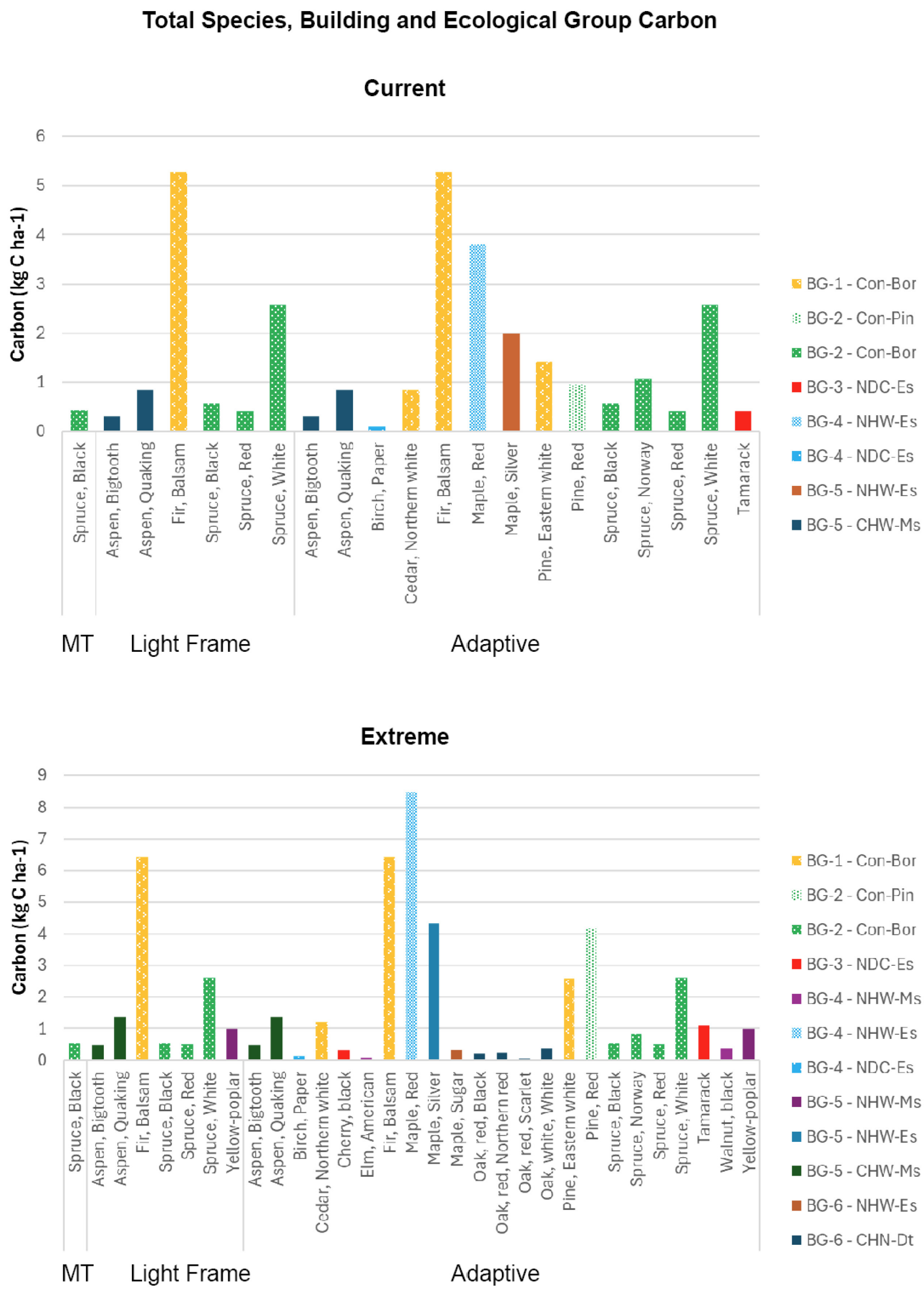


*Figure 44 – Total building and ecological group carbon pools per hectare (kg C ha-1) comparing construction approaches across the 190 year simulation. Top: BAU forest management and Current climate. Bottom: FDN25 forest management and RCP 8.5 climate change scenarios shown. The adaptability of the Adaptive approach is illustrated by the increased number of species and building-ecological group combinations present in the Extreme scenario.*

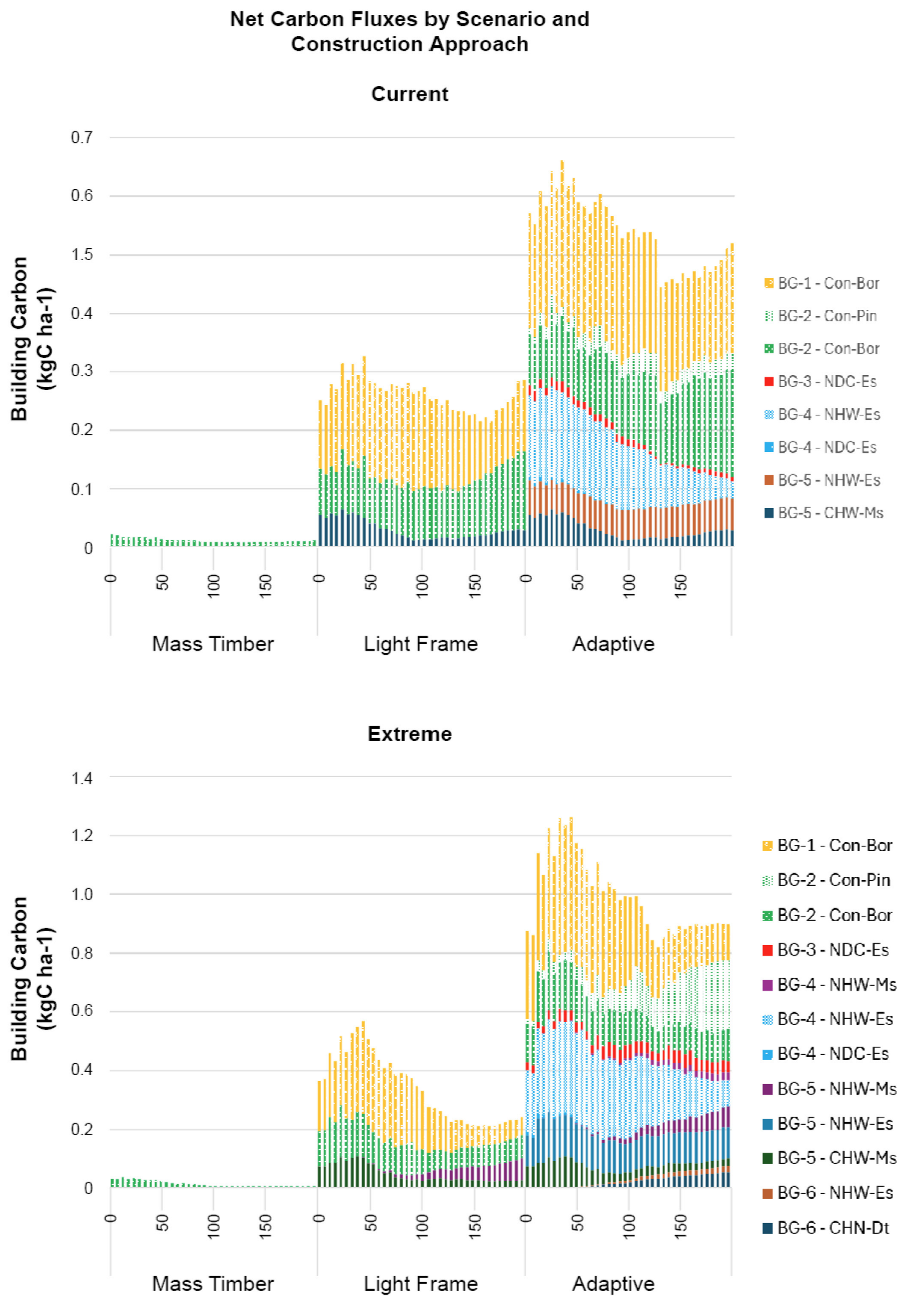


*Figure 45 – Net carbon fluxes per hectare (kg C/ha) of wood in building describing what building and ecological groups will be useable by each construction approach for the 190 year simulation period. Top: BAU forest management and Current climate. Bottom: FDN25 forest management and RCP 8.5 climate change scenarios shown. Note the different scale in the axis. The adaptive approach is least affected by the increasing ecological diversity, and resultant building group diversity in the Extreme scenario(bottom). In contrast, the light frame scenario declines by nearly half from it's peak around year 50.*

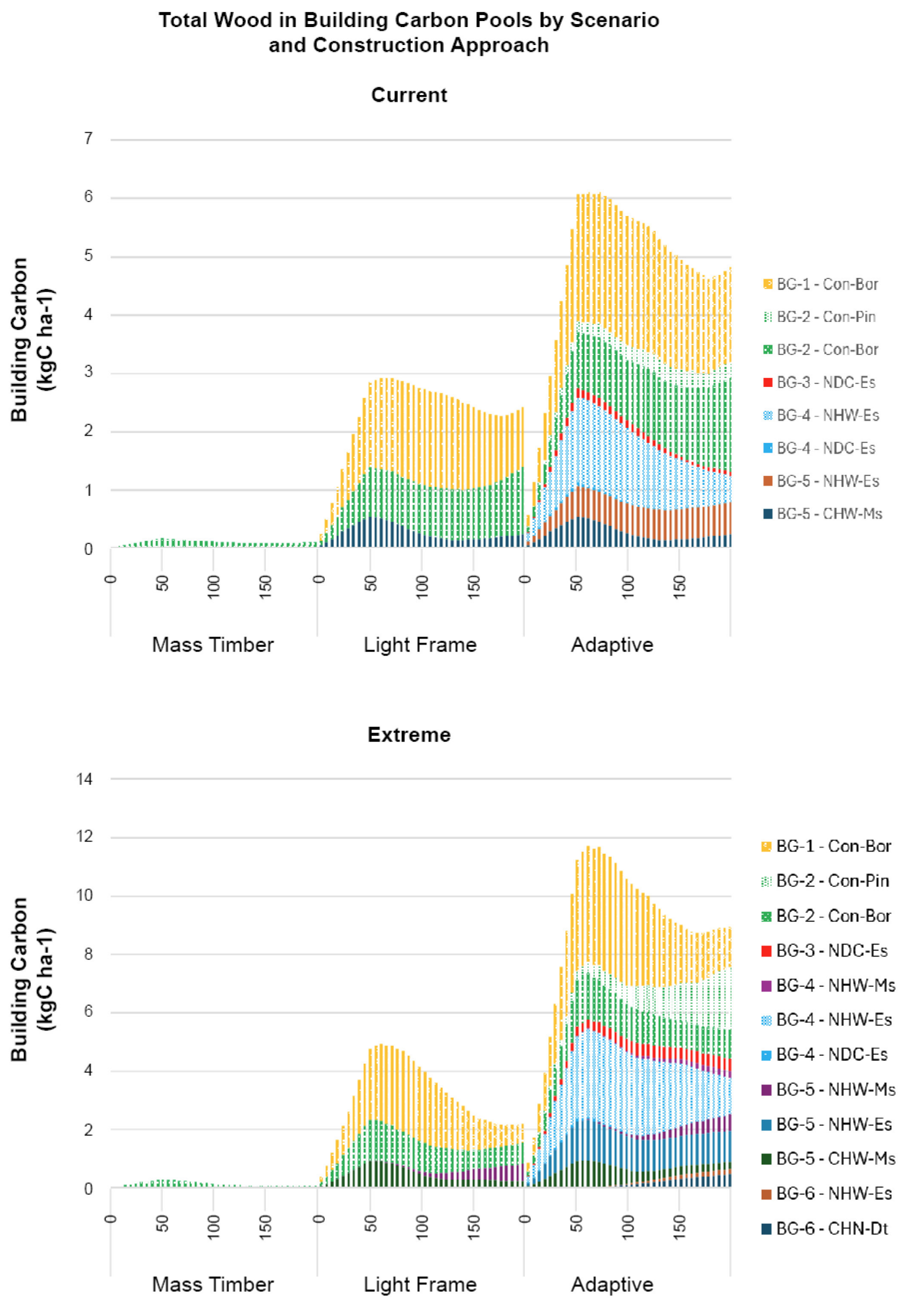


*Figure 46 – Total carbon pools of wood in building per hectare (kg C/ha) showing the building and ecological group composition of buildings constructed throughout the 190 year simulation period. Top: BAU forest management and Current climate. Bottom: FDN25 forest management and RCP 8.5 climate change scenarios shown. The results illustrate a two to four times greater building carbon pooling potential by adapting our current approaches to construction (e.g. Light Frame). Note the cumulative impact of the declining wood in building carbon pools around year 50 when the first demolitions occur in the model and harvest rates begin to decline (see Figure 45).*

### 6.4.3 Wood building, co-product and end-of-life carbon pools

This section demonstrates the Forest-Building Carbon Model outputs with the carbon stored in buildings, co-products and end-of-life landfill sites and emissions in each simulated scenario. The fate of carbon from the roundwood logs harvested is illustrated through all carbon pools over 190 simulation years of the three wood construction approaches (Figure 47). For each construction scenario, the wood species percentage utilization (Figure 43) and manufacturing processes impact the total carbon pools over time. For the mass timber and light frame approach, the inability to utilize substantial amounts of hardwoods diverts the majority of roundwood carbon toward the unutilized roundwood pool. In contrast, with its high species and wood utilization percentage, the adaptive approach transfers the majority of carbon towards manufacturing HWPs and to wood stored in buildings. Following the partitioning of utilizable roundwood, roughly 50% of the carbon is transferred to the wood in building carbon pool across all scenarios. Throughout the sawmilling and manufacturing process, approximately 35% is transferred to other uses through the sale of sawmill and manufacturing co-products, such as wood fiber insulation or the sawmill recycling process. The remaining carbon is transferred to landfills and either decomposes to produce $CO_2$ and $CH_4$emissions or remains in the landfill (modelled together as combined $CO_2$ emissions). Within the simulation, the increased wood species utilization of the Light Frame and Adaptive wood construction approaches means a greater cumulative carbon is stored in buildings. Therefore, more cumulative carbon is transferred from the wood product manufacturing process towards co-products, recycling, and other end-of-life pools.

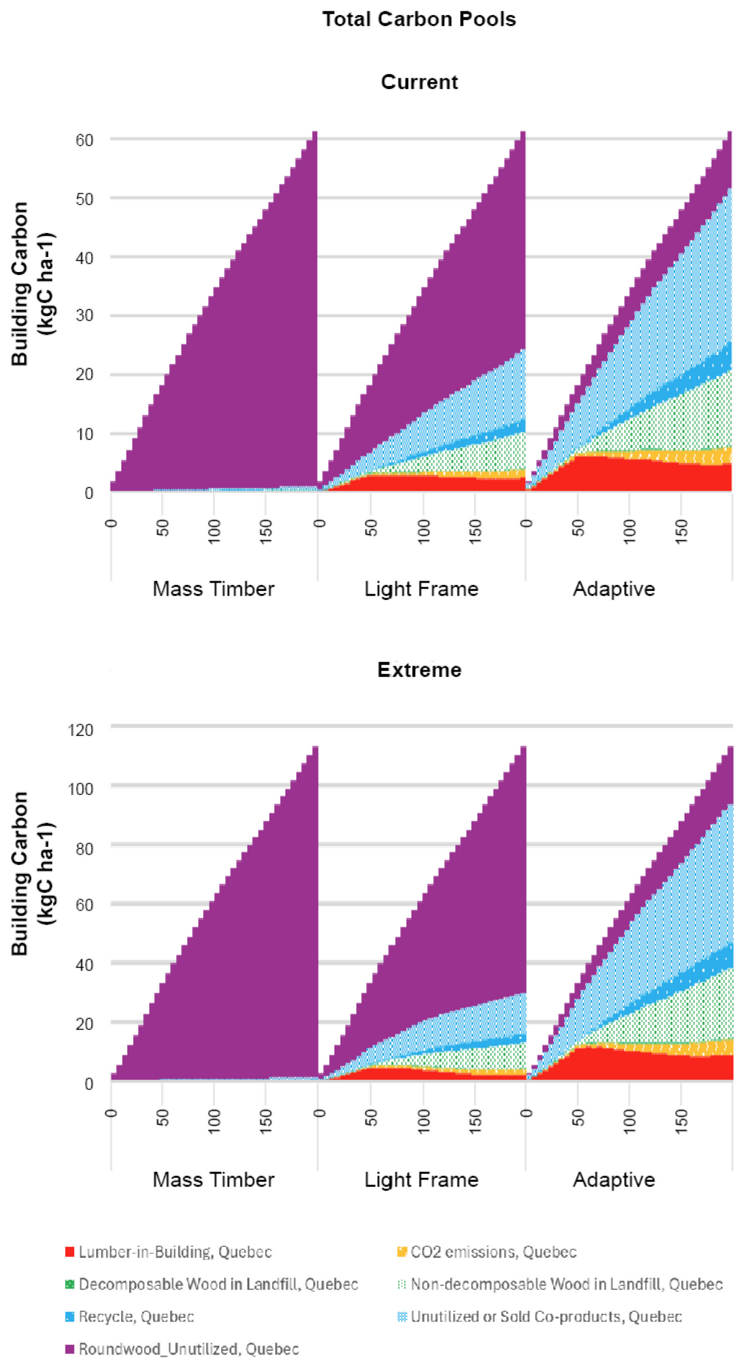


*Figure 47 – Estimates of total carbon pools per ha for all wood construction scenarios over 190-year simulations. Top: Current and business as usual forest management (BAU). Bottom: Hot climate(Rcp 8.5) and functional trait-based forest management (FND25).For all scenarios, the lumber in building increases up to year 55 when the first building demolitions occur and carbon is transferred to the end-of-life pools. After this point, the lumber in building pool stabilizes relative to harvest species composition. Note that the lumber-in-building carbon pool is relatively small proportion of the total carbon pool potential of harvested wood products. Co-products, end-of-life and recycled wood products will play a major roll in maximizing the future carbon pooling potential of wood harvested from forests. Note the difference in the vertical axis.*

#### 6.4.3.1 Wood-in-building pool

For the Adaptive wood construction scenario, an additional 4.6-8.7kg C per ha was stored as wood-in building at the end of the 190-year simulation, depending on the climate and management scenarios. This represents an increase in building carbon stocks by 12-16% compared to the current climate while increasing forest resilience by applying the FDN approach, which resulted in an increase in building carbon stocks by 59-65% compared to the starting BAU scenario.

For the light frame wood construction scenario, an additional 2.2kg C per ha was stored as a wood-in building in 2200 compared to 2000, depending on the climate and management scenarios. For the light frame wood scenario, the impacts of climate change resulted in a decrease in building carbon stocks by 7-8% compared to the current climate. Furthermore, increasing forest resilience by applying the FDN approach increased building carbon stocks by 4% compared to the starting BAU scenario.

Finally, for the Mass Timber wood construction scenario, there was an additional 0.03-0.1kg C per ha stored as wood-in building in 2200 as compared to 2000, depending on the climate and management scenarios. For the Mass Timber wood scenario, the impacts of climate changed resulted in a decrease in building carbon stocks by 3% as compared to the current climate. Furthermore, increasing forest resilience by applying the FDN approach resulted in an increase in building carbon stocks by 7-8% compared to the starting BAU scenario.

#### 6.4.3.2 Co-products and end-of-life pools

The wood construction approach, including species used and HWP manufactured also affects the co-products and end-of life-pools (Figure 48 & Figure 49). The ratio of lumber in building to co-products/waste remained unchanged across climate and management scenarios but differed between wood construction approaches. This is a function of two factors: the percentage of roundwood transferred to main and co-products and the percentage of manufacturing and construction waste recycled, landfilled or incinerated for bioenergy during the manufacturing, construction and demolition process (see Figure 39; Table 7, Table 11, Table 12). Pulp chips were the most significant co-product across all construction approaches, while only the light frame and adaptive approaches had significant carbon transferred to waste for incineration. This is primarily due to the inclusion of panelized HWPs such as plywood and OSB. This is due to the relative $CO_2$ emissions occurring from bioenergy production during the manufacturing process for plywood, and OSB are considerably higher than those of lumber and CLT. In contrast, the proportion of landfilled co-products for lumber and CLT is greater than that of plywood and OSB.

The building lifespan determines the delay of carbon transferred from the wood in the building to landfill and $CO_2$ emissions. For all scenarios, the rate of landfill carbon increases at year 55 of the simulation when the first building demolition occurs (Figure 49). As such, the choice of the time horizon is critical to determining the lifecycle carbon sinks for each scenario. Note that while the percentage transferred to co-product, recycling, and end-of-life pools may be similar between wood construction approaches, the significant differences in harvested wood utilization across climate and management scenarios ensure that the total transfers to these pools remain significantly higher for the light frame (~14kg C/ha) and adaptive approach (~47kg C/ha) when compared to the mass timber (>1kg C/ha).

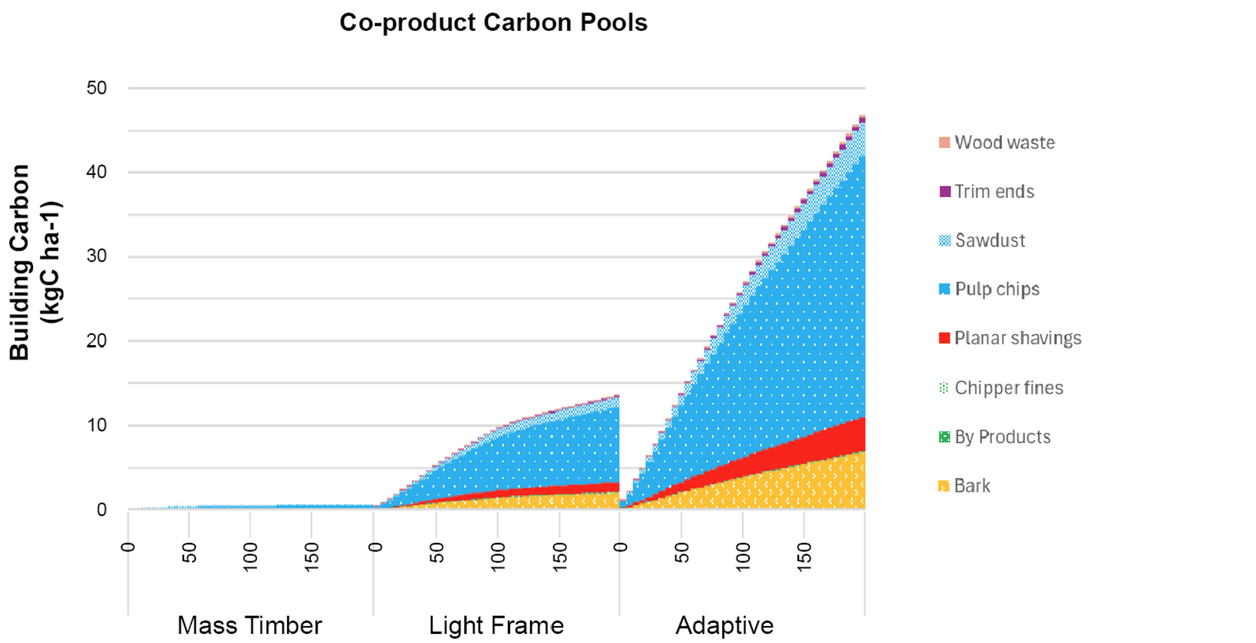


*Figure 48 – Comparing co-product carbon pools per hectare (kgC ha-1) for wood construction approaches. The higher wood utilization of the Light Frame and Adaptive approach increases the quantities of co-product pools. The highest co-products for both Light Frame and Adaptive wood construction approaches are pulp chips, bark, planar shavings, and sawdust. Finding long-lived wood products for these co-products is essential to maximizing the land-based carbon pooling potential of the Forest-Building approach*

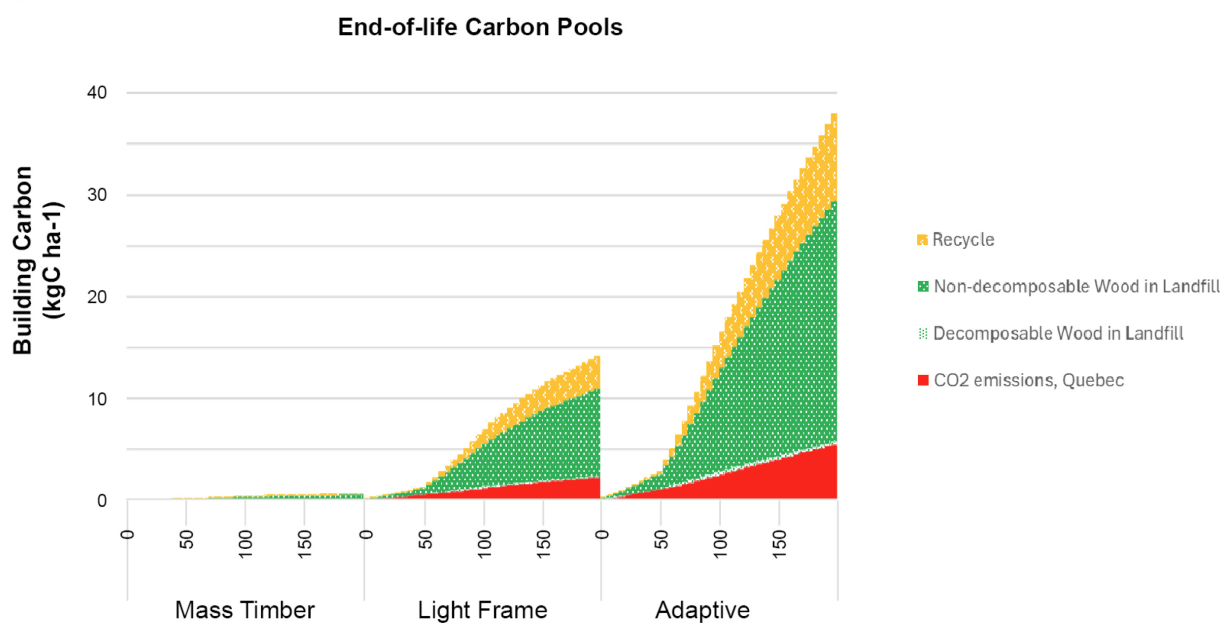


*Figure 49 - Comparing end-of-life carbon pools per hectare (kgC ha-1) for wood construction approaches. For all scenarios, the lumber in building increases up to year 55 when the first building demolitions occur and carbon is transferred to the end-of-life pools. The large amount of wood in landfill demonstrates a great need to focus future manufacturing and design efforts on end-of-life, adaptive reuse, and retrofitting existing construction. For every timber product reused, this reduces the demand on the forests.*

### 6.4.4 Construction resilience and the land-based carbon sink potential of building

The results of this study suggest that the wood construction approach's resilience (functional diversity and redundancy) was found to influence the species utilization and overall contribution that buildings may make to the forest-building carbon pool. In assessing the carbon sink potential of wood construction approaches that utilized both commercially important and low-value and underutilized species, the results suggest that adaptive building design may be able to significantly alter the carbon dynamics of forest-building systems and maximize the building carbon sink potential of forests.

For the temperate forest landscape of our study region, having a synchronized forest management and construction objective to increase forest resilience was effective in creating combined Forest-Building resilience, as indicated by greater species diversity, harvest output and building carbon sink. **For the study region, the results suggest that changing from the Light Frame to Adaptive construction approach stands to increase the building carbon sink by 105% (+2.3kg C/ha) under current climate and BAU forest management and by 295% (+6.5kg C/ha) with increase climate warming (Rcp 8.5) and FDN25 forest management approach.** The study results suggest that functionally adaptive wood construction approaches can better adapt to what the forests can give. Additionally, the impacts become greater with increasing forest diversity and climate warming over the length of the simulation.

Yet, alongside increasing wood construction resilience and species utilization comes an increase in co-product, recycling, landfill and $CO_2$ emissions. The fate of the co-product and recycling and end-of-life carbon pools may significantly impact the land-based carbon sink (Xie, Kurz, and McFarlane 2023). If the co-products are manufactured into long-lived HWPs used in building, such as wood fibre insulation, their carbon will further contribute to the land-based building carbon sink. Conversely, should the co-products be used for bioenergy or short-lived wood products, such as paper, substantial amounts of carbon will be emitted as $CO_2$ to the atmosphere through incineration or decomposition in landfills. Furthermore, the large amount of wood in landfill demonstrates a great need to focus future manufacturing and design efforts on end-of-life, adaptive reuse, and retrofitting exiting construction. For every timber product reused will extend the residency time as well as reduce the demand for timber on the forests. Additionally, while forest residues from harvest are typically left on-site in Canada (Thiffault et al. 2015), these could also be collected and thus would be considered a co-product of wood harvesting. The utilization of forest residues for bioenergy, for example, could influence how the carbon impacts are allocated and thus the building carbon sink results.

## 6.5 Conclusion

This chapter presented an innovative Forest-Building Carbon Model that can track species, buildings, and ecological group utilization, from harvested logs to their use in buildings and ultimate end-of-life. This species-level HWP carbon model can be used to assess the resilience of wood construction approaches to changes in forest composition and the impact each species, building and ecological group will have on the land-based building carbon sink. This model complements existing HWP carbon models such as MitigAna (Xie, Kurz, and McFarlane 2021; 2023; Xie et al. 2024) and the British Columbia Harvested Wood Products (Dymond 2012). When extended across additional bioclimatic zones in Canada, this model can provide a clear picture of the impacts of different wood construction approaches on Canada’s building carbon sink potential.

This study utilized the Forest-Building Carbon Model to explore the potential for resilient wood construction approaches to increase buildings' land-based carbon sink potential in response to a changing climate and forest management. The results reveal that resilience-oriented construction approaches may maximize forested landscapes' near- and long-term building carbon sink potential. Therefore, rather than assuming that forest-based climate change adaptation strategies will reduce the ongoing provisioning of wood, forest managers, HWP manufacturers and wood builders should consider synchronized strategies prioritizing ecological resilience as a management objective. Forestry and construction approaches that use what forests can give, distributing HWPs and wood building demands across more tree species, will likely result in a more resilient supply of wood for building and a increased building carbon sink potential.

### 6.5.1 Study Limitations

The forest management approaches chosen for this study determined whether the Centre-du-Quebec’s forests remained resilient and adaptable to various climate change and other disturbance scenarios over the 200-year simulation. Yet, forest management and climate changes determined what species the forest can give (Figure 44). Choosing alternative management approaches, such as CCA, as described earlier in this dissertation, would influence the wood utilization of the construction approaches studied and, thus, the land-based building carbon sink.

A further limitation of this study is the inability to determine the age, size and quality of wood harvested. When designing this study's adaptive wood construction approach scenario, it was envisioned that changes to harvesting practices and wood product utilization would diverge quite a bit from those of the mass timber and light frame approaches. For example, while the three approaches may share similar HWPs, each species' utilization differed substantially (Figure 44).

These differences introduced many low and underutilized species not traditionally commercially harvested or used within contemporary construction. The influence these changes may have on the carbon emissions of silvicultural and HWP manufacturing was beyond the scope of this dissertation and requires further study to determine the suitability of individual species for use in HWP and buildings.

# 6.6 References


ASMI. “A Cradle-to-Gate LCA of Canadian Glulam Manufacture–an Update.” Ottawa, Canada: Athena Sustainable Materials Institute, 2012.

———. “A Cradle-to-Gate LCA of Canadian Laminated Veneer Lumber (LVL) MANUFACTURE.” Ottawa, Canada: Athena Sustainable Materials Institute, 2013.

———. “A Cradle-to-Gate LCA of Canadian Oriented Strand Board - An Update.” Ottawa, Canada: Athena Sustainable Materials Institute, 2012.

———. “A Cradle-to-Gate LCA of Canadian Softwood Plywood Sheathing.” Ottawa, Canada: Athena Sustainable Materials Institute, 2012.

———. “A Cradle-to-Gate LCA of Canadian Surfaced Dry Softwood Lumber.” Ottawa, Canada: Athena Sustainable Materials Institute, 2012.

———. “A Cradle-to-Gate LCA of Canadian Wood i-Joist Manufacture.” Ottawa, Canada: Athena Sustainable Materials Institute, 2013.

———. “A Cradle-to-Gate Life Cycle Assessment of Canadian Glulam.” Ottawa, Canada: Athena Sustainable Materials Institute, 2018.

———. “A Cradle-to-Gate Life Cycle Assessment of Canadian Plywood.” Ottawa, Canada: Athena Sustainable Materials Institute, 2018.

———. “A Cradle-to-Gate Life Cycle Assessment of Eastern Canadian Surfaced Dry Softwood Lumber.” Ottawa, Canada: Athena Sustainable Materials Institute, 2018.

———. “A LCA of Cross-Laminated Timber Produced in Canada.” Ottawa, Canada: Athena Sustainable Materials Institute, 2013.

Breton, Charles, Pierre Blanchet, Ben Amor, Robert Beauregard, and Wen-Shao Chang. “Assessing the Climate Change Impacts of Biogenic Carbon in Buildings: A Critical Review of Two Main Dynamic Approaches.” Sustainability 10, no. 6 (June 14, 2018): 2020. https://doi.org/10.3390/su10062020.

Brunet-Navarro, Pau, Hubert Jochheim, and Bart Muys. “Modelling Carbon Stocks and Fluxes in the Wood Product Sector: A Comparative Review.” Global Change Biology 22, no. 7 (2016): 2555–69. https://doi.org/10.1111/gcb.13235.

Canada, Natural Resources. “Abstract Network Simulation Engine (ANSE).” Natural Resources Canada, January 27, 2023. https://natural-resources.canada.ca/climate-change/climate-change-impacts-forests/carbon-accounting/forest-carbon-accounting-tools/abstract-network-simulation-engine-anse/24901.

Chen, Jiaxin, Stephen J. Colombo, Michael T. Ter-Mikaelian, and Linda S. Heath. "Future Carbon Storage in Harvested Wood Products from Ontario's Crown Forests." Canadian Journal of Forest Research 38, no. 7 (July 2008): 1947–58. https://doi.org/10.1139/X08-046.

Churkina, Galina, Alan Organschi, Christopher P. O. Reyer, Andrew Ruff, Kira Vinke, Zhu Liu, Barbara K. Reck, T. E. Graedel, and Hans Joachim Schellnhuber. "Buildings as a Global Carbon Sink." Nature Sustainability 3, no. 4 (April 2020): 269–76. https://doi.org/10.1038/s41893-019-0462-4.

Craig, Salmaan, Anna Halepaska, Jacob Elbrecht, Katherine Ferguson, Preston Rains, Andrew Freear, David Kennedy, and Kiel Moe. "Buildings as a Global Carbon Sink? The Design of Mass Timber Panels as Heat-Exchangers (Dynamic Insulation)," August 12, 2020. https://doi.org/10.20944/preprints202008.0278.v1.

Dymond, Caren C. "Forest Carbon in North America: Annual Storage and Emissions from British Columbia's Harvest, 1965–2065." Carbon Balance and Management 7, no. 1 (July 24, 2012): 8. https://doi.org/10.1186/1750-0680-7-8.

Head, Marieke, Pierre Bernier, Annie Levasseur, Robert Beauregard, and Manuele Margni. "Forestry Carbon Budget Models to Improve Biogenic Carbon Accounting in Life Cycle Assessment." Journal of Cleaner Production 213 (March 2019): 289–99. https://doi.org/10.1016/j.jclepro.2018.12.122.

Head, Marieke, Michael Magnan, Werner A. Kurz, Annie Levasseur, Robert Beauregard, and Manuele Margni. "Temporally-Differentiated Biogenic Carbon Accounting of Wood Building Product Life Cycles." SN Applied Sciences 3, no. 1 (January 2021): 62. https://doi.org/10.1007/s42452-020-03979-2.

Hoxha, Endrit, Alexander Passer, Marcella Ruschi Mendes Saade, Damien Trigaux, Amie Shuttleworth, Francesco Pittau, Karen Allacker, and Guillaume Habert. "Biogenic Carbon in Buildings: A Critical Overview of LCA Methods." Buildings and Cities 1, no. 1 (August 12, 2020): 504–24. https://doi.org/10.5334/bc.46.

IPCC. "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories — IPCC," 2019. https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/.

———. Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part B: Regional Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report: Volume 2: Regional Aspects. Vol. 2. Cambridge: Cambridge University Press, 2014. https://doi.org/10.1017/CBO9781107415386.

Krackler, Verena, Daniel Keunecke, Peter Niemz, and Andreas Hurst. "POSSIBLE FIELDS OF HARDWOOD APPLICATION." WOOD RESEARCH 56 (2011).

Kull, S. J., G. J. Rampley, S. Morken, J. M. Metsaranta, E. T. Neilson, and W. A. Kurz. Operational-Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Version 1.2: User's Guide. 2019., 2019. http://cfs.nrcan.gc.ca/publications?id=39768.

Kurz, W. A., C. C. Dymond, T. M. White, G. Stinson, C. H. Shaw, G. J. Rampley, C. Smyth, et al. "CBM-CFS3: A Model of Carbon-Dynamics in Forestry and Land-Use Change Implementing IPCC Standards." Ecological Modelling 220, no. 4 (February 24, 2009): 480–504. https://doi.org/10.1016/j.ecolmodel.2008.10.018.

Kurz, Werner, Cindy Shaw, Céline Boisvenue, Graham Stinson, J. Metsaranta, Don Leckie, Andrew Dyk, Carolyn Smyth, and Eric Neilson. "Carbon in Canada's Boreal Forest — A Synthesis W.A. Kurz, C.H. Shaw, C. Boisvenue, G. Stinson, J. Metsaranta, D. Leckie, A.

Dyk, C. Smyth, E.T. Neilson Environmental Reviews, 2013, 21:260-292, 10.1139/Er-2013-0041." Environmental Reviews 21 (January 1, 2013): 260–92.

Larson, Christopher, Jeffrey Chatellier, Reid Lifset, and Thomas Graedel. "Role of Forest Products in the Global Carbon Cycle: From the Forest to Final Disposal." In Managing Forest Carbon in a Changing Climate, edited by Mark S. Ashton, Mary L. Tyrrell, Deborah Spalding, and Bradford Gentry, 257–82. Dordrecht: Springer Netherlands, 2012. https://doi.org/10.1007/978-94-007-2232-3_12.

Lecina-Diaz, Judit, Albert Alvarez, Adrián Regos, Pierre Drapeau, Alain Paquette, Christian Messier, and Javier Retana. "The Positive Carbon Stocks-Biodiversity Relationship in Forests: Co-Occurrence and Drivers across Five Subclimates." Ecological Applications: A Publication of the Ecological Society of America 28, no. 6 (September 2018): 1481–93. https://doi.org/10.1002/eap.1749.

Levasseur, Annie, Pascal Lesage, Manuele Margni, and Réjean Samson. "Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment." Journal of Industrial Ecology 17, no. 1 (2013): 117–28. https://doi.org/10.1111/j.1530-9290.2012.00503.x.

Lucey, Taylor K., Nadia Tase, Prakash Nepal, Richard D. Bergman, David L. Nicholls, Poonam Khatri, Kamalakanta Sahoo, and Andrew N. Gray. "A Synthesis of Harvested Wood Product Carbon Models." Gen. Tech. Rep. PNW-GTR-1020. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 73 p. 1020 (2024). https://doi.org/10.2737/PNW-GTR-1020.

Messier, C., K. J. Puettmann, and K. D. Coates. Managing Forests as Complex Adaptive Systems: Building Resilience to the Challenge of Global Change. New York: Routledge, 2013.

Mina, Marco, Christian Messier, Matthew J. Duveneck, Marie-Josée Fortin, and Núria Aquilué. "Managing for the Unexpected: Building Resilient Forest Landscapes to Cope with Global Change." Global Change Biology n/a, no. n/a (March 2022). https://doi.org/10.1111/gcb.16197.

Oliver C.D., Nassar N.T., Lippke B.R., and McCarter J.B. "Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests." Journal of Sustainable Forestry 33, no. 3 (2014): 248–75. https://doi.org/10.1080/10549811.2013.839386.

Osborne, Peter, Núria Aquilué, Marco Mina, Kiel Moe, Michael Jemtrud, and Christian Messier. "A Trait-Based Approach to Both Forestry and Timber Building Can Synchronize Forest Harvest and Resilience." PNAS Nexus 2, no. 8 (August 1, 2023): pgad254. https://doi.org/10.1093/pnasnexus/pgad254.

Pan, Yude, Richard A. Birdsey, Oliver L. Phillips, Richard A. Houghton, Jingyun Fang, Pekka E. Kauppi, Heather Keith, et al. "The Enduring World Forest Carbon Sink." Nature 631, no. 8021 (July 18, 2024): 563–69. https://doi.org/10.1038/s41586-024-07602-x.

Perry, Guy, and Michael VanderPol. "Characterization & Management of Construction, Renovation & Demolition Waste in Canada." Presented at the Recycling Council of Alberta Conference, 2014.

Phillips, Carly A., Brendan M. Rogers, Molly Elder, Sol Cooperdock, Michael Moubarak, James T. Randerson, and Peter C. Frumhoff. "Escalating Carbon Emissions from North American Boreal Forest Wildfires and the Climate Mitigation Potential of Fire Management." Science Advances 8, no. 17 (April 27, 2022): eabl7161. https://doi.org/10.1126/sciadv.abl7161.

Pittau, Francesco, Felix Krause, Gabriele Lumia, and Guillaume Habert. "Fast-Growing Bio-Based Materials as an Opportunity for Storing Carbon in Exterior Walls." Building and Environment 129 (February 1, 2018): 117–29. https://doi.org/10.1016/j.buildenv.2017.12.006.

Puhlick, Joshua J., Aaron R. Weiskittel, Laura S. Kenefic, Christopher W. Woodall, and Ivan J. Fernandez. "Strategies for Enhancing Long-Term Carbon Sequestration in Mixed-Species, Naturally Regenerated Northern Temperate Forests." Carbon Management 11, no. 4 (July 3, 2020): 381–97. https://doi.org/10.1080/17583004.2020.1795599.

Service Canada. "Opportunities for Circularity of Wood in Construction, Renovation and Demolition in Canada." Readouts, August 12, 2024. https://www.canada.ca/en/services/environment/conservation/sustainability/circular-economy/workshop-report-opportunities-circularity-wood-construction-renovation-demolition.html.

Simard, Suzanne W., W. Jean Roach, Camille E. Defrenne, Brian J. Pickles, Eva N. Snyder, Alyssa Robinson, and Les M. Lavkulich. "Harvest Intensity Effects on Carbon Stocks and Biodiversity Are Dependent on Regional Climate in Douglas-Fir Forests of British Columbia." Frontiers in Forests and Global Change 3 (2020). https://www.frontiersin.org/articles/10.3389/ffgc.2020.00088.

Skog, Kenneth E., Theodore H. Wegner, E. M. Bilek, and Charles H. Michler. "Desirable Properties of Wood for Sustainable Development in the Twenty-First Century." Annals of Forest Science 72, no. 6 (September 2015): 671–78. https://doi.org/10.1007/s13595-014-0406-0.

Smyth, C. E., B. P. Smiley, M. Magnan, R. Birdsey, A. J. Dugan, M. Olguin, V. S. Mascorro, and W. A. Kurz. "Climate Change Mitigation in Canada's Forest Sector: A Spatially Explicit Case Study for Two Regions." Carbon Balance and Management 13, no. 1 (December 2018): 11. https://doi.org/10.1186/s13021-018-0099-z.

Thiffault, Evelyne, Ariane Béchard, David Paré, and Darren Allen. "Recovery Rate of Harvest Residues for Bioenergy in Boreal and Temperate Forests: A Review." WIREs Energy and Environment 4, no. 5 (2015): 429–51. https://doi.org/10.1002/wene.157.

Thompson, Ian D. Forest Resilience, Biodiversity, and Climate Change: A Synthesis of the Biodiversity / Resiliende / Stability Relationship in Forest Ecosystems. Montreal: Secretariat of the Convention on Biological Diversity, 2009.

Wang, Xiaoming, Jennifer M. Padgett, John S. Powell, and Morton A. Barlaz. "Decomposition of Forest Products Buried in Landfills." Waste Management 33, no. 11 (November 1, 2013): 2267–76. https://doi.org/10.1016/j.wasman.2013.07.009.

Xie, Sheng H., Werner A. Kurz, and Paul N. McFarlane. "Inward- versus Outward-Focused Bioeconomy Strategies for British Columbia's Forest Products Industry: A Harvested Wood Products Carbon Storage and Emission Perspective." Carbon Balance and Management 16, no. 1 (September 25, 2021): 30. https://doi.org/10.1186/s13021-021-00193-4.

———. "Substitution Benefits of British Columbia's Mitigation Strategies in the Bioeconomy." Mitigation and Adaptation Strategies for Global Change 28, no. 3 (March 23, 2023): 18. https://doi.org/10.1007/s11027-023-10055-8.

Xie, Sheng H., Werner A. Kurz, Carolyn Smyth, Zhen Xu, and Dominik Roeser. "Forest Products Circular Economy in an Export-Focused Jurisdiction: Can It Fill the Emission

Reduction Gap?" Cleaner and Circular Bioeconomy 8 (August 2024): 100096. https://doi.org/10.1016/j.clcb.2024.100096.

Ximenes, Fabiano, Charlotte Björdal, Annette Cowie, and Morton Barlaz. "The Decay of Wood in Landfills in Contrasting Climates in Australia." Waste Management 41 (July 1, 2015): 101–10. https://doi.org/10.1016/j.wasman.2015.03.032.

# 7 Conclusions: Towards Forest-Building

The main objectives of this thesis were twofold: first, to develop methodological approaches for exploring how different wood construction approaches respond to changes in forest management, natural disturbances and climate change, this I call Forest-Building; second, to provide tools for the wood construction industry and designers on how to adapt their practices to better support more resilient and adaptable forest landscapes facing global changes.  The methodological approaches developed in the Forest-Building framework were intended to:

(1) Capture the integrated complexity of forest and building systems where global change exerts multiple pressures;

(2) Quantitatively explore the impact landscape-scale forest management regimes on the provisioning of wood for construction;

(3) Test the response of wood construction approaches to current and future climate change and natural disturbance;

(4) Work at the landscape scale of forests rather than the individual building so the construction approaches applied can realistically shape the land-based building carbon sink potential of the region's forests, and

(5) Explicitly quantify wood construction system properties directly related to resilience to management and climate driven forest composition change.

To address these challenges, the Forest-Building approach was developed to model the effects of wood construction on forest ecological resilience. Following a broad literature review on the methods and practices in forestry, wood building and impact assessment (Chapter 2 and Chapter

3), the need for a synchronized Forest-Building approach following the principles of complex adaptive systems was identified. Chapter 4 provided the foundation of the Forest-Building approach and the plant-trait based functional building traits concept. Chapter 5 applied the functional traits concept to evaluate the resilience and adaptability existing wood construction approaches to changes in forest species composition resulting from forest management and climate change. Finally, Chapter 6 presented and innovative land-based carbon model to compare the building carbon sink potential of existing and functional trait-based resilient wood construction approaches under increasing climate change and various forest management approaches. This approach was applied in Centre-du-Quebec region of southern Canada to evaluate whether a functionally adaptive approach to wood construction can effectively increase the carbon sink potential of forests and buildings. This dissertation made the following contributions to the study of forests and buildings:

1. **Wood species building traits: a plant-trait-based approach to design Forest-Building systems**

First, Chapter 4 introduced the functional building traits concept and provides the foundation of Forest-Building approach and its use at the core of a plant-trait based approach to wood construction. Seven functional groups based on the ecological traits of tree species in the region were linked to a similar functional grouping of building traits to characterize the push and pull of managing forests and wood buildings together. A process-based forest landscape model was used 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 provisioning of wood for the construction industry (Figure 50).

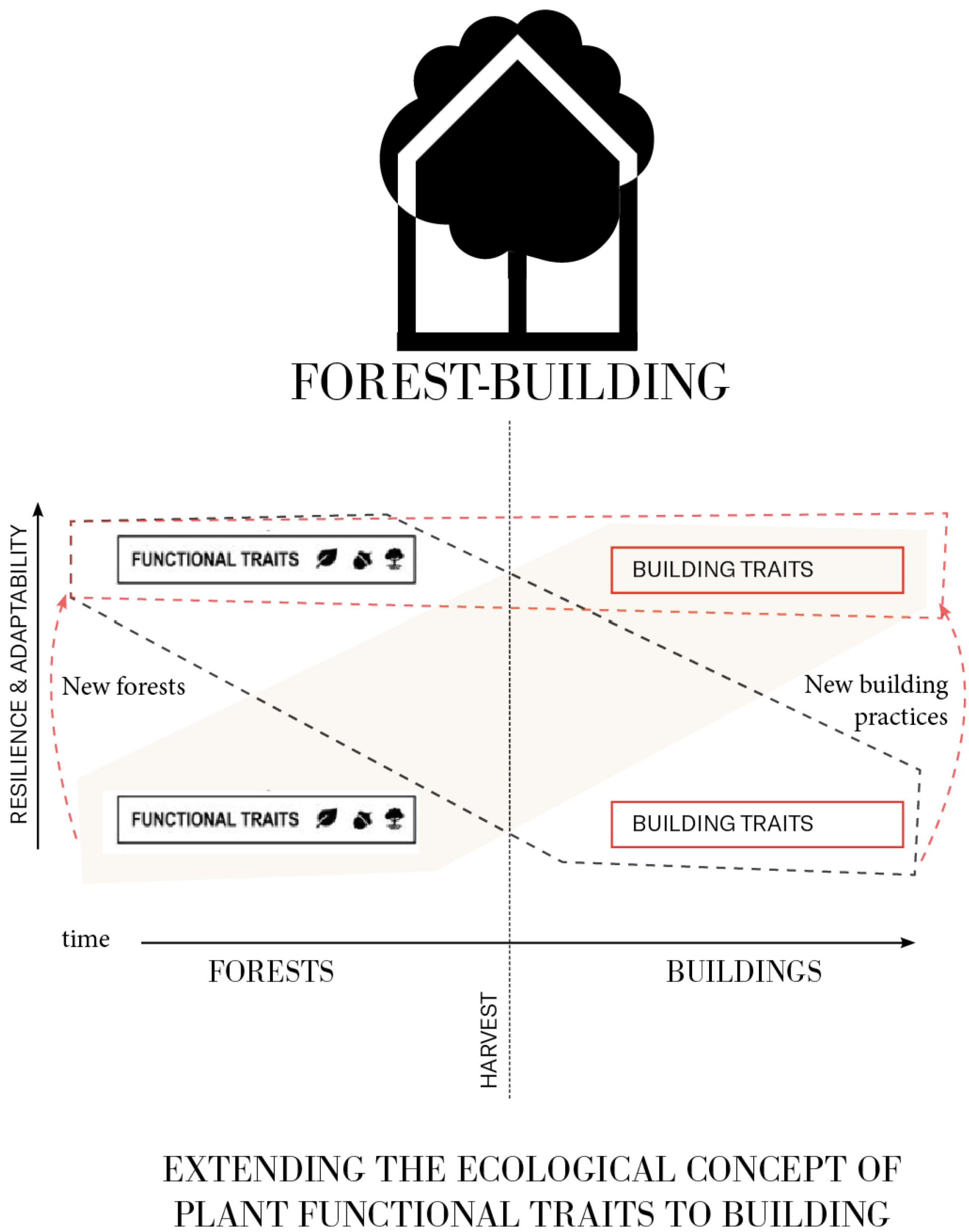


*Figure 50 – Just as ecologists have moved from species to functional traits, so to do designers and the wood construction industry needs to move from commercial groups to building traits. By understanding the relationships between ecological and building traits, foresters and builders can design new forests and building practices which synchronize the resilience and adaptability of both forests and buildings.*

2. **Functional diversity and redundancy: indicators to assess the resilience of wood construction to changing forest composition**

Second, Chapter 5 investigated the potential of the building-traits concept and outlined how to apply this plant-trait based approach to assess the resilience of existing wood construction approaches. It was found that the dominant approaches being used to offset construction industry emissions (such as single species CLT) are not resilient to climate change and alternative forest management approaches and may only be suitable in very limited regions. The results reveal the need to diversify the wood construction industry with key building and ecological traits in order to bring important benefits in terms of social and ecological adaptation (see Figure 51). Our results suggest that high functional diversity and redundancy in wood products diverts the greatest quantity of harvested wood towards buildings but considerations of quantity demanded by each construction approach – e.g. how many buildings can be constructed with a specified amount of wood – is a critical factor in regions with limited resource availability.

3. **Forest-Building carbon assessment: a synchronized approach critical to the future of the wood construction carbon sink**

Finally, Chapter 6 applied a multi-scale land-based biogenic carbon assessment – the ANSE Forest-Building Carbon Model – to assess the impact of adopting a more functionally adaptive approach to wood construction. The model results suggest that construction approaches based on maximizing the functional diversity and redundancy of species utilized may significantly increase the land-based carbon pooling potential of buildings. We found that shifting from the dominant approaches currently used – light frame SPF wood construction – to a functionally adaptive approach stands to increase the land-based building carbon pool in the study region by 105-295% depending on climate and management scenarios. Therefore, adopting a whole system, plant-building approach to forests and wood buildings, is key to enhancing forest ecological and timber construction industry resilience and increasing regional forest and building carbon sinks through a functionally adaptive approach to wood construction.

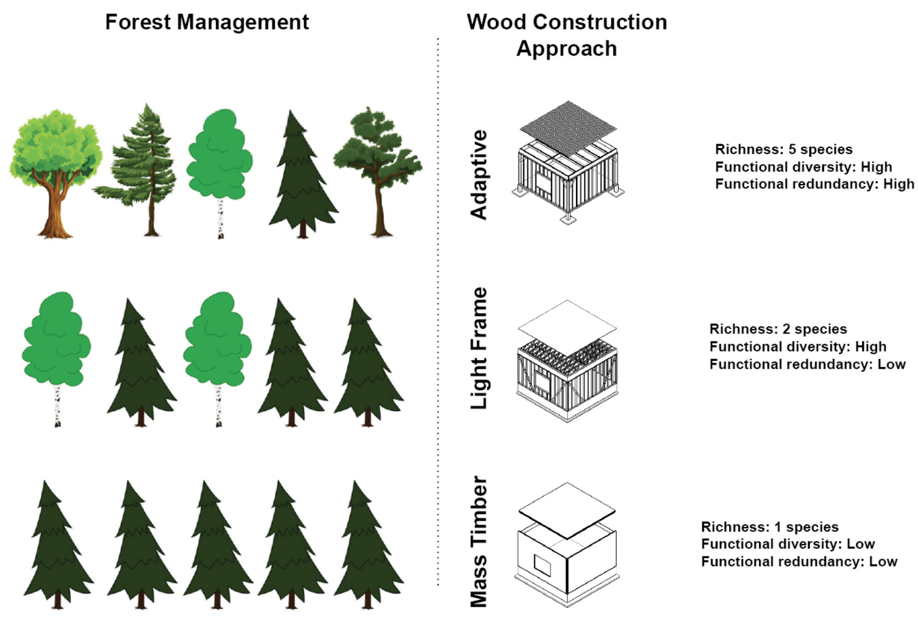


*Figure 51 - Simplified diagram illustrating the concept of functional diversity and redundancy for harvested wood products and construction approaches.* ***Mass Timber*** *The lower stand has a low functional diversity with only a single species. In addition, the functional redundancy is weak and if a species disappears, all ecological and building functional traits will be lost.* ***Light Frame*** *The middle stand has a high functional diversity with only two species because they have largely different functional traits: e.g., one species is an angiosperm, the other a gymnosperm. In contrast, the functional redundancy is weak and if a species disappears, several particular functional ecological and building traits will be lost.* ***Adaptive*** *The upper stand also has a high functional diversity because it is composed of five different species, two gymnosperms and three angiosperms with relatively similar traits. Functional redundancy is however high in this case and if a species disappears, functional traits will be maintained in the stand.*

## 7.1 Policy, manufacturing and design implications

Together, the Forest-Building framework and modelling approach developed in this dissertation can help improve the management of forests as well as the design and construction of wood building and architecture in order to increase forest and wood construction resilience to global change as well as increase the land-based carbon sink potential of forests and buildings. The impact of a synchronized Forest-Building approach has been proposed and evaluated throughout Chapters 4, 5 and 6 for the temperate region of Central Quebec, Canada. Yet, instead of providing or discussing precise management and design guidelines for the stakeholders within the study areas of this thesis, this section will highlight some key issues for all stakeholders to be aware of when managing forests and designing with wood in an uncertain and changing context: temporality and legacies, adaptive design, and trade-offs. Each of thesis issues have arisen from observations of both forest and building systems throughout this dissertation. Firstly, the need to emphasize the importance of long-term studies for understanding both the legacies and cumulative effects on forest ecosystems of management and building practices currently being applied. Driven by demand from the wood construction industry, the footprints on ecosystem structure, composition, and function of forest management approaches can persist over centuries. Secondly, when analyzing the outcomes and impacts of a specific wood construction and forest management approaches, rather than looking at a benchmark future (e.g. 50 years or the building lifespan), try to focus on the trajectory of the system at shorter time intervals until reaching the target time horizon. This approach will allow for the detection of critical thresholds of the system that could otherwise go undetected. Such critical thresholds may require adaptation to species, building group, or wood construction approaches. For example, in chapter 4 and 5, by analyzing the changes in building group capacity every five years, it was possible to identify the time available to forest managers, HWP manufacturers and wood builders to adapt their practices to the changing forest landscapes and composition. Thirdly, to recognize that significant trade-offs exist between specific wood construction and forest management practices for creating resilient and adaptive forest-building ecosystems in response to unknown environmental conditions (Côté and Darling 2010). For example, the adaptive wood construction approach proposed in Chapters 5 and 6 was successful at sequestering the highest volume of wood biomass and increasing the carbon pooling potential of buildings in the region, but little is known about either the impact on forest harvesting and manufacturing methods required for many non- and under-utilized wood species, more research is required to test their long-term suitability in buildings, and the diversion of wood away from other product categories, such as energy and heating, may also conflict with current bioenergy policies (Xie, Kurz, and McFarlane 2023). Finally, whenever possible, it is critical to adopt a synchronized and participative approach towards both the management of forests and design of wood buildings. Designers must collaborate with stakeholders, local forest management agencies, regional governments, and manufacturers, to the impacts of design decisions are taken into account.

### 7.1.1 Lessons for policymakers

The Forest-Building approach provides a framework for policymakers to ensure the health of Canada's forests, the ongoing provisioning of ecosystem services such as wood for construction and increasing the forest and wood building carbon sink potential of our forests and built environments. By extending the plant-trait based approach used in ecology to include building related traits, policymakers can better assess ability for local, regional and national forests to provide the necessary ecological and building traits needed to maintain resilient forests and wood construction industry.  By assessing critical industry resilience to changes in forest composition, such as the softwood lumber industry, policymakers can provide early warning signs, incentives and policies that prioritize new and novel and regionally specific approaches to wood construction. The regional specificity of wood construction here is critical. One evident result from this dissertation is that single species mass timber is not suitable for the region. This stands in opposition to current incentives from the Quebec and Canadian government and industry to build with mass timber. Finally, policymakers can integrate the species-level Forest-Building Carbon model into existing HWP models such as the National Forest Carbon Monitoring, Accounting, and Reporting System for Harvested Wood Products (NFCMARS-HWP) model and the Carbon Budget Model for Harvested Wood Products (CBM-HWP) to asses the mitigation potential of shifting non and underutilized wood species in long lived wood products such as buildings.

### 7.1.2 Lessons for hardwood products industry and manufacturers

The Forest-Building Approach provides tools to address issues related to uncertainty in lumber supply, the declining of ‘cheap wood’, and how industry should adapt to the impacts of forest composition and climate change.  First, the building-traits concept allows the harvested wood products industry and manufacturers to assess the specific resilience of their existing product lines and provides species and wood product adaptation recommendations where necessary. The building groups concept allows manufacturers to broaden the species utilization to include greater ecological diversity as well as redundancy within their products to ensure the resilience to changing forest composition. Furthermore, by looking at future forest compositions, industry and manufacturers can better understand the future adaptations to their manufacturing processes necessary – such as tolerances to alternative species with different physical and mechanical properties – to ensure ongoing operations.

An example of this approach is already being practiced in Europe. At Pollmeier (Germany), a local abundance of material and observations of a growing demand for structural and engineered timber products has led to the development of BauBuche; laminated veneer lumber (LVL) made from beech trees sourced within 100km of the manufacturing facility. With high volumes of beech available in the region, but of a mixed quality, the need at Pollmeier was to develop a product that makes efficient use of local wood. A response to material availability and available timber properties. By following the Forest-Building approach, manufacturers could synchronize the adaptation of their facilities and products with what the forest can give, rather than following the boom and bust strategy.

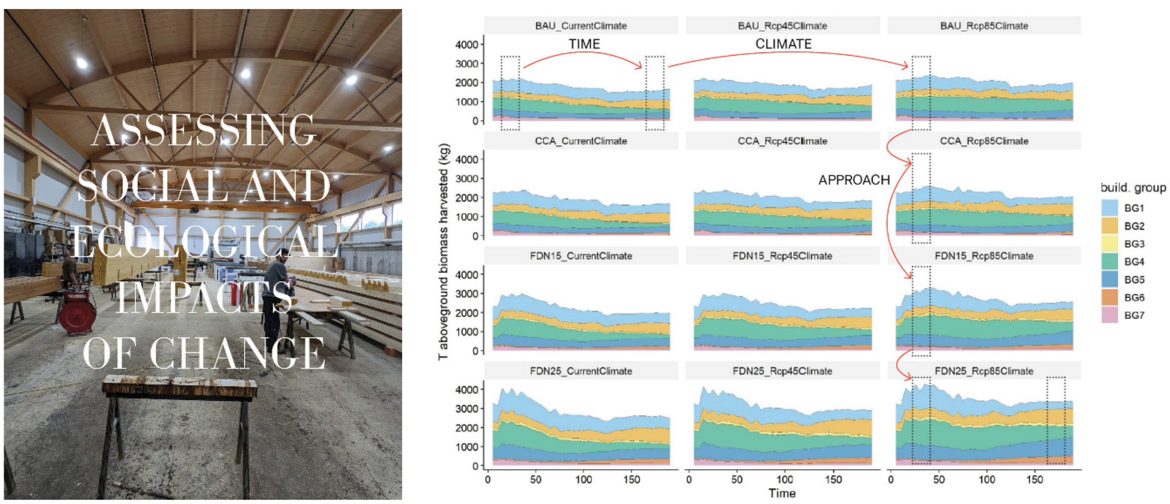


*Figure 52 – The Forest-Building approach and building traits concept allows manufacturers to assess the social and ecological impacts of change in time, climate and forest management approach on their manufacturing processes. This approach can help stakeholders understand when, with what species and how to build with wood. Photo: Peter Osborne*

### 7.1.3 Lessons for architects and designers

In the past, material specification would have been led by what was abundant in the area - timber, stone, clay etc., a material vernacular specific to the region. The command-and-control mentality dominating industry over the past century has led to more demand-led specification. In practice this has translated to building designs being drawn up and materials being specified on the assumption that a limitless supply of material can be procured that is right for the design. Yet, from the results of this dissertation on the Forest-Building supply chain, it is evident that this is not the case, and a forest-resilience approach to wood construction is needed. In other words, we need to change to a supply-led design paradigm that focuses more on material origin, availability, and forest resilience.

This dissertation provides the tools to support this transition to a supply-led design paradigm. The building traits concept gives designers the tools to understand the ecological impact and possible building use of wood species beyond the typical commercial groups. The functional resiliency assessment tools allow designers to assess, identify and specify products which have the highest adaptability and redundancy to present and future forest composition change. Finally, Forest-Building carbon model provides a novel land-based assessment of the building carbon pooling potential of a functionally adaptive approach to construction. The results clearly indicate that high volume single species approaches, such as black spruce mass timber, are not a suitable approach for a supply-led approach to wood construction. Instead, a more adaptive approach, relying on a basket of wood products – from commercial lumber, oriented strandboard and plywood using both soft and hardwoods, and engineered wood products capable of utilizing low value and underutilized species – will best ensure the health of our forests as well as the ongoing provisioning of wood for construction. This way architects and engineers will begin to explore the design of wood building and their social and ecological effects as a single design act, and thus change the way they source, design, and build for this century.

# 8 Supplemental information

## 8.1 ANNEX A: Background Survey on Assessment Methodologies – Chapter 3

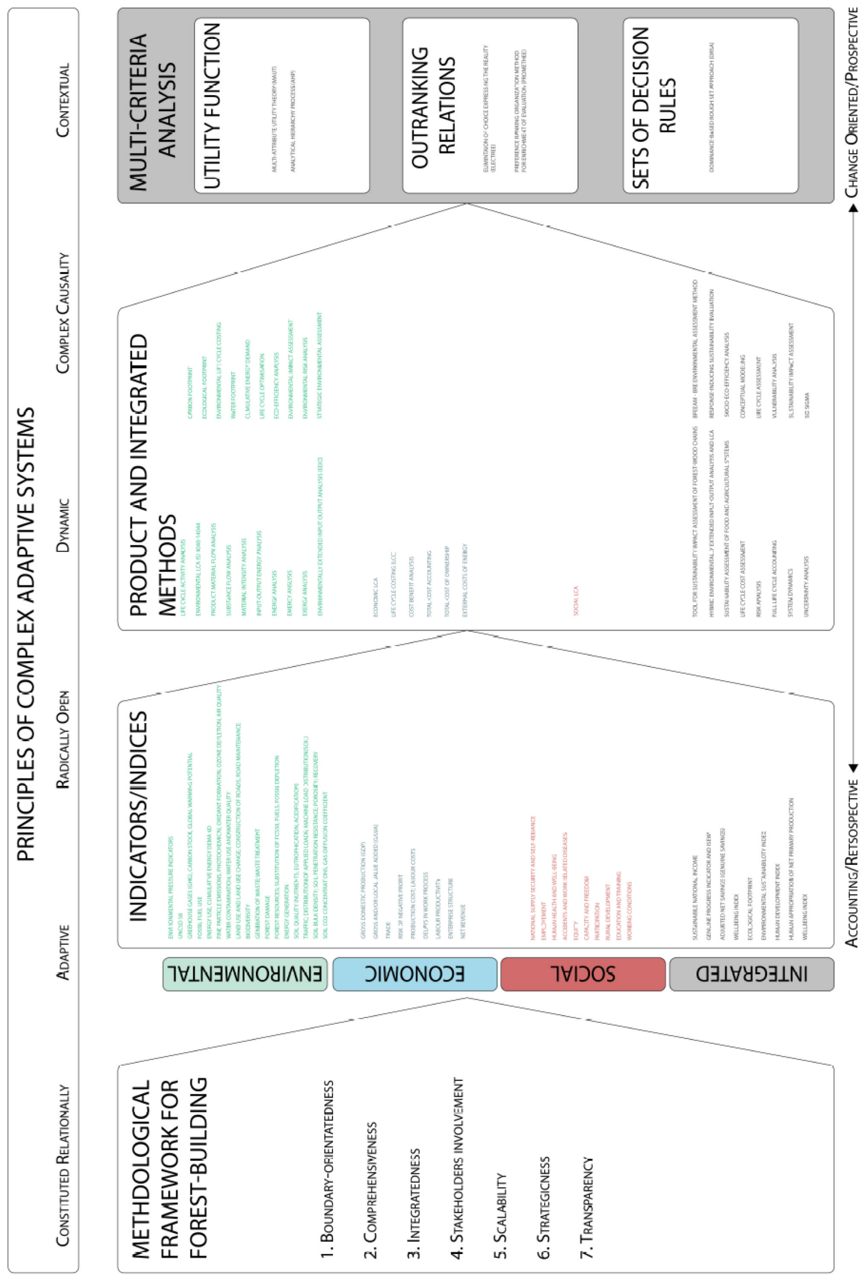


*Figure 53 - Schematic representation of the conceptual framework to assess indicators, methods, and tools for forest-building.*

*Table 9 - Criteria used in the reviewed papers to categorize sustainability assessment methodologies, methods, indicators and tools.*

| Sustainability Aspects | Assessment Criteria | Interaction | Reference |
|---|---|---|---|
| **Ontology** | Subject of the assessment | Product, project, plan, policies, etc. | Ananda and Herath (2009); Finnveden and Moberg (2005); Jeswani et al. (2010); Karvonen et al. (2017); Marchi et al. (2018); Patterson et al. (2017) |
| | Sustainability indicators | Scope of measurement | Ananda and Herath (2009); Karvonen et al. (2017); Schweier et al. (2019) |
| | Ability to consider three pillars of sustainability | Comprehensiveness | Gasparatos et al. (2008); Hacking and Guthrie (2008); Jeswani et al. (2010); Marchi et al. (2018); Ness et al. (2007); Schweier et al. (2019) |
| | Level of integration | Integratedness | Hacking and Guthrie (2008); Jeswani et al. (2010); Karvonen et al. (2017); Marchi et al. (2018); Mayer (2008); Ness et al. (2007) |
| | Kinds of impacts covered (use of resource, environmental, social, economic, soil, ergonomics, quality) | Focus | Ananda and Herath (2009); Finnveden and Moberg (2005); Karvonen et al. (2017); Marchi et al. (2018); Schweier et al. (2019) |
| | Adressing indirect and emergent inputs and effects | | Karvonen et al. (2017); Patterson et al. (2017) |
| | Scenario Development | | Ananda and Herath (2009); Gasparatos et al. (2008); Marchi et al. (2018) |
| | System boundaries | Local, regional and national impacts | Ananda and Herath (2009); Gasparatos et al. (2008); Hacking and Guthrie (2008); Karvonen et al. (2017); Marchi et al. (2018) |
| | Accounting vs change oriented | | Finnveden and Moberg (2005); Schweier et al. (2019) |

| | | | |
|---|---|---|---|
| **Epistomology** | Stakeholder engagement | Communication and knowledge building | Gasparatos et al. (2008) |
| **Methodology** | Analytic vs procedural tools | | Finnveden and Moberg (2005); Jeswani et al. (2010) |
| | Aggregation method | Bottom-up vs Top-down, weighting techniques<br>Multicriteria analysis methods | Ananda and Herath (2009); Mayer (2008)<br>Ananda and Herath (2009) |
| | System boundaries | | Karvonen et al. (2017); Mayer (2008); Patterson et al. (2017); Schweier et al. (2019) |
| | Unidimensinoal/multidimentional | | Ananda and Herath (2009); Karvonen et al. (2017); Marchi et al. (2018) |
| | Stategy and technique employed for construction of criteria and indices | Qualitative/Quantitive, Substituability, Incommensurability | Ananda and Herath (2009); Karvonen et al. (2017); Schweier et al. (2019) |
| | Metrics adopted | Absolute vs relative scaling | |
| | Abstraction | Monetary vs bio-physical methods | Gasparatos et al. (2008); Karvonen et al. (2017) |
| | Data availability | Source and applicability | Karvonen et al. (2017) |
| | Flexibility | Flexibility of indicators and methods to allow for change, purpose, method and comparative application | Karvonen et al. (2017) |
| | | Standardization level | Patterson et al. (2017) |
| | Transparency | Clarity and simplicity of content and communication | |
| | Spatio/temporal focus | Retrospective or prospective<br>Short vs long term<br>Spatial Scale<br>Interregional linkages<br>Global vs local | Gasparatos et al. (2008); Ness et al. (2007)<br>Ness et al. (2007)<br>Ananda and Herath (2009); Karvonen et al. (2017)<br>Ananda and Herath (2009); Jeswani et al. (2010); Kissinger et al. (2011)<br>Marchi et al. (2018); Ness et al. (2007) |

# 8.2 ANNEX B: Functional traits, clustering methods and functional groups – Chapter 4

This section contains the methods, data sources, rationales behind the climate and management scenarios, building traits, and clustering present in this dissertation. Further details on the functional diversification network approach and the impact on forest functional diversity, network connectivity, and resilience for the Centre-du-Quebec study region were previously published by (Mina et al. 2022). Trait collection and clustering was done for a total of 77 tree species typical of biogeographical regions of northeastern woodlands (e.g., the Mixedwood Plains ecozone in Canada and Northern Lakes and Forests ecoregion in the United States). The list of species was made for consistency with other previous studies (Aquilué et al. 2021b; Mina et al. 2022) to cover a larger array of traits and functions from species that could potentially grow in our region and/or have value in wood construction and to obtaining a more extensive representation of each functional group.

## 8.2.1 Ecological traits and groups

To characterize each species ecological traits and groups,  I used data and methods from shared by Aquilué et al. (2021b) and selected nine functional traits: 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, m2 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). All traits were retrieved from the TRY Database, except for drought and shade tolerance, which were obtained from (Niinemets and Valladares 2006). Ecological trait data as collected from the TRY Plant Trait Database (Kattge et al. 2020).

To classify the species into functional groups, we followed the steps previously described by the co-authors (Aquilué et al. 2021b; Mina et al. 2022) and is summarized here for reference. We first used a generalization of the Gower's distance metric to calculate the functional dissimilarity matrix based on the nine traits (Pavoine et al. 2009). This step was followed by an agglomerative hierarchical clustering using a Ward linkage method to quantify the overall distance among tree species in the trait space based on this matrix to aggregate functionally similar tree species into functional groups. The optimal number of clusters was determined by analyzing different cluster validation measures implemented in the clValid R-package (Handl, Knowles, and Kell 2005) following the approach described in (Aquilué et al. 2021b). The 77 tree species were finally divided into seven functional groups (Table 3) categorized as follows: (1) late seral, drought intolerant conifers; (2) early seral, drought tolerant conifers; (3) early- and mid-seral northern hardwoods; (4) mid- and late-seral northern hardwoods; (5) boreal deciduous pioneers; (6) mid-seral central hardwoods; and (7) drought tolerant central hardwoods with large seed mass. For further details on traits selected and clustering methods, see (Aquilué et al. 2021b).

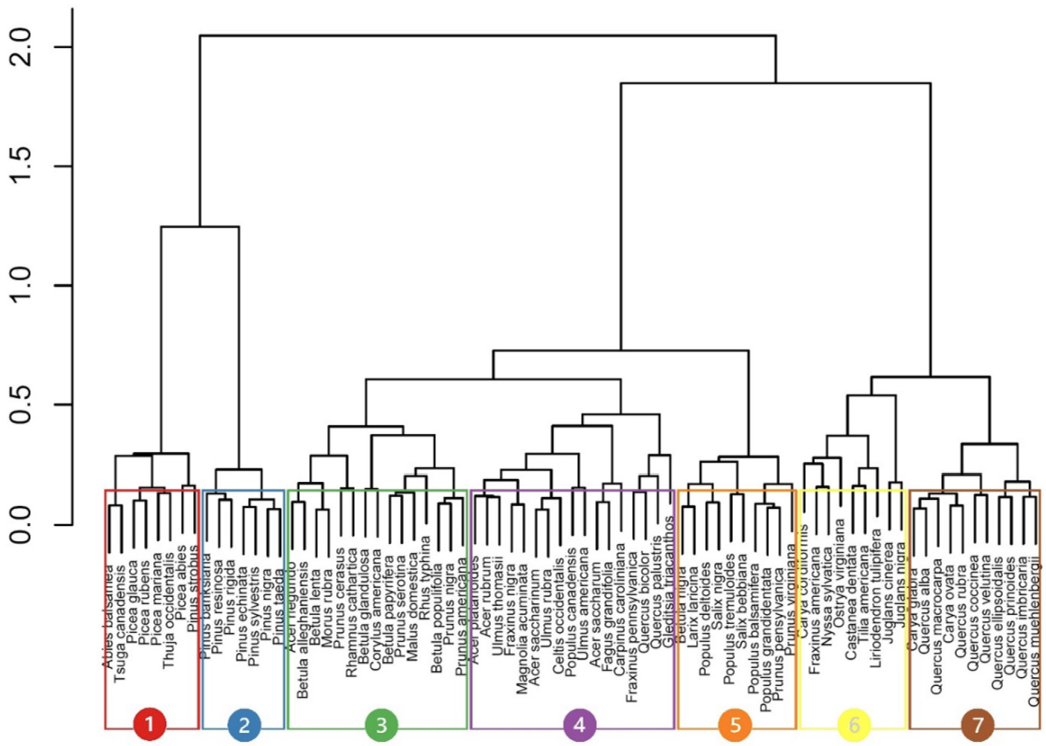


*Figure 54 – Functional dendrogram of the Eastern North American tree species clustered into the seven ecological groups. The 35 tree species currently present in the study area are considered for planning are included in this list. Reproduced from Supplementary Information for Osborne et al. (2023).*

## 8.2.2 **Building traits and groups**

To characterize each species building traits and groups, I 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 (Ross 2022). We selected ten 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). For building traits, we used data from the TRY Plant Trait Database where available (Kattge et al. 2020). For traits not present within the TRY Plant Traits Database, we relied upon construction industry publications, including the USDA FPL Wood Handbook (Ross 2022), data from the Canadian Wood Council ("Grades," n.d.), and the Wood Database ("Inside Wood - Search the Inside Wood Database," n.d.). Traits selected were prioritized based on data availability for all species within the study and consistency between sources. Traits relevant for each property are summarized below:

*Physical properties:* height (m), trunk diameter (m), wood density (g/cm$^{-3}$), and shrinkage (radial, tangential, volumetric). Where a range was provided, the average was used.

*Mechanical Properties:* Modulus of rupture (kPa), modulus of elasticity (MPa). Compression parallel to grain(kPa) and side hardness(N).

Natural durability and treatability: While the traits resistance to fungi, dry wood borers and termites (Ross 2022; Gérard, Jean et al. 2011) are available for species used in construction, limited data available for many species within our study region required us to rely on density following (Morris, n.d.; Santini Jr. et al. 2019).

*Preservative Treatment:* The effectiveness of preservative treatment is influenced by the penetration and distribution of the preservative in the wood. For maximum protection, it is desirable to select species for which good penetration is assured. The density and proportions of sapwood to heartwood significantly influence different wood species' preservative penetration (Thomasson et al. 2015). Ease of treatment (least difficult to very difficult) has been used to characterize wood species according to their ability to accept various preservatives, yet is only available for a limited number of species in our study (Halverson and Lebow 2022) and was therefore omitted from our selection, relying on density as a correlated indicator.

*Fire Safety:* Multiple standards exist between Canada and the United States, which are not comparable due to characterization methods. The United States uses the ASTM Standard(Fire Spread Index and Smoke Developed Index), while Canada uses the CAN/ULC-S102 (Flame Spread Index and Smoke Developed Classification). Furthermore, in both standards, fire safety indicators are only available for species commonly used in construction. Research has indicated that species, density, and moisture content are the most significant traits influencing fire safety for wood species (Bartlett, Hadden, and Bisby 2019). As moisture content is related to the drying process and remains relatively similar for all finished lumber, we relied on density as the sole indicator for fire safety.

*Bonding & Adhesives:* The effectiveness of bonding depends on the surface properties but also the physical properties of wood, particularly density, moisture content, strength, and swelling/shrinking properties(Pizzi and Mittal 2010; Thomasson et al. 2015). The USDA Wood Handbook categorizes wood species according to ease of bonding for a limited species selection. We, therefore, rely on the physical and mechanical properties described earlier to account for the wood species' bonding ability.

*Finishing and Workability:* Wood species (thus its anatomy) is the primary factor that determines the surface properties of wood that affect the adhesion and performance of finishes. Finish performance is affected by density (overall density, earlywood (EW)–latewood (LW) density difference, and how abruptly density changes at the EW–LW boundary), the thickness of LW bands, ray cells (number and placement), vessels (size and location), extractives content, and growth rate (some species grow faster than others, and environment affects growth rate within a specific species). These factors are combined with industry knowledge in the USDA Wood

Handbook as paintability, workability and effect on cutting tools. These traits were only available for a limited species selection and, therefore, not included in this study.

To classify the species into building groups, I followed the steps described above to group species according to ecological traits. The 77 tree species were divided into seven functional groups (BG1-7) (see Figure 55, Figure 56, Table 1). BG1 and BG2 contain most species currently used in construction and are primarily composed of softwood species.

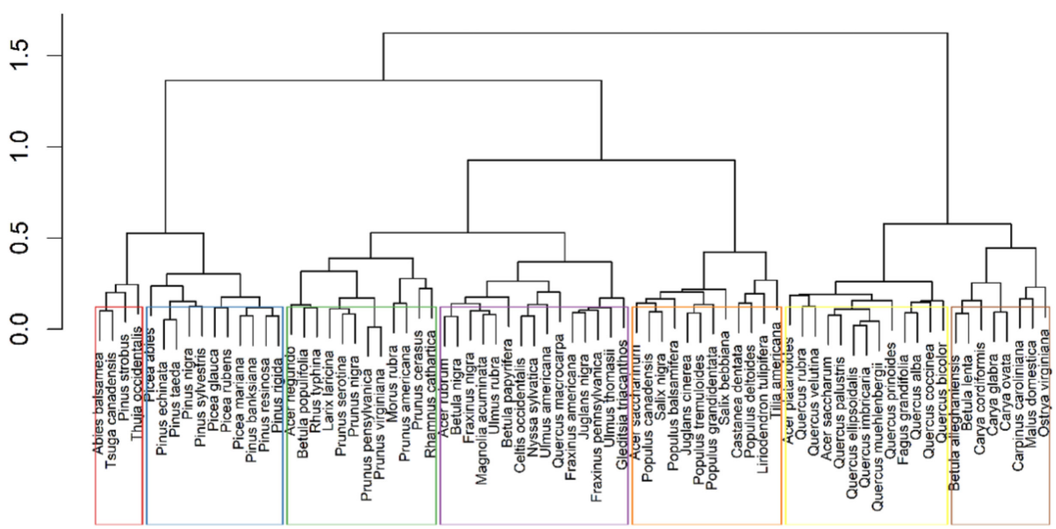

*Figure 55 - Functional dendrogram of the Eastern North American tree species clustered into the seven building groups.. The 35 tree species currently present in the study area are considered for planning are included in this list. Reproduced from Supplementary Information for Osborne et al. (2023).*

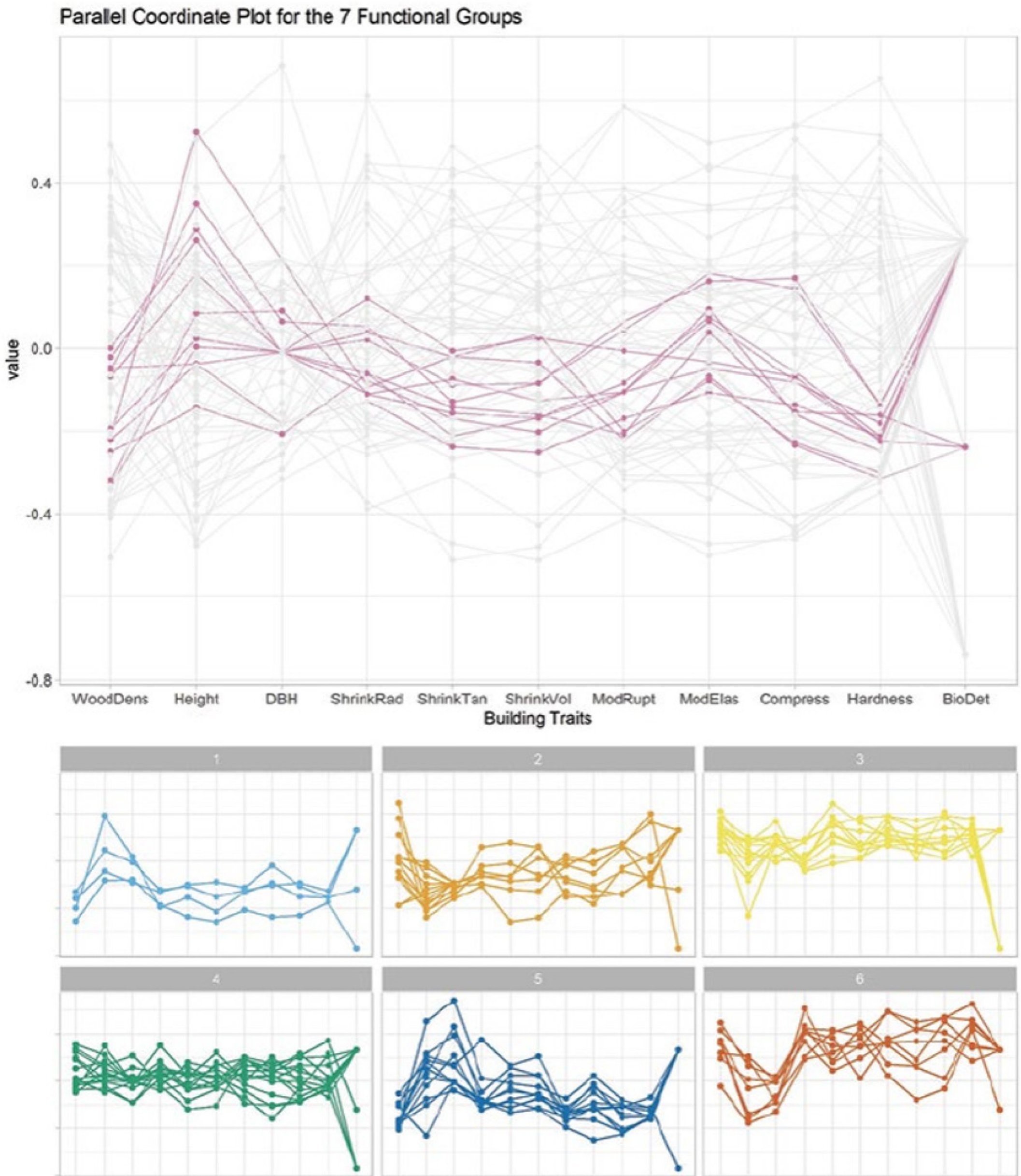


*Figure 56 – Parallel coordinates chart for eleven building traits showing building group clustering within the possible trait space. See Table 2 for species and summary of key characteristics of building groups. Reproduced from Supplementary Information for Osborne et al. (2023).*

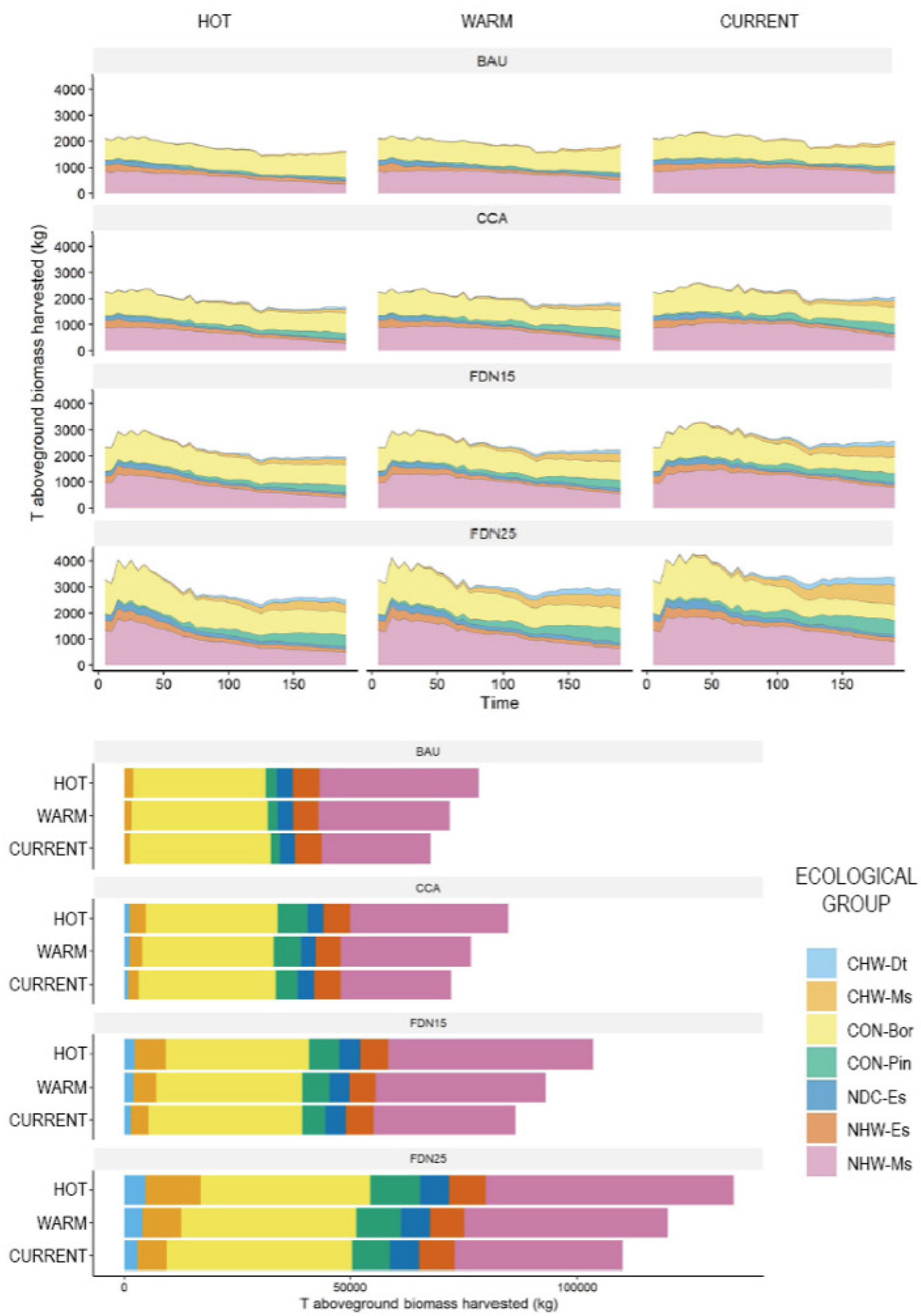


*Figure 57- Above: Aboveground biomass harvested (kg*10³) by species ecological functional group (Table 3) under the different scenarios (columns: climate; rows: management treatment). Below: Total Harvested biomass (kg*10³) for the study period (190 years). Reproduced from Supplementary Information for Osborne et al. (2023).*

## 8.3 ANNEX C: Inputs and parameterization of the LANDIS-II forest landscape model

This dissertation used harvest data from multiple sources to initialize and parameterize the LANDIS-II forest landscape model(calibrated and simulated by Dr. Marco Mina) for the study region. Simulations are sensitive to model inputs such as maps of initial vegetation conditions, biophysical ecoregions, management units and model parameters. Mina et al. (2022; 2020) previously published details of the parameterization, calibration and validation of the model for the Centre-du-Quebec, where the model setup for this landscape is extensively described. Climate and management scenarios provided for this dissertation by Macro Mina are summarized below for reference.

### 8.3.1 Climate scenarios

The LANDIS-II PnET-Succession extension was used to simulate forest dynamics for this study (de Bruijn et al. 2014). PnET-Succession requires the following inputs: average monthly temperature (minimum and maximum), the sum of monthly precipitation, mean monthly photosynthetically active radiation (PAR) during daylight hours and mean monthly atmospheric $CO_2$ concentration associated with each climatic region. We chose three climate scenarios following those described in the authors' previous study (Mina et al. 2022) and summarized below.

#### 8.3.1.1 **Historical climate (current)**

Data for historical monthly temperatures and precipitation, such as time series from meteorological stations, were obtained from Environment and Climate Change Canada (E. and C. C. Canada 2020). For PAR, we used records from Environment and Climate Change Canada of solar radiation data (KJ/m2) at hourly resolution for the period 1996-2016 from the only meteorological station in the region for which this variable was available (Nicolet, 46º23’ N – 72º33’ W). Carbon dioxide concentration for the period 1800-2013 was derived from datasets compiled by the Institute for Atmospheric and Climate Science at ETH Zürich for the CMIP6 project (Eyring et al. 2016). For 2014 and 2018, monthly means were filled with observations from the global greenhouse gas reference network at the Mauna Loa sampling site (NOAA/ESRL; http://www.esrl.noaa.gov/gmd/ccgg/trends). For the contemporary climate scenario, we projected a continuation of normal climatic conditions (temperature, precipitation, and PAR) until 2200 by imputing a randomly selected year from the historical time series 1960–2000. $CO_2$ concentration was held constant as the last complete observation year (2018).

#### 8.3.1.2 **Regional climate change scenarios (warm, hot)**

Data for the future temperature and precipitation representing climate change for 2010-2100 were derived from daily regional projections of maximum temperature, minimum temperature and precipitation provided by the Innovation Cluster on Regional Climatology Ouranos (Ouranos 2015). We chose climate change projections from the Canadian Earth System Model version 2 (Arora and Boer 2010) under two Representative Concentration Pathways: RCP 4.5 (moderate emissions scenario; warm) and RCP 8.5 (high emission scenario; hot). As future projections of solar radiation were not available for our region, future PAR was generated by randomly selecting monthly values from the observed period following similar methods described in (Duveneck et al. 2014).

### 8.3.2 Management Scenarios

The LANDIS-II Biomass-Harvest extension was used for simulating logging and other forest management activities. This extension requires spatial inputs (management unit maps defining areas with collections of stands to which specific harvesting prescriptions are applied and stand maps) and other inputs with specifics for each silvicultural prescription (e.g., rank order of stands, criteria to qualify for harvesting, cell selection within stands, biomass removed after each entry, species to plant post-harvest, percent of management unit to harvest each time step). For more details on the management scenarios, refer to Supporting Data of (Mina et al. 2022). This section summarized data sources, methods and assumptions for the three management scenarios analyzed in the current study.

#### 8.3.2.1 **Business-as-usual (BAU)**

BAU was based on silvicultural guidelines and information from the forestry agency of Centre-du-Québec (AFBF 2015). This scenario represents our best guess of the currently implemented forest management planning for timber production in the study region. We also retrieved information on the main typologies of commercial silvicultural interventions carried out in the region on different forest types: (1) selection cutting in uneven-aged stands, deciduous or mixed, dominated mainly by hardwoods; (2) commercial thinning in conifer plantations; (3) cutting with protection of regeneration and soils (CPRS), a modified clear-cutting system executed on conifer plantations and in even-aged, mixed but conifer-dominated stand; (4) shelterwood felling, implemented in two to three successive harvesting interventions to promote regeneration in even-aged stands; and (5) selection cutting in sugarbushes, a modified and lighter single-tree selection felling promoting health and productivity of maples, mostly in stands devoted to syrup production. Percentages of harvested landscape for each silvicultural prescription were estimated from the dataset of silvicultural interventions recorded by the agency between 2003 and 2017. We estimated the harvested hectares per prescription every simulated harvesting time step (5-

years) and implemented them as percentages of harvested landscape (Table 10). Further details on the design of this management scenario are found in (Mina et al. 2022).

#### 8.3.2.2 **Climate Change Adaptation (CCA)**

The CCA scenario was implemented to maintain the same elements of BAU but to include changes to silvicultural practices in response to climate warming, such as increased harvest rates to take advantage of anticipated higher tree growth and enrichment planting post-harvesting, to introduce a limited number of tree species more adapted to a future climate. Silvicultural prescriptions were implemented across the landscape using the same management units as BAU and with the same inclusion rules for stands eligible for harvesting (e.g., minimum/maximum age, stand composition). Further details on the design of this management scenario are found in (Mina et al. 2022), while features of the silvicultural prescriptions as implemented in the model are given in Table 10.

#### 8.3.2.3 **Functional Diversification Network (FDN)**

The FDN treatment was designed to incorporate the functional complex network approach principles to enhance forest landscape resilience to global change. The FDN approach begins by assessing the functional traits of each stand within the landscape (e.g., functional diversity). This is then followed by computing the spatial structure of the forest-stands network to assess functional connectivity between patches according to seed dispersal and tree establishment capacity (i.e., functional connectivity), as described in (Aquilué et al. 2021b).

In contrast to BAU and CCA, for FDN, we defined different management units for the Biomass-Harvest extension. We prioritized zones within the study region for which sylvicultural interventions would have the most significant impact at a regional scale. We consider three stand-level characteristics to rank stands and prioritize management interventions. The foremost characteristic was stand-level functional diversity, prioritizing the functional enrichment of those with lower functional diversity. Also, the area-weighted mean functional diversity of all the adjacent stands (that is, stands that are directly linked to the target one) to detect those stands that, once managed, can become a source of functional diversity to neighboring functionally poor areas and have a positive impact beyond it. Lastly, the connectivity of the target stand within the forest network, detecting those highly connected stands with a consequent higher potential to spread seeds and diversity across the network, like hubs or stands that concentrate a high number of connections and bridges or stands that strongly connect two otherwise disjoint sections of the network.

To quantify the functional diversity of a stand and, by extension of its neighborhood, we measured the relative abundance of the seven functional groups within each forest stand using the exponent of the Shannon diversity index (ranging from 1 – null to 7 – maximum diversity). To rank the stands and their neighborhoods according to functional diversity, we considered three main levels of functional diversity: low (1-3), medium (3-5) and high (5-7). Stand centrality within the network was measured as the PCflux fraction of the probability of connectivity index. This index describes how likely two random stands can be reached across the network via seed dispersal, and the PCflux fraction estimates the potential amount of dispersal flux expected to depart or arrive to a stand.

Management units with low functional diversity and high functional connectivity were considered a high priority as sylvicultural interventions will have the greatest impact at multiple spatial scales. Similarly, those with low functional diversity or highly fragmented levels were regarded as a high priority. Units with opposing levels of indicators were assigned a medium priority, while units with medium/high levels of indicators were allocated to low priority. High priority does not refer to interventions being executed earlier but to higher management intensity (i.e., percent of MU under harvesting and planting per year). Silvicultural prescriptions were implemented on the seven management units with the same inclusion rules for stands eligible for harvesting as BAU and CCA.

Compared to CCA, the main differences were harvest area, the inclusion of enrichment planting and assisted migration, and the intensity of post-harvest planting. Harvest area was simulated at 15-25% every 5 years and varied according to management unit priority. The harvested area ranges from 3% to 6% (from low to high-priority MU), and planting intensity is 100% in high-priority stands and 80-90% in others. In addition to the six species planted with CCA, FDN treatment introduced ten tree species previously absent in the region. Species were selected to increase forest and landscape functional diversity and not increase harvest output or wood yield for construction expressly. Finally, according to the management unit, the intensity of post-harvest planting in selection harvest prescriptions varied from 90% to 100% (Table 10). Further details on the design of this management scenario are found (Mina et al. 2022).

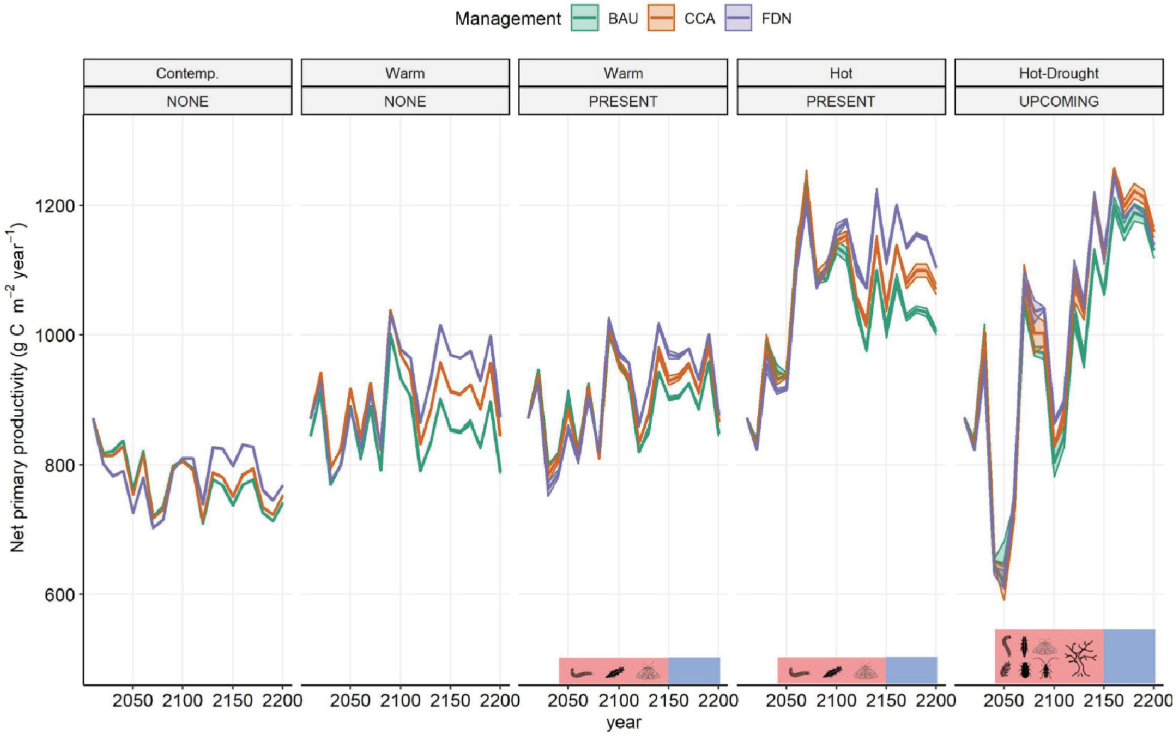


*Figure 58 – Annual net primary productivity as landscape level averages across the Central Quebec Study region comparing forest management approaches in response to climate change and disturbances. Red boxes indicate periods of simulated disturbances (2040-2150; three or six insects plus drought) and blue boxes indicate when periods when the landscape was left undisturbed to recover (2150-2200). Reproduced from Mina et al. (2022)*

*Table 10 - Ecological, building groups and key features of silvicultural prescriptions by management treatment. From Osborne et al. (2023)*

| Treat-ment | Prescription | Forest Type | Landscape (%/5yrs) | Age Range | Max ha harvested | Harvest Intensity (% biomass)[1] | Regeneration | Ecological Group | Building Group | Species planted |
|---|---|---|---|---|---|---|---|---|---|---|
| BAU | Commercial thinning | Conifer plantations | 4.2 | 20-40 | 70 | 35% | Natural | | | |
| | Clearcut | Conifer plantations[2] | 0.6 | 60-70 | 4 | 100/97/97% | Natural and artificial | CON-Bor, CON-Pin | BG1, BG2 | *Picea glauca, P. mariana, P. rubens, P. abies, Pinus resinosa* |
| | Thinning | Mixed stands - even-aged | 3.5 | 90-110 | 20 | 33% | Natural | | | |
| | First shelterwood | Mixed stands - even-aged | 0.6 | 110-130 | 20 | 33% | Natural | | | |
| | Second shelterwood | Mixed stands - even-aged | 0.7 | 120-150 | 4 | 90% | Natural | | | |
| | Selection harvest | Deciduous uneven-aged | 5.3 | uneven | 20 | 20/30/35%[3] | Natural | | | |
| CCA | Commercial thinning | Conifer plantations | 4.2 | 20-40 | 70 | 35% | Natural | | | |
| | Clearcut | Conifer plantations2 | 0.6 | 60-70 | 4 | 100/95/95% | Natural and artificial | CON-Bor, CON-Pin | BG1, BG2 | *Pinus resinosa, P. strobus, Picea rubens* |
| | Thinning | Mixed stands - even-aged | 3.5 | 90-110 | 20 | 37% | Natural | | | |
| | First shelterwood | Mixed stands - even-aged | 0.6 | 110-130 | 20 | 37% | Natural | | | |
| | Second shelterwood | Mixed stands - even-aged | 0.7 | 120-150 | 4 | 95% | Natural and artificial | CON-Bor, CON-Pin | BG1, BG2 | *Pinus resinosa, P. strobus, Picea rubens* |
| | Selection harvest[4] | Deciduous uneven-aged | 5.3 | uneven | 40 | 25/35/40%[3] | Natural (40%). | NHW-Es, CHW-Dt, CHW-Ms | BG3-BG6 | *Prunus serotina, Quercus rubra, Q. alba, Q. macrocarpa, Tilia americana, Juglans nigra* |
| | | | | | | 25/35/40% | Natural plus enrichment planting (60%) | | | |

1 Biomass removed after each harvest entry. Differ by age classes (approx. small / medium / large-sized trees). 2 Split by monospecific plantation (BAU and CCA-FDN until 2070: applied on existing conifer plantations - white/black/red/Norway spruce, red pine; CCA-FDN from 2070: applied on existing plus planted conifer stands, split into two prescriptions: 1) replant mixed pines plantation; 2) replant mixed spruce and larch). 3 Modified in sugarbushes management unit: BAU 15/15/20% sugar maple, 20/30/35% red maple, 70/85/85% other species; CCA 20/20/25% sugar maple, 25/35/40% red maple, 25/35/90% CCA species allowed to mix if establish from near stands; 90/90/90% other species. 4 After 2020, increased harvest intensities and split into two prescriptions: 1) natural regeneration only (40% stands), 2) natural plus enrichment planting with mid-seral hardwoods (60% stands). 5 Differs by management unit according to level of priority (Table S2). 6 After 2020 split into three prescriptions: 1) natural regeneration only (no planting), 2) natural plus planting with mid-seral hardwoods (5 spp.); 3) planting with mid-/early seral hardwoods (5 spp.), 3) planting with early-seral hardwoods (4 spp.).

| Treat-ment | Prescription | Forest Type | Landscape (%/5yrs) | Age Range | Max ha harvested | Harvest Intensity (% biomass)[1] | Regeneration | Ecological Group | Building Group | Species planted |
|---|---|---|---|---|---|---|---|---|---|---|
| FDN | Commercial thinning | Conifer plantations | 4.2-8.4[5] | 20-40 | 70 | 35% | Natural | | | |
| | Clearcut | Conifer plantations2 | 0.6-1.3[5] | 60-70 | 4 | 100/95/95% | Natural and artificial | CON-Bor, CON-Pin, NDC-Es | BG1-BG3 | *Pinus strobus, P. rigida, P. taeda, Picea rubens, Larix laricina* |
| | Thinning | Mixed stands - even-aged | 3.5-6.9[5] | 90-110 | 20 | 37% | Natural | | | |
| | First shelterwood | Mixed stands - even-aged | 0.6-1.2[5] | 110-130 | 20 | 37% | Natural | | | |
| | Second shelterwood | Mixed stands - even-aged | 0.7-1.4[5] | 120-150 | 4 | 95% | Natural and artificial | CON-Bor, CON-Pin, CHW-Ms, CHW-Dt | BG1, BG2, BG5, BG6 | *Picea rubens, Pinus resinosa, Tilia americana, Quercus rubra* |
| | Selection harvest[6] | Deciduous uneven-aged | 5.3-10.6[5] | uneven | 40 | 25/35/40% | Natural (0-20%) | CHW-Dt, CHW-Ms, NHW-Ms, NHW-Es | BG3-BG7 | *Quercus alba, Q. macrocarpa, Q. coccinea, Q.velutina, Carya cordiformis, C. glabra, Acer saccharinum, Tilia americana, Betula lenta, Ulmus americana, Juglans nigra, Prunus serotina, Liriodendron tulipifera* |
| | | | | | | 25/40/85% | Natural plus assisted migration (80-100%) | | | |

1 Biomass removed after each harvest entry. Differ by age classes (approx. small / medium / large-sized trees). 2 Split by monospecific plantation (BAU and CCA-FDN until 2070: applied on existing conifer plantations - white/black/red/Norway spruce, red pine; CCA-FDN from 2070: applied on existing plus planted conifer stands, split into two prescriptions: 1) replant mixed pines plantation; 2) replant mixed spruce and larch). 3 Modified in sugarbushes management unit: BAU 15/15/20% sugar maple, 20/30/35% red maple, 70/85/85% other species; CCA 20/20/25% sugar maple, 25/35/40% red maple, 25/35/90% CCA species allowed to mix if establish from near stands; 90/90/90% other species. 4 After 2020, increased harvest intensities and split into two prescriptions: 1) natural regeneration only (40% stands), 2) natural plus enrichment planting with mid-seral hardwoods (60% stands). 5 Differs by management unit according to level of priority (Table S2). 6 After 2020 split into three prescriptions: 1) natural regeneration only (no planting), 2) natural plus planting with mid-seral hardwoods (5 spp.); 3) planting with mid-/early seral hardwoods (5 spp.), 3) planting with early-seral hardwoods (4 spp.).

# 8.4 ANNEX D: Inputs for ANSE HWP Carbon Model – Chapter 6

Included in this section are the inputs and parametrization data used to Model the Forest-Building Carbon model in Chapter 6.

*Table 11 - End-of-life fate of clean wood (lumber) and composite/engineered wood (CLT, glulam, I-joist, LVL, OSB, plywood)*

| Jurisdiction | Solid wood | | | | Composite/engineered wood | | | |
|---|---|---|---|---|---|---|---|---|
| | Construction | | Demolition | | Construction | | Demolition | |
| | Recycled | Landfilled | Recycled | Landfilled | Recycled | Landfilled | Recycled | Landfilled |
| Canada | 18% | 82% | 21% | 79% | 26% | 74% | 23% | 77% |
| British Columbia | 30% | 70% | 42% | 58% | 41% | 59% | 44% | 56% |
| Alberta | 8% | 92% | 9% | 91% | 13% | 87% | 10% | 90% |
| Saskatchewan | 1% | 99% | 1% | 99% | 2% | 98% | 1% | 99% |
| Manitoba | 4% | 96% | 4% | 96% | 6% | 94% | 5% | 95% |
| Ontario | 16% | 84% | 17% | 83% | 24% | 76% | 19% | 81% |
| Quebec | 21% | 79% | 27% | 73% | 30% | 70% | 29% | 71% |
| New Brunswick | 2% | 98% | 2% | 98% | 4% | 96% | 2% | 98% |
| Nova Scotia | 40% | 60% | 47% | 53% | 51% | 49% | 49% | 51% |
| Prince Edward Island | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% |
| Newfoundland | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% |
| Northwest Territories | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% |
| Nunavut | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% |
| Yukon | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% |

*"Construction" refers to waste occurring at the construction site at the beginning of a building's life, whereas "demolition" is waste occurring at the end of a building life. Source:* (Perry and VanderPol 2014)

*Table 12 - Wood coproduct fates, by product type*

| Product Type | | % from log | Treatment | | | |
|---|---|---|---|---|---|---|
| | | | Main product | Sold | Landfill | Bioenergy |
| Lumber | Main product | 43.1% | | | | |
| | Bark | 8.9% | | 85.0% | 3.0% | 12.0% |
| | Planer shavings | 6.3% | | 72.0% | | 28.0% |
| | Sawdust | 5.6% | | 79.0% | 21.0% | |
| | Pulp chips | 34.5% | | 100.0% | | |
| | Trim ends | 0.6% | | 100.0% | | |
| | Chipper fines | 0.2% | | | | 100.0% |
| | Wood waste | 0.7% | | 42.0% | 58.0% | |
| CLT | Main product | 54.0% | 87.3% | | 12.7% | |
| | Bark | 9.0% | | 97.0% | 3.0% | |
| | Sawdust | 4.4% | | 99.2% | | 0.8% |
| | Pulp chips | 32.5% | | 100.0% | | |
| | Chipper fines | 0.2% | | 100.0% | | |
| Glulam | Main product | 50.3% | 86.9% | 10.9% | | 2.2% |
| | Bark | 8.7% | | 85.0% | 3.0% | 12.0% |
| | Planer shavings | 2.9% | | 72.0% | | 28.0% |
| | Sawdust | 4.8% | | 79.0% | 21.0% | |
| | Pulp chips | 32.5% | | 100.0% | | |
| | Trim ends | 0.3% | | 100.0% | | |
| | Chipper fines | 0.2% | | | | 100.0% |
| | Wood waste | 0.3% | | 42.0% | 58.0% | |
| I-Joist | Main product | 55.0% | | | | |
| | Bark | 6.7% | | 71.0% | 1.3% | 27.7% |
| | Planer shavings | 2.1% | | 72.0% | | 28.0% |
| | Sawdust | 1.9% | | 79.0% | 21.0% | |
| | Pulp chips | 21.1% | | 100.0% | | |
| | Trim ends | 0.2% | | 100.0% | | |
| | Chipper fines | 0.1% | | 100.0% | | |
| | Wood waste | 0.3% | | 29.4% | 70.6% | 0.0% |
| | Off-spec | 2.4% | | 100.0% | | |
| | Peeler cores | 3.4% | | 100.0% | | |
| | Wood for hog fuel | 5.8% | | | | 100.0% |
| | Byproducts | 1.0% | | 100.0% | | |
| LVL | Main product | 47.3% | | | | |
| | Bark | 11.3% | | 60.0% | | 40.0% |
| | Pulp chips | 28.7% | | 100.0% | | |
| | Off-spec | 2.6% | | 100.0% | | |
| | Peeler cores | 10.1% | | 100.0% | | |
| OSB | Main product | 79.3% | | | | |
| | Wood waste | 0.3% | | | 100.0% | |
| | wood for hog fuel | 17.4% | | | | 100.0% |
| | Byproducts | 2.9% | | 100.0% | | |
| Plywood | Main product | 49.8% | | | | |
| | Pulp chips | 19.4% | | 100.0% | | |
| | Peeler cores | 9.0% | | 100.0% | | |
| | Wood, hog fuel, internal | 13.9% | | | | 100.0% |
| | Wood, hog fuel, external | 7.6% | | 100.0% | | |
| | Veneer | 0.3% | | 100.0% | | |

Source: Athena Reports (ASMI 2012a-d; 2013a-c; 2018a-c)

*Table 13 - Landfill decay rates in Canada*

| **Province** | **decay constant lambda (years-1)** |
|---|---|
| ***Degradable wood in landfills*** | |
| British Columbia | 0.083 |
| Alberta | 0.012 |
| Saskatchewan | 0.012 |
| Manitoba | 0.019 |
| Ontario | 0.046 |
| **Quebec** | **0.059** |
| New Brunswick | 0.059 |
| Nova Scotia | 0.075 |
| Prince Edward Island | 0.061 |
| Newfoundland & Labrador | 0.078 |
| Yukon | 0.002 |
| Northwest Territories | 0.003 |
| ***Degradable wood in wood waste landfills*** | |
| **Canada, average** | **0.03** |

*Source:* (Government of Canada 2002)

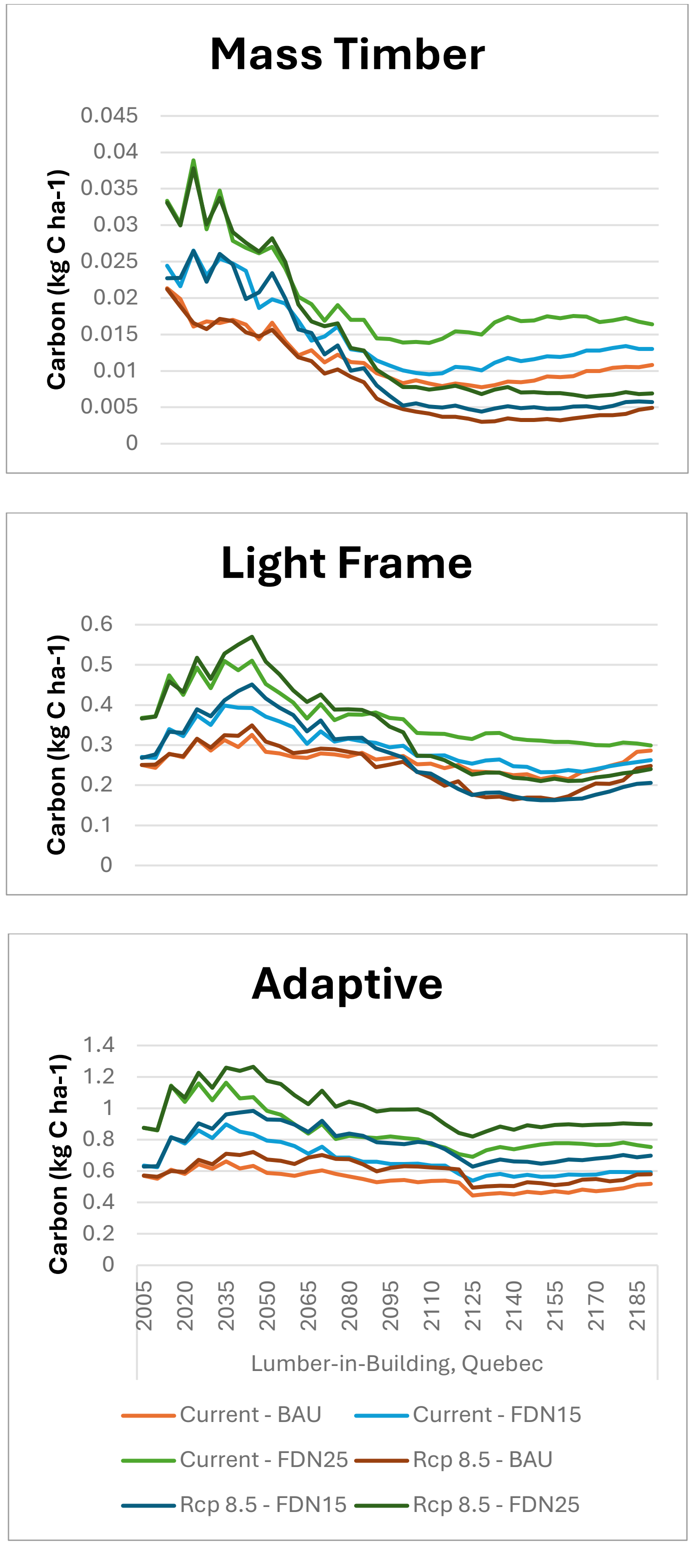


*Figure 59 – ANSE Forest Building Carbon Model results Net carbon fluxes of lumber in building over time for the three building scenarios, climate change, and management scenarios. Note the difference in range for the vertical axis.*

## 8.5 ANNEX E: Datasets

The data that support the findings of this study (model input files, R scripts) will be permanently archived in the Zenodo digital repository. A version of the LANDIS-II and ANSE model input data is available at https://zenodo.org/badge/DOI/10.5281/zenodo.8184010.svg. Technical model documentation of LANDIS-II and its extensions is available at https://www.landis-ii.org/. The code of the LANDIS-II simulation model is distributed under an open-source license and is freely available at https://github.com/LANDIS-II-Foundation**.** Technical model documentation of ANSE and the NRCan HWP model and is available at https://natural-resources.canada.ca/climate-change/climate-change-impacts-forests/carbon-accounting/forest-carbon-accounting-tools/abstract-network-simulation-engine-anse/24901.

# References


AFBF. 2015. “Plan de protection et de mise en valeur des forêts privées du Centre-du-Québec.” Agence forestière des Bois-Francs. 2015. https://www.afbf.qc.ca/.

Alam, Ashraful, Antti Kilpeläinen, and Seppo Kellomäki. 2012. “Impacts of Initial Stand Density and Thinning Regimes on Energy Wood Production and Management-Related CO2 Emissions in Boreal Ecosystems.” https://pubag.nal.usda.gov/catalog/517455.

Allen, T. F. H. 2015. *Toward a Unified Ecology*. New York : Columbia University Press,.

Allen, Timothy F.H. 2002. “Applying the Principles of Ecological Emergence to Building Design and Construction.” In *Construction Ecology: Nature as the Basis for Green Buildings*, edited by Charles J. Kibert, Jan Sendzimir, and G. Bradley Guy, 108–26. Taylor & Francis.

Alvarez, Sergio, and Agustín Rubio. 2016. “Wood Use and Forest Management for Carbon Sequestration in Community Forestry in Sierra Juárez, Mexico.” *Small-Scale Forestry* 15 (3): 357–74. https://doi.org/10.1007/s11842-016-9325-2.

Amin, Samir, and Brian Pearce. 1976. *Unequal Development: An Essay on the Social Formations of Peripheral Capitalism*. New York: Monthly Review Press.

Ananda, Jayanath, and Gamini Herath. 2009. “A Critical Review of Multi-Criteria Decision Making Methods with Special Reference to Forest Management and Planning.” *Ecological Economics* 68 (10): 2535–48. https://doi.org/10.1016/j.ecolecon.2009.05.010.

Aquilue, Nuria. 2018. “MANAGING FOREST LANDSCAPES UNDER GLOBAL CHANGES: SIMULATION MODELS FOR SCENARIO EVALUATION.” https://doi.org/10.13140/RG.2.2.36008.01288.

Aquilué, Núria, Élise Filotas, Dylan Craven, Marie-Josée Fortin, Lluís Brotons, and Christian Messier. 2020. “Evaluating Forest Resilience to Global Threats Using Functional Response Traits and Network Properties.” *Ecological Applications* 30 (5): e02095. https://doi.org/10.1002/eap.2095.

Aquilué, Núria, Marie-Josée Fortin, Christian Messier, and Lluís Brotons. 2019. “The Potential of Agricultural Conversion to Shape Forest Fire Regimes in Mediterranean Landscapes.” *Ecosystems* 23 (1): 34–51. https://doi.org/10.1007/s10021-019-00385-7.

Aquilué, Núria, Christian Messier, Kyle T. Martins, Véronique Dumais-Lalonde, and Marco Mina. 2021a. “A Simple-to-Use Management Approach to Boost Adaptive Capacity of Forests to Global Uncertainty.” *Forest Ecology and Management* 481 (February):118692. https://doi.org/10.1016/j.foreco.2020.118692.

———. 2021b. “A Simple-to-Use Management Approach to Boost Adaptive Capacity of Forests to Global Uncertainty.” *Forest Ecology and Management* 481 (February):118692. https://doi.org/10.1016/j.foreco.2020.118692.

Arora, V. K., and G. J. Boer. 2010. “Uncertainties in the 20th Century Carbon Budget Associated with Land Use Change.” *Global Change Biology* 16 (12): 3327–48. https://doi.org/10.1111/j.1365-2486.2010.02202.x.

ASMI. 2012a. “A Cradle-to-Gate LCA of Canadian Glulam Manufacture–an Update.” Ottawa, Canada: Athena Sustainable Materials Institute.

———. 2012b. “A Cradle-to-Gate LCA of Canadian Oriented Strand Board - An Update.” Ottawa, Canada: Athena Sustainable Materials Institute.
———. 2012c. “A Cradle-to-Gate LCA of Canadian Softwood Plywood Sheathing.” Ottawa, Canada: Athena Sustainable Materials Institute.
———. 2012d. “A Cradle-to-Gate LCA of Canadian Surfaced Dry Softwood Lumber.” Ottawa, Canada: Athena Sustainable Materials Institute.
———. 2013a. “A Cradle-to-Gate LCA of Canadian Laminated Veneer Lumber (LVL) MANUFACTURE.” Ottawa, Canada: Athena Sustainable Materials Institute.
———. 2013b. “A Cradle-to-Gate LCA of Canadian Wood i-Joist Manufacture.” Ottawa, Canada: Athena Sustainable Materials Institute.
———. 2013c. “A LCA of Cross-Laminated Timber Produced in Canada.” Ottawa, Canada: Athena Sustainable Materials Institute.
———. 2018a. “A Cradle-to-Gate Life Cycle Assessment of Canadian Glulam.” Ottawa, Canada: Athena Sustainable Materials Institute.
———. 2018b. “A Cradle-to-Gate Life Cycle Assessment of Canadian Plywood.” Ottawa, Canada: Athena Sustainable Materials Institute.
———. 2018c. “A Cradle-to-Gate Life Cycle Assessment of Eastern Canadian Surfaced Dry Softwood Lumber.” Ottawa, Canada: Athena Sustainable Materials Institute.
Aubin, I., L. Boisvert-Marsh, H. Kebli, D. McKenney, J. Pedlar, K. Lawrence, E. H. Hogg, Y. Boulanger, S. Gauthier, and C. Ste-Marie. 2018. “Tree Vulnerability to Climate Change: Improving Exposure-Based Assessments Using Traits as Indicators of Sensitivity.” *Ecosphere* 9 (2): e02108. https://doi.org/10.1002/ecs2.2108.
Aubin, I., C. Messier, S Gatchet, K. Lawrence, D. McKenney, A. Arseneault, L. De Grandpré, B. Shipley, J.-P. Ricard, and A.D. Munson. 2012. “TOPIC - Traits of Plants in Canada.” [Internet] Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie, Ontario, Canada. https://www.nrcan.gc.ca/science-data/research-centres-labs/forestry-research-centres/great-lakes-forestry-centre/topic-network-traits-plants-canada-database-topic-and-canadian-repository-invertebrate-traits-and/20303.
Aubin, I., A.D. Munson, F. Cardou, P.J. Burton, N. Isabel, J.H. Pedlar, A. Paquette, et al. 2016. “Traits to Stay, Traits to Move: A Review of Functional Traits to Assess Sensitivity and Adaptive Capacity of Temperate and Boreal Trees to Climate Change.” *Environmental Reviews* 24 (2): 164–86. https://doi.org/10.1139/er-2015-0072.
Ayres, M. P., and M. J. Lombardero. 2000. “Assessing the Consequences of Global Change for Forest Disturbance from Herbivores and Pathogens.” *The Science of the Total Environment* 262 (3): 263–86. https://doi.org/10.1016/s0048-9697(00)00528-3.
Bartlett, Alastair I., Rory M. Hadden, and Luke A. Bisby. 2019. “A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction.” *Fire Technology* 55 (1): 1–49. https://doi.org/10.1007/s10694-018-0787-y.
Baumann, Henrikke. 1999. “An Evaluative Framework for Conceptual and Analytical Approaches Used in Environmental Management.” *Greener Management International*, no. 26, 109–22.
Borgatti, Stephen P., Ajay Mehra, Daniel J. Brass, and Giuseppe Labianca. 2009. “Network Analysis in the Social Sciences.” *Science* 323 (5916): 892–95. https://doi.org/10.1126/science.1165821.
Boulanger, Yan, Dominique Arseneault, Yan Boucher, Sylvie Gauthier, Dominic Cyr, Anthony R. Taylor, David T. Price, and Sébastien Dupuis. 2019. “Climate Change Will Affect the

Ability of Forest Management to Reduce Gaps between Current and Presettlement Forest Composition in Southeastern Canada." *Landscape Ecology* 34 (1): 159–74. https://doi.org/10.1007/s10980-018-0761-6.
Breton, Charles, Pierre Blanchet, Ben Amor, Robert Beauregard, and Wen-Shao Chang. 2018. "Assessing the Climate Change Impacts of Biogenic Carbon in Buildings: A Critical Review of Two Main Dynamic Approaches." *Sustainability* 10 (6): 2020. https://doi.org/10.3390/su10062020.
Brown, M.T. 2002. "Emergy Evaluations and Environmental Loading of Electricity Production Systems." *Journal of Cleaner Production* 10 (4): 321–34. https://doi.org/10.1016/S0959-6526(01)00043-9.
Bruijn, Arjan de, Eric J. Gustafson, Brian R. Sturtevant, Jane R. Foster, Brian R. Miranda, Nathanael I. Lichti, and Douglass F. Jacobs. 2014. "Toward More Robust Projections of Forest Landscape Dynamics under Novel Environmental Conditions: Embedding PnET within LANDIS-II." *Ecological Modelling* 287 (September):44–57. https://doi.org/10.1016/j.ecolmodel.2014.05.004.
Brunet-Navarro, Pau, Hubert Jochheim, and Bart Muys. 2016. "Modelling Carbon Stocks and Fluxes in the Wood Product Sector: A Comparative Review." *Global Change Biology* 22 (7): 2555–69. https://doi.org/10.1111/gcb.13235.
Brunetti, Michele, Michela Nocetti, Benedetto Pizzo, Francesco Negro, Giovanni Aminti, Paolo Burato, Corrado Cremonini, and Roberto Zanuttini. 2020. "Comparison of Different Bonding Parameters in the Production of Beech and Combined Beech-Spruce CLT by Standard and Optimized Tests Methods." *Construction and Building Materials* 265 (December):120168. https://doi.org/10.1016/j.conbuildmat.2020.120168.
Bunker, Stephen. 2005. "The Poverty of Resource Extraction." *Research in Rural Sociology and Development* 11 (November):211–26. https://doi.org/10.1016/S1057-1922(05)11008-7.
Bunker, Stephen G. 1985. *Underdeveloping the Amazon: Extraction, Unequal Exchange, and the Failure of the Modern State*. Urbana: University of Illinois Press.
Burton, Philip. 2013. "Exploring Complexity in Boreal Forests." In , 79–109. https://doi.org/10.13140/2.1.2422.6885.
Cadotte, Marc W., Kelly Carscadden, and Nicholas Mirotchnick. 2011. "Beyond Species: Functional Diversity and the Maintenance of Ecological Processes and Services." *Journal of Applied Ecology* 48 (5): 1079–87. https://doi.org/10.1111/j.1365-2664.2011.02048.x.
Canada, Environment and Climate Change. 2020. "Environment and Climate Change Canada." Organizational descriptions. October 28, 2020. https://www.canada.ca/en/environment-climate-change.html.
Canada, Natural Resources. 2014. "Taxonomy of Wood Products." Natural Resources Canada. January 23, 2014. https://natural-resources.canada.ca/our-natural-resources/forests/industry-and-trade/forest-products-applications/taxonomy-wood-products/14510.
———. 2017. "The TOPIC Network: Traits of Plants in Canada Database (TOPIC) and the Canadian Repository of Invertebrate Traits and Trait-like Ecological Records (CRITTER)." Natural Resources Canada. November 29, 2017. https://www.nrcan.gc.ca/science-data/research-centres-labs/forestry-research-centres/great-lakes-forestry-centre/topic-network-traits-plants-canada-database-topic-and-canadian-repository-invertebrate-traits-and/20303.

———. 2023. “Abstract Network Simulation Engine (ANSE).” Natural Resources Canada. January 27, 2023. https://natural-resources.canada.ca/climate-change/climate-change-impacts-forests/carbon-accounting/forest-carbon-accounting-tools/abstract-network-simulation-engine-anse/24901.

———. n.d. “Canadian Wildland Fire Information System | Interactive Map.” Accessed January 2, 2025. https://cwfis.cfs.nrcan.gc.ca/interactive-map.

Canada, Natural Resources, and Canadian Forest Service. 2020. “The State of Canada’s Forests. Annual Report 2020.” http://cfs.nrcan.gc.ca/publications?id=40219.

Canadian Wood Council. 2021. *Wood Design Manual, 2020: The Complete Reference for Wood Design in Canada*. 9th edition, 2021. Ottawa, Ontario, Canada: Canadian Wood Council.

Chen, Cindy X, Francesca Pierobon, and Indroneil Ganguly. 2019. “Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) Produced in Western Washington: The Role of Logistics and Wood Species Mix,” 17.

Chen, Jiaxin, Stephen J. Colombo, Michael T. Ter-Mikaelian, and Linda S. Heath. 2008. “Future Carbon Storage in Harvested Wood Products from Ontario’s Crown Forests.” *Canadian Journal of Forest Research* 38 (7): 1947–58. https://doi.org/10.1139/X08-046.

Cherubini, Francesco, Glen P. Peters, Terje Berntsen, Anders H. Strømman, and Edgar Hertwich. 2011. “CO2 Emissions from Biomass Combustion for Bioenergy: Atmospheric Decay and Contribution to Global Warming.” *GCB Bioenergy* 3 (5): 413–26. https://doi.org/10.1111/j.1757-1707.2011.01102.x.

Churkina, Galina, Alan Organschi, Christopher P. O. Reyer, Andrew Ruff, Kira Vinke, Zhu Liu, Barbara K. Reck, T. E. Graedel, and Hans Joachim Schellnhuber. 2020. “Buildings as a Global Carbon Sink.” *Nature Sustainability* 3 (4): 269–76. https://doi.org/10.1038/s41893-019-0462-4.

Cinelli, Marco, Stuart R. Coles, and Kerry Kirwan. 2014. “Analysis of the Potentials of Multi Criteria Decision Analysis Methods to Conduct Sustainability Assessment.” *Ecological Indicators* 46 (November):138–48. https://doi.org/10.1016/j.ecolind.2014.06.011.

Cordier, Sylvain, François Robichaud, Pierre Blanchet, and Ben Amor. 2019. “Exploring the Regional-Scale Potential of the Use of Wood Products in Non-Residential Buildings: A Building Permits-Based Quantitative Approach.” *BioResources* 15 (1): 787–813. https://doi.org/10.15376/biores.15.1.787-813.

Costanza, Robert. 2008. “Ecosystem Services: Multiple Classification Systems Are Needed.” *Biological Conservation* 141 (2): 350–52. https://doi.org/10.1016/j.biocon.2007.12.020.

Côté, Isabelle M., and Emily S. Darling. 2010. “Rethinking Ecosystem Resilience in the Face of Climate Change.” *PLOS Biology* 8 (7): e1000438. https://doi.org/10.1371/journal.pbio.1000438.

Craig, Salmaan, Anna Halepaska, Jacob Elbrecht, Katherine Ferguson, Preston Rains, Andrew Freear, David Kennedy, and Kiel Moe. 2020. “Buildings as a Global Carbon Sink? The Design of Mass Timber Panels as Heat-Exchangers (Dynamic Insulation),” August. https://doi.org/10.20944/preprints202008.0278.v1.

Craven, D., E. Filotas, V. A. Angers, and C. Messier. 2016. “Evaluating Resilience of Tree Communities in Fragmented Landscapes: Linking Functional Response Diversity with Landscape Connectivity.” *Diversity and Distributions* 22 (5): 505–18. https://doi.org/10.1111/ddi.12423.

Creutzburg, Megan K., Robert M. Scheller, Melissa S. Lucash, Stephen D. LeDuc, and Mark G. Johnson. 2017. “Forest Management Scenarios in a Changing Climate: Trade-Offs

between Carbon, Timber, and Old Forest." *Ecological Applications* 27 (2): 503–18. https://doi.org/10.1002/eap.1460.
Dale, M. R. T., and M. J. Fortin. 2010. "From Graphs to Spatial Graphs." *Annu Rev Ecol Evol Syst* 41. https://doi.org/10.1146/annurev-ecolsys-102209-144718.
Danneyrolles, Victor, Sébastien Dupuis, Gabriel Fortin, Marie Leroyer, André de Römer, Raphaële Terrail, Mark Vellend, et al. 2019. "Stronger Influence of Anthropogenic Disturbance than Climate Change on Century-Scale Compositional Changes in Northern Forests." *Nature Communications* 10 (1): 1265. https://doi.org/10.1038/s41467-019-09265-z.
DarrenRD. 2016. *2016 Fort McMurray Wildfire. Large Flames and Heavy Smoke Surround Congested Highway 63 South.* File:Landscape view of wildfire near Highway 63 in south Fort McMurray.jpg. https://commons.wikimedia.org/wiki/File:Landscape_view_of_wildfire_near_Highway_63_in_south_Fort_McMurray_(cropped).jpg.
Das, Sumanta, Miroslav Gašparík, Anil Kumar Sethy, Tomáš Kytka, Gourav Kamboj, and Fatemeh Rezaei. 2023. "Bonding Performance of Mixed Species Cross Laminated Timber from Poplar (Populus Nigra L.) and Maple (Acer Platanoides L.) Glued with Melamine and PUR Adhesive." *Journal of Building Engineering* 68 (June):106159. https://doi.org/10.1016/j.jobe.2023.106159.
DeFries, Ruth, and Harini Nagendra. 2017. "Ecosystem Management as a Wicked Problem." *Science* 356 (6335): 265–70. https://doi.org/10.1126/science.aal1950.
Desrochers, Michaël, Jennifer Pinna, Angela Fahdi, and Julien Beaulieu. 2022. "Forest Sector in Quebec – Circularity Assessment and Market Opportunities." CENTRE DE TRANSFERT TECHNOLOGIQUE EN ÉCOLOGIE INDUSTRIELLE.
Devuyst, Dimitri, Luc Hens, Walter De Lannoy, and W. de Lannoy. 2001. *How Green Is the City?: Sustainability Assessment and the Management of Urban Environments*. Columbia University Press.
Díaz, Sandra, Jens Kattge, Johannes H. C. Cornelissen, Ian J. Wright, Sandra Lavorel, Stéphane Dray, Björn Reu, et al. 2016. "The Global Spectrum of Plant Form and Function." *Nature* 529 (7585): 167–71. https://doi.org/10.1038/nature16489.
Diaz-Balteiro, Luis, and Carlos Romero. 2008. "Making Forestry Decisions with Multiple Criteria: A Review and an Assessment." *Forest Ecology and Management* 255 (8): 3222–41. https://doi.org/10.1016/j.foreco.2008.01.038.
Duncker, Philipp, Susana Barreiro, Geerten Hengeveld, Torgny Lind, William Mason, Slawomir Ambrozy, and Heinrich Spiecker. 2012. "Classification of Forest Management Approaches: A New Conceptual Framework and Its Applicability to European Forestry." *Ecology and Society* 17 (4). https://doi.org/10.5751/ES-05262-170451.
Duveneck, Matthew J, Robert M Scheller, Mark A White, Stephen D Handler, and Catherine Ravenscroft. 2014. "Climate Change Effects on Northern Great Lake (USA) Forests: A Case for Preserving Diversity." *Ecosphere* 5 (2): art23. https://doi.org/10.1890/ES13-00370.1.
Duveneck, Matthew J., Jonathan R. Thompson, Eric J. Gustafson, Yu Liang, and Arjan M. G. de Bruijn. 2017. "Recovery Dynamics and Climate Change Effects to Future New England Forests." *Landscape Ecology* 32 (7): 1385–97. https://doi.org/10.1007/s10980-016-0415-5.

Dymond, Caren C. 2012. “Forest Carbon in North America: Annual Storage and Emissions from British Columbia’s Harvest, 1965–2065.” *Carbon Balance and Management* 7 (1): 8. https://doi.org/10.1186/1750-0680-7-8.

Emmanuel, Arghiri. 1972. *Unequal Exchange; a Study of the Imperialism of Trade.* Modern Reader, PB-188. New York: [Monthly Review Press].

Ercin, Ertug, and Arjen Ysbert Hoekstra. 2012. *Carbon and Water Footprints : Concepts, Methodologies and Policy Responses*. United Nations Educational, Scientific and Cultural Organization (UNESCO). https://research.utwente.nl/en/publications/carbon-and-water-footprints-concepts-methodologies-and-policy-res.

Eyring, Veronika, Sandrine Bony, Gerald A. Meehl, Catherine A. Senior, Bjorn Stevens, Ronald J. Stouffer, and Karl E. Taylor. 2016. “Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) Experimental Design and Organization.” *Geoscientific Model Development* 9 (5): 1937–58. https://doi.org/10.5194/gmd-9-1937-2016.

Fahey, Robert T., Brandon C. Alveshere, Julia I. Burton, Anthony W. D’Amato, Yvette L. Dickinson, William S. Keeton, Christel C. Kern, et al. 2018. “Shifting Conceptions of Complexity in Forest Management and Silviculture.” *Forest Ecology and Management*, Special issue on Linking basic and applied research in North American forest ecosystems – the 11th North American Forest Ecology Workshop, 421 (August):59–71. https://doi.org/10.1016/j.foreco.2018.01.011.

Fall, Andrew, Marie-Josée Fortin, Micheline Manseau, and Dan O’Brien. 2007. “Spatial Graphs: Principles and Applications for Habitat Connectivity.” *Ecosystems* 10 (3): 448–61. https://doi.org/10.1007/s10021-007-9038-7.

Felton, Adam, Rupert Seidl, David B. Lindenmayer, Christian Messier, Magnus Löf, Johannes H. C. De Koning, Thomas Ranius, et al. 2024. “The Choice of Path to Resilience Is Crucial to the Future of Production Forests.” *Nature Ecology & Evolution*, July. https://doi.org/10.1038/s41559-024-02473-x.

Fenner, Andriel Evandro, Charles Joseph Kibert, Junghoon Woo, Shirley Morque, Mohamad Razkenari, Hamed Hakim, and Xiaoshu Lu. 2018. “The Carbon Footprint of Buildings: A Review of Methodologies and Applications.” *Renewable and Sustainable Energy Reviews* 94 (October):1142–52. https://doi.org/10.1016/j.rser.2018.07.012.

Filotas, E., L. Parrott, P. J. Burton, R. L. Chazdon, K. D. Coates, L. Coll, S. Haeussler, et al. 2014. “Viewing Forests through the Lens of Complex Systems Science.” *Ecosphere* 5. https://doi.org/10.1890/ES13-00182.1.

Finnveden, Goran, and Asa Moberg. 2005. “Environmental Systems Analysis Tools – an Overview.” *Journal of Cleaner Production* 13 (12): 1165–73. https://doi.org/10.1016/j.jclepro.2004.06.004.

Folke, Carl. 2006. “Resilience: The Emergence of a Perspective for Social–Ecological Systems Analyses.” *Global Environmental Change* 16 (3): 253–67. https://doi.org/10.1016/j.gloenvcha.2006.04.002.

Foster, John Bellamy, and Hannah Holleman. 2014. “The Theory of Unequal Ecological Exchange: A Marx-Odum Dialectic.” *Journal of Peasant Studies* 41 (2): 199–233. https://doi.org/10.1080/03066150.2014.889687.

Franklin, Jerry F., David Lindenmayer, James A. MacMahon, Arthur McKee, John Magnuson, David A. Perry, Robert Waide, and David Foster. 2000. “Threads of Continuity.” *Conservation in Practice* 1 (1): 8–17. https://doi.org/10.1111/j.1526-4629.2000.tb00155.x.

Gasparatos, Alexandros, Mohamed El-Haram, and Malcolm Horner. 2008. “A Critical Review of Reductionist Approaches for Assessing the Progress towards Sustainability.” *Environmental Impact Assessment Review* 28 (4): 286–311. https://doi.org/10.1016/j.eiar.2007.09.002.

Geng, Aixin, Hongqiang Yang, Jiaxin Chen, and Yinxing Hong. 2017. “Review of Carbon Storage Function of Harvested Wood Products and the Potential of Wood Substitution in Greenhouse Gas Mitigation.” *Forest Policy and Economics* 85 (December):192–200. https://doi.org/10.1016/j.forpol.2017.08.007.

Gérard, Jean, Guibal, Daniel, Paradis, Sébastien, Vernay, Michel, Beauchêne, Jacques, Brancheriau, Loïc, Châlon, Isabelle, et al. 2011. “Tropix 7.” Application/x-msdownload. CIRAD. https://doi.org/10.18167/74726F706978.

Gibson, Robert B., Meinhard Doelle, and A. John Sinclair. 2015. “Fulfilling the Promise: Basic Components of Next Generation Environmental Assessment.” SSRN Scholarly Paper ID 2670009. Rochester, NY: Social Science Research Network. https://papers.ssrn.com/abstract=2670009.

Givens, Jennifer E., Xiaorui Huang, and Andrew K. Jorgenson. 2019. “Ecologically Unequal Exchange: A Theory of Global Environmental Injustice.” *Sociology Compass* 13 (5). https://doi.org/10.1111/soc4.12693.

Gonzalès, Rodolphe, and Lael Parrott. 2012. “Network Theory in the Assessment of the Sustainability of Social–Ecological Systems.” *Geography Compass* 6 (2): 76–88. https://doi.org/10.1111/j.1749-8198.2011.00470.x.

Government of Canada, Public Services and Procurement Canada. 2002. “National Inventory Report : Greenhouse Gas Sources and Sinks in Canada.: En81-4E-PDF - Government of Canada Publications - Canada.Ca.” July 1, 2002. https://publications.gc.ca/site/eng/9.506002/publication.html.

“Grades.” n.d. The Canadian Wood Council - CWC. Accessed October 7, 2022. https://cwc.ca/en/how-to-build-with-wood/wood-products/lumber/grades/.

Guest, Geoffrey, Francesco Cherubini, and Anders H. Strømman. 2013. “Global Warming Potential of Carbon Dioxide Emissions from Biomass Stored in the Anthroposphere and Used for Bioenergy at End of Life.” *Journal of Industrial Ecology* 17 (1): 20–30. https://doi.org/10.1111/j.1530-9290.2012.00507.x.

Gül, Atila, Abdullah Gezer, and Brian Kane. 2006. “Multi-Criteria Analysis for Locating New Urban Forests: An Example from Isparta, Turkey.” *Urban Forestry & Urban Greening* 5 (2): 57–71. https://doi.org/10.1016/j.ufug.2006.05.003.

Gunderson, Lance H. 2000. “Ecological Resilience--In Theory and Application.” *Annual Review of Ecology and Systematics* 31:425–39.

———. 2001. *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press.

Gustafson, Eric J, Stephen R Shifley, David J Mladenoff, Kevin K Nimerfro, and Hong S He. 2000. “Spatial Simulation of Forest Succession and Timber Harvesting Using LANDIS.” *Canadian Journal of Forest Research* 30 (1): 32–43. https://doi.org/10.1139/x99-188.

Halverson, Steve, and Stan Lebow. 2022. “Observed Relationships between Wood Density and Solution Uptake during Pressure Treatment.” *Proceedings, One Hundred Seventh Annual Meeting of the American Wood Protection Association ... Fort Lauderdale, Florida, May 15-17, 2011: Volume 107. Birmingham, Ala. : American Wood Protection Association, C2011: P. 93-98.*, March. https://research.fs.usda.gov/treesearch/40824.

Handl, Julia, Joshua Knowles, and Douglas B. Kell. 2005. “Computational Cluster Validation in Post-Genomic Data Analysis.” *Bioinformatics* 21 (15): 3201–12. https://doi.org/10.1093/bioinformatics/bti517.

Head, Marieke, Pierre Bernier, Annie Levasseur, Robert Beauregard, and Manuele Margni. 2019. “Forestry Carbon Budget Models to Improve Biogenic Carbon Accounting in Life Cycle Assessment.” *Journal of Cleaner Production* 213 (March):289–99. https://doi.org/10.1016/j.jclepro.2018.12.122.

Head, Marieke, Michael Magnan, Werner A. Kurz, Annie Levasseur, Robert Beauregard, and Manuele Margni. 2021. “Temporally-Differentiated Biogenic Carbon Accounting of Wood Building Product Life Cycles.” *SN Applied Sciences* 3 (1): 62. https://doi.org/10.1007/s42452-020-03979-2.

Helin, Tuomas, Laura Sokka, Sampo Soimakallio, Kim Pingoud, and Tiina Pajula. 2013. “Approaches for Inclusion of Forest Carbon Cycle in Life Cycle Assessment – a Review.” *GCB Bioenergy* 5 (5): 475–86. https://doi.org/10.1111/gcbb.12016.

Hennigar, Chris R., David A. MacLean, and Luke J. Amos-Binks. 2008. “A Novel Approach to Optimize Management Strategies for Carbon Stored in Both Forests and Wood Products.” *Forest Ecology and Management* 256 (4): 786–97. https://doi.org/10.1016/j.foreco.2008.05.037.

Himes, Austin, and Gwen Busby. 2020. “Wood Buildings as a Climate Solution.” *Developments in the Built Environment* 4 (November):100030. https://doi.org/10.1016/j.dibe.2020.100030.

Hoang, Nguyen Tien, and Keiichiro Kanemoto. 2021. “Mapping the Deforestation Footprint of Nations Reveals Growing Threat to Tropical Forests.” *Nature Ecology & Evolution*, March. https://doi.org/10.1038/s41559-021-01417-z.

Holling, C S. 1973. “Resilience and Stability of Ecological Systems.” *Annual Review of Ecology and Systematics* 4 (1): 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245.

Holling, C. S., and Gary K. Meffe. 1996. “Command and Control and the Pathology of Natural Resource Management.” *Conservation Biology* 10 (2): 328–37. https://doi.org/10.1046/j.1523-1739.1996.10020328.x.

Hornborg A. 2009. “Zero-Sum World: Challenges in Conceptualizing Environmental Load Displacement and Ecologically Unequal Exchange in the World-System.” *International Journal of Comparative Sociology* 50 (3–4): 237–62. https://doi.org/10.1177/0020715209105141.

Hornborg, Alf. 1998. “Towards an Ecological Theory of Unequal Exchange: Articulating World System Theory and Ecological Economics.” *Ecological Economics* 25 (1): 127–36. https://doi.org/10.1016/S0921-8009(97)00100-6.

———. 2012. *Global Ecology and Unequal Exchange : Fetishism in a Zero-Sum World*. Routledge. https://doi.org/10.4324/9780203806890.

Hoxha, Endrit, Alexander Passer, Marcella Ruschi Mendes Saade, Damien Trigaux, Amie Shuttleworth, Francesco Pittau, Karen Allacker, and Guillaume Habert. 2020. “Biogenic Carbon in Buildings: A Critical Overview of LCA Methods.” *Buildings and Cities* 1 (1): 504–24. https://doi.org/10.5334/bc.46.

Huang, Ivy B., Jeffrey Keisler, and Igor Linkov. 2011. “Multi-Criteria Decision Analysis in Environmental Sciences: Ten Years of Applications and Trends.” *Science of The Total Environment* 409 (19): 3578–94. https://doi.org/10.1016/j.scitotenv.2011.06.022.

Ibañez, Daniel, Jane Hutton, and Kiel Moe, eds. 2020. *Wood Urbanism: From the Molecular to the Territorial*. English edition. New York ; Barcelona: Actar.
"Inside Wood - Search the Inside Wood Database." n.d. Accessed March 21, 2022. https://insidewood.lib.ncsu.edu/search;jsessionid=N3mOEyfXYLEpluWQG_JqUg7Cyw7BagZt2n95Dgm1?1.
Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES. 2016. "The Methodological Assessment Report on Scenarios and Models of Biodiversity and Ecosystem Services." Zenodo. https://doi.org/10.5281/ZENODO.3235428.
IPCC. 2014. *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part B: Regional Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report: Volume 2: Regional Aspects*. Vol. 2. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107415386.
———. 2019. "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories — IPCC." https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/.
———. 2023. *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009325844.
Jactel, Hervé, Jürgen Bauhus, Johanna Boberg, Damien Bonal, Bastien Castagneyrol, Barry Gardiner, Jose Ramon Gonzalez-Olabarria, Julia Koricheva, Nicolas Meurisse, and Eckehard G. Brockerhoff. 2017. "Tree Diversity Drives Forest Stand Resistance to Natural Disturbances." *Current Forestry Reports* 3 (3): 223–43. https://doi.org/10.1007/s40725-017-0064-1.
Jahedi, Sina, Lech Muszynski, Mariapaola Riggio, and Rakesh Gupta. 2019. "Evaluation of Bond Integrity in Low-Value Blue-Stain Ponderosa Pine CLT." In *Proceedings of the 62nd International Convention of Society of Wood Science and Technology*. enaya Lodge, Yosemite, California USA.
Jalilova, Gulnaz, Chiranjeewee Khadka, and Harald Vacik. 2012. "Developing Criteria and Indicators for Evaluating Sustainable Forest Management: A Case Study in Kyrgyzstan." *Forest Policy and Economics* 21 (August):32–43. https://doi.org/10.1016/j.forpol.2012.01.010.
Janssen, Marco, Örjan Bodin, John Anderies, Thomas Elmqvist, Henrik Ernstson, Ryan R. J. McAllister, Per Olsson, and Paul Ryan. 2006. "Toward a Network Perspective of the Study of Resilience in Social-Ecological Systems." *Ecology and Society* 11 (1). https://doi.org/10.5751/ES-01462-110115.
Jantz, Patrick, Scott Goetz, and Nadine Laporte. 2014. "Carbon Stock Corridors to Mitigate Climate Change and Promote Biodiversity in the Tropics." *Nature Climate Change* 4 (2): 138–42. https://doi.org/10.1038/nclimate2105.
Jeswani, Harish Kumar, Adisa Azapagic, Philipp Schepelmann, and Michael Ritthoff. 2010. "Options for Broadening and Deepening the LCA Approaches." *Journal of Cleaner Production* 18 (2): 120–27. https://doi.org/10.1016/j.jclepro.2009.09.023.
Jost, Lou. 2006. "Entropy and Diversity." *Oikos* 113 (2): 363–75. https://doi.org/10.1111/j.2006.0030-1299.14714.x.
Kaboli, Hamid, Peggi L. Clouston, and Seth Lawrence. 2020. "Feasibility of Two Northeastern Species in Three-Layer ANSI-Approved Cross-Laminated Timber." *Journal of Materials*

*in Civil Engineering* 32 (3): 04020006. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003058.
Kalt, Gerald. 2018. “Carbon Dynamics and GHG Implications of Increasing Wood Construction: Long-Term Scenarios for Residential Buildings in Austria.” *Carbon Management* 9 (3): 265–75. https://doi.org/10.1080/17583004.2018.1469948.
Kangas, Annika, Jyrki Kangas, and Mikko Kurttila. 2008. *Decision Support for Forest Management*. Managing Forest Ecosystems. Springer Netherlands. https://doi.org/10.1007/978-1-4020-6787-7.
Karvonen, Jaakko, Pradipta Halder, Jyrki Kangas, and Pekka Leskinen. 2017. “Indicators and Tools for Assessing Sustainability Impacts of the Forest Bioeconomy.” *Forest Ecosystems* 4 (1): 2. https://doi.org/10.1186/s40663-017-0089-8.
Kates, Robert W., William C. Clark, Robert Corell, J. Michael Hall, Carlo C. Jaeger, Ian Lowe, James J. McCarthy, et al. 2001. “Sustainability Science.” *Science* 292 (5517): 641–42. https://doi.org/10.1126/science.1059386.
Kattge, Jens, Gerhard Bönisch, Sandra Díaz, Sandra Lavorel, Iain Colin Prentice, Paul Leadley, Susanne Tautenhahn, et al. 2020. “TRY Plant Trait Database – Enhanced Coverage and Open Access.” *Global Change Biology* 26 (1): 119–88. https://doi.org/10.1111/gcb.14904.
Kay, J. J. 2002. “On Complexity Theory, Exergy and Industrial Ecology. Some Implications for Construction Ecology.” In *Construction Ecology: Nature as the Basis for Green Buildings*, edited by Charles J. Kibert, Jan Sendzimir, and G. Bradley Guy, 72–107. Taylor & Francis.
Kayo, Chihiro, Toshiya Aramaki, and Keisuke Hanaki. 2011. “Effect of Change of Forest Carbon Storage on Net Carbon Dioxide Balance of Wood Use for Energy in Japan.” *Journal of Industrial Ecology* 15 (1): 122–36. https://doi.org/10.1111/j.1530-9290.2010.00308.x.
Kibert, Charles J., Jan Sendzimir, and G. Bradley Guy. 2002. *Construction Ecology: Nature as the Basis for Green Buildings*. Taylor & Francis.
Kissinger, Meidad, William E. Rees, and Vanessa Timmer. 2011. “Interregional Sustainability: Governance and Policy in an Ecologically Interdependent World.” *Environmental Science & Policy* 14 (8): 965–76. https://doi.org/10.1016/j.envsci.2011.05.007.
Kosoy, Nicolás, and Esteve Corbera. 2010. “Payments for Ecosystem Services as Commodity Fetishism.” *Ecological Economics*, Special Section - Payments for Environmental Services: Reconciling Theory and Practice, 69 (6): 1228–36. https://doi.org/10.1016/j.ecolecon.2009.11.002.
Krackler, Verena, Daniel Keunecke, Peter Niemz, and Andreas Hurst. 2011. “POSSIBLE FIELDS OF HARDWOOD APPLICATION.” *WOOD RESEARCH* 56.
Krause, Ann E., Kenneth A. Frank, Doran M. Mason, Robert E. Ulanowicz, and William W. Taylor. 2003. “Compartments Revealed in Food-Web Structure.” *Nature* 426 (6964): 282–85. https://doi.org/10.1038/nature02115.
Kull, S. J., G. J. Rampley, S. Morken, J. M. Metsaranta, E. T. Neilson, and W. A. Kurz. 2019. *Operational-Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Version 1.2: User’s Guide. 2019.* http://cfs.nrcan.gc.ca/publications?id=39768.
Kurz, W. A., C. C. Dymond, T. M. White, G. Stinson, C. H. Shaw, G. J. Rampley, C. Smyth, et al. 2009. “CBM-CFS3: A Model of Carbon-Dynamics in Forestry and Land-Use Change

Implementing IPCC Standards.” *Ecological Modelling* 220 (4): 480–504. https://doi.org/10.1016/j.ecolmodel.2008.10.018.

Kurz, Werner A, Graham Stinson, and Greg Rampley. 2008. “Could Increased Boreal Forest Ecosystem Productivity Offset Carbon Losses from Increased Disturbances?” *Philosophical Transactions of the Royal Society B: Biological Sciences* 363 (1501): 2261–69. https://doi.org/10.1098/rstb.2007.2198.

Kurz, Werner, Cindy Shaw, Céline Boisvenue, Graham Stinson, J. Metsaranta, Don Leckie, Andrew Dyk, Carolyn Smyth, and Eric Neilson. 2013. “Carbon in Canada’s Boreal Forest — A Synthesis W.A. Kurz, C.H. Shaw, C. Boisvenue, G. Stinson, J. Metsaranta, D. Leckie, A. Dyk, C. Smyth, E.T. Neilson Environmental Reviews, 2013, 21:260-292, 10.1139/Er-2013-0041.” *Environmental Reviews* 21 (January):260–92.

La Notte, Alessandra, Dalia D’Amato, Hanna Mäkinen, Maria Luisa Paracchini, Camino Liquete, Benis Egoh, Davide Geneletti, and Neville D. Crossman. 2017. “Ecosystem Services Classification: A Systems Ecology Perspective of the Cascade Framework.” *Ecological Indicators* 74 (March):392–402. https://doi.org/10.1016/j.ecolind.2016.11.030.

Laliberté, Etienne, and Pierre Legendre. 2010. “A Distance-Based Framework for Measuring Functional Diversity from Multiple Traits.” *Ecology* 91 (1): 299–305. https://doi.org/10.1890/08-2244.1.

Lang, Daniel J., Arnim Wiek, Matthias Bergmann, Michael Stauffacher, Pim Martens, Peter Moll, Mark Swilling, and Christopher J. Thomas. 2012. “Transdisciplinary Research in Sustainability Science: Practice, Principles, and Challenges.” *Sustainability Science* 7 (1): 25–43. https://doi.org/10.1007/s11625-011-0149-x.

Larson, Christopher, Jeffrey Chatellier, Reid Lifset, and Thomas Graedel. 2012. “Role of Forest Products in the Global Carbon Cycle: From the Forest to Final Disposal.” In *Managing Forest Carbon in a Changing Climate*, edited by Mark S. Ashton, Mary L. Tyrrell, Deborah Spalding, and Bradford Gentry, 257–82. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-2232-3_12.

Laughlin, Daniel C. 2014. “Applying Trait-Based Models to Achieve Functional Targets for Theory-Driven Ecological Restoration.” *Ecology Letters* 17 (7): 771–84. https://doi.org/10.1111/ele.12288.

Laughlin, Daniel C., Robert T. Strahan, David W. Huffman, and Andrew J. Sánchez Meador. 2017. “Using Trait-Based Ecology to Restore Resilient Ecosystems: Historical Conditions and the Future of Montane Forests in Western North America.” *Restoration Ecology* 25 (S2): S135–46. https://doi.org/10.1111/rec.12342.

Lecina-Diaz, Judit, Albert Alvarez, Adrián Regos, Pierre Drapeau, Alain Paquette, Christian Messier, and Javier Retana. 2018. “The Positive Carbon Stocks-Biodiversity Relationship in Forests: Co-Occurrence and Drivers across Five Subclimates.” *Ecological Applications: A Publication of the Ecological Society of America* 28 (6): 1481–93. https://doi.org/10.1002/eap.1749.

Lemprière, T.C., W.A. Kurz, E.H. Hogg, C. Schmoll, G.J. Rampley, D. Yemshanov, D.W. McKenney, et al. 2013. “Canadian Boreal Forests and Climate Change Mitigation.” *Environmental Reviews* 21 (4): 293–321. https://doi.org/10.1139/er-2013-0039.

Leontief, Wassily. 1970. “Environmental Repercussions and the Economic Structure: An Input-Output Approach.” *The Review of Economics and Statistics* 52 (3): 262–71.

———. 1986. *Input-Output Economics*. 2nd ed. New York: Oxford University Press. http://www.gbv.de/dms/bowker/toc/9780195035278.pdf.

Levasseur, Annie, Pascal Lesage, Manuele Margni, Louise Deschênes, and Réjean Samson. 2010. “Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments.” *Environmental Science & Technology* 44 (8): 3169–74. https://doi.org/10.1021/es9030003.

Levasseur, Annie, Pascal Lesage, Manuele Margni, and Réjean Samson. 2013. “Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment.” *Journal of Industrial Ecology* 17 (1): 117–28. https://doi.org/10.1111/j.1530-9290.2012.00503.x.

Levin, Simon A. 1999. *Fragile Dominion: Complexity and the Commons*. Helix Books. Reading, Mass.: Perseus Books. http://catdir.loc.gov/catdir/enhancements/fy0830/99061538-d.html.

———. 2005. “Self-Organization and the Emergence of Complexity in Ecological Systems.” *BioScience* 55 (12): 1075–79. https://doi.org/10.1641/0006-3568(2005)055[1075:SATEOC]2.0.CO;2.

Li, Mingyue, and Haiqing Ren. 2022. “Study on the Interlaminar Shear Properties of Hybrid Cross-Laminated Timber (HCLT) Prepared with Larch, Poplar and OSB.” *Industrial Crops and Products* 189 (December):115756. https://doi.org/10.1016/j.indcrop.2022.115756.

Lindborg, Regina, and Ove Eriksson. 2004. “Historical Landscape Connectivity Affects Present Plant Species Diversity.” *Ecology* 85 (7): 1840–45. https://doi.org/10.1890/04-0367.

Lindner, Marcus, Michael Maroschek, Sigrid Netherer, Antoine Kremer, Anna Barbati, Jordi Garcia-Gonzalo, Rupert Seidl, et al. 2010. “Climate Change Impacts, Adaptive Capacity, and Vulnerability of European Forest Ecosystems.” *Forest Ecology and Management*, Adaptation of Forests and Forest Management to Changing Climate, 259 (4): 698–709. https://doi.org/10.1016/j.foreco.2009.09.023.

Liu, J., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, et al. 2007. “Complexity of Coupled Human and Natural Systems.” *Science* 317 (5844): 1513–16. https://doi.org/10.1126/science.1144004.

Lucey, Taylor K., Nadia Tase, Prakash Nepal, Richard D. Bergman, David L. Nicholls, Poonam Khatri, Kamalakanta Sahoo, and Andrew N. Gray. 2024. “A Synthesis of Harvested Wood Product Carbon Models.” *Gen. Tech. Rep. PNW-GTR-1020. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 73 p.* 1020. https://doi.org/10.2737/PNW-GTR-1020.

Marchi, Enrico, Woodam Chung, Rien Visser, Dalia Abbas, Tomas Nordfjell, Piotr S. Mederski, Andrew McEwan, Michal Brink, and Andrea Laschi. 2018. “Sustainable Forest Operations (SFO): A New Paradigm in a Changing World and Climate.” *Science of The Total Environment* 634 (September):1385–97. https://doi.org/10.1016/j.scitotenv.2018.04.084.

Martinez-Alier, Joan. 2002. *The Environmentalism of the Poor: A Study of Ecological Conflicts and Valuation*. 1 online resource (xi, 312 pages) vols. Northhampton, MA: Edward Elgar Pub. http://public.ebookcentral.proquest.com/choice/publicfullrecord.aspx?p=472042.

Martin-Fernandez, Susana, and Eugenio Martinez-Falero. 2018. “Sustainability Assessment in Forest Management Based on Individual Preferences.” *Journal of Environmental Management* 206 (January):482–89. https://doi.org/10.1016/j.jenvman.2017.10.057.

Mayer, Audrey L. 2008. “Strengths and Weaknesses of Common Sustainability Indices for Multidimensional Systems.” *Environment International* 34 (2): 277–91. https://doi.org/10.1016/j.envint.2007.09.004.

Messier, C., K. Puettmann, R. Chazdon, K. P. Andersson, V. A. Angers, L. Brotons, E. Filotas, R. Tittler, L. Parrott, and S. A. Levin. 2015. “From Management to Stewardship: Viewing Forests As Complex Adaptive Systems in an Uncertain World.” *Conservation Letters* 8 (5): 368–77. https://doi.org/10.1111/conl.12156.

Messier, C., K. J. Puettmann, and K. D. Coates. 2013. *Managing Forests as Complex Adaptive Systems: Building Resilience to the Challenge of Global Change*. New York: Routledge.

Messier, Christian, Jürgen Bauhus, Frederik Doyon, Fanny Maure, Rita Sousa-Silva, Philippe Nolet, Marco Mina, Núria Aquilué, Marie-Josée Fortin, and Klaus Puettmann. 2019. “The Functional Complex Network Approach to Foster Forest Resilience to Global Changes.” *Forest Ecosystems* 6 (1): 21. https://doi.org/10.1186/s40663-019-0166-2.

Messier, Christian, Klaus Puettmann, Elise Filotas, and Dave Coates. 2016. “Dealing with Non-Linearity and Uncertainty in Forest Management.” *Current Forestry Reports* 2 (2): 150–61. https://doi.org/10.1007/s40725-016-0036-x.

Messier, Christian, Klaus J. Puettmann, and K. David Coates. 2013. *Managing Forests as Complex Adaptive Systems: Building Resilience to the Challenge of Global Change*. Routledge.

Metzger, Jean, Pedro Fidelman, Claudia Sattler, Barbara Schröter, Martine Maron, Felix Eigenbrod, Marie-Josee Fortin, Camila Hohlenwerger, and Jonathan Rhodes. 2020. “Connecting Governance Interventions to Ecosystem Services Provision: A Social-ecological Network Approach.” *People and Nature*, November. https://doi.org/10.1002/pan3.10172.

Miles, Patrick D., and W. Brad Smith. 2022. “Specific Gravity and Other Properties of Wood and Bark for 156 Tree Species Found in North America.” *Res. Note NRS-38. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 35 p.*, March. https://doi.org/10.2737/NRS-RN-38.

Mina, Marco, Markus O. Huber, David I. Forrester, Esther Thürig, and Brigitte Rohner. 2018. “Multiple Factors Modulate Tree Growth Complementarity in Central European Mixed Forests.” *Journal of Ecology* 106 (3): 1106–19. https://doi.org/10.1111/1365-2745.12846.

Mina, Marco, Christian Messier, Matthew Duveneck, Marie-Josée Fortin, and Núria Aquilué. 2020. “Network Analysis Can Guide Resilience-Based Management in Forest Landscapes under Global Change.” *Ecological Applications* n/a (n/a): e2221. https://doi.org/10.1002/eap.2221.

Mina, Marco, Christian Messier, Matthew J. Duveneck, Marie-Josée Fortin, and Núria Aquilué. 2022. “Managing for the Unexpected: Building Resilient Forest Landscapes to Cope with Global Change.” *Global Change Biology* n/a (n/a). https://doi.org/10.1111/gcb.16197.

Moe, Kiel. 2017. *Empire, State & Building*. Actar.

Moore, John R., Andrew J. Lyon, and Stefan Lehneke. 2012. “Effects of Rotation Length on the Grade Recovery and Wood Properties of Sitka Spruce Structural Timber Grown in Great Britain.” *Annals of Forest Science* 69 (3): 353–62. https://doi.org/10.1007/s13595-011-0168-x.

Mori, Akira S., Takuya Furukawa, and Takehiro Sasaki. 2013. “Response Diversity Determines the Resilience of Ecosystems to Environmental Change.” *Biological Reviews of the Cambridge Philosophical Society* 88 (2): 349–64. https://doi.org/10.1111/brv.12004.

Morris, P I. n.d. "Understanding Biodeterioration of Wood in Structures," 26.
Munda, Giuseppe. 2005. "Multiple Criteria Decision Analysis and Sustainable Development." In *Multiple Criteria Decision Analysis: State of the Art Surveys*, edited by JosÉ Figueira, Salvatore Greco, and Matthias Ehrogott, 953–86. International Series in Operations Research & Management Science. New York, NY: Springer. https://doi.org/10.1007/0-387-23081-5_23.
Muszynski, Lech, Mariapaola Riggio, Rakesh Gupta, and Jeff Morrell. 2022. "Defining Custom CLT Grade Utilizing Low-Value Ponderosa Pine." TallWood Design Institute. 2022. https://tallwoodinstitute.org/defining-custom-clt-grade-utilizing-low-value-ponderosa-pine/.
"Naturally:Wood | British Columbia's Sustainable Forestry Resource." n.d. Naturally:Wood. Accessed December 16, 2024. https://www.naturallywood.com/.
Ness, Barry, Evelin Urbel-Piirsalu, Stefan Anderberg, and Lennart Olsson. 2007. "Categorising Tools for Sustainable Assessment." *Ecological Economics* 60 (January):498–508. https://doi.org/10.1016/j.ecolecon.2006.07.023.
Ni, Yuanming, Gunnar S. Eskeland, Jarl Giske, and Jan-Petter Hansen. 2016. "The Global Potential for Carbon Capture and Storage from Forestry." *Carbon Balance and Management* 11 (1): 1–8. https://doi.org/10.1186/s13021-016-0044-y.
Niinemets, Ülo, and Fernando Valladares. 2006. "Tolerance to Shade, Drought, and Waterlogging of Temperate Northern Hemisphere Trees and Shrubs." *Ecological Monographs* 76 (4): 521–47. https://doi.org/10.1890/0012-9615(2006)076[0521:TTSDAW]2.0.CO;2.
NLGA. 2022. "STANDARD GRADING RULES for CANADIAN LUMBER." National Lumber Grades Authority (NLGA). https://nlga.org/en/.
Nordström, Eva-Maria, Ljusk Ola Eriksson, and Karin Öhman. 2010. "Integrating Multiple Criteria Decision Analysis in Participatory Forest Planning: Experience from a Case Study in Northern Sweden." *Forest Policy and Economics* 12 (8): 562–74. https://doi.org/10.1016/j.forpol.2010.07.006.
Núñez-Florez, Rafael, Uriel Pérez-Gómez, and Fernando Fernández-Méndez. 2019. "Functional Diversity Criteria for Selecting Urban Trees." *Urban Forestry & Urban Greening* 38 (February):251–66. https://doi.org/10.1016/j.ufug.2019.01.005.
Nygaard, Marius, Isaak Elias Skjeseth Bashevkin, Ute Groba, and Catherine Sunter. 2019. "Increased Use of Timber in New Buildings in Oslo and Akershus: Potentials and GHG Emission Effects." *Frontiers in Built Environment* 5. https://www.frontiersin.org/articles/10.3389/fbuil.2019.00131.
Odum, Howard T. 1996. *Environmental Accounting: EMERGY and Environmental Decision Making*. New York: Wiley. http://catdir.loc.gov/catdir/toc/onix04/95011683.html.
———. 2002. "Material Circulation, Energy Hierarchy, and Building Construction." In *Construction Ecology: Nature as the Basis for Green Buildings*, edited by Charles J. Kibert, Jan Sendzimir, and G. Bradley Guy, 37–71. Taylor & Francis.
Odum, Howard T., and Elisabeth C. Odum. 2001. *A Prosperous Way down: Principles and Policies*. 1 online resource (345 pages) : illustrations vols. Boulder, Colorado: University Press of Colorado. http://site.ebrary.com/id/10761475.
Oliver, C. D. 2001. "Policies and Practices: Options for Pursuing Forest Sustainability." *FORESTRY CHRONICLE* 77 (Part 1): 49–60.

———. 2017. “The Bumpy Road to Ecosystem Management.” *Journal of Forestry* 115 (1): 66–67.

Oliver C.D. 2014. “Functional Restoration of Social-Forestry Systems Across Spatial and Temporal Scales.” *Journal of Sustainable Forestry* 33 (SUP1): S123–48. https://doi.org/10.1080/10549811.2014.884003.

Oliver C.D., Nassar N.T., Lippke B.R., and McCarter J.B. 2014. “Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests.” *Journal of Sustainable Forestry* 33 (3): 248–75. https://doi.org/10.1080/10549811.2013.839386.

Oliver, Chadwick Dearing, and Bruce C. Larson. 1996. *Forest Stand Dynamics*. Update ed. New York: Wiley. http://catdir.loc.gov/catdir/toc/onix03/96148932.html.

Osborne, Peter. 2022. “Forest-Building: Exploring Carbon Sequestration in Wood Buildings and Forests with System Dynamics Modelling.” In *Structures and Architecture A Viable Urban Perspective?*, by Paulo J.S. Cruz and Marie Frier Hvejsel, 1st ed., 279–86. London: CRC Press. https://doi.org/10.1201/9781003023555-34.

Osborne, Peter, Núria Aquilué, Marco Mina, Kiel Moe, Michael Jemtrud, and Christian Messier. 2023. “A Trait-Based Approach to Both Forestry and Timber Building Can Synchronize Forest Harvest and Resilience.” *PNAS Nexus* 2 (8): pgad254. https://doi.org/10.1093/pnasnexus/pgad254.

Ouranos. 2015. “Towards Adaptation. Summary of the Synthesis on Climate Change Knowledge in Quebec.” 2015. https://www.ouranos.ca/publication-scientifique/SyntheseRapportfinal.pdf.

Pan, Yude, Richard A. Birdsey, Oliver L. Phillips, Richard A. Houghton, Jingyun Fang, Pekka E. Kauppi, Heather Keith, et al. 2024. “The Enduring World Forest Carbon Sink.” *Nature* 631 (8021): 563–69. https://doi.org/10.1038/s41586-024-07602-x.

Paquette, A., and Christian Messier. 2013. “Managing Tree Plantations as Complex Adaptive Systems.” In *Managing Forests as Complex Adaptive Systems: Building Resilience to the Challenge of Global Change*, edited by Klaus J. Puettmann, K. David Coates, and Christian Messier, 299–326. Routledge.

Parrott, L., and H. Lange. 2013. “An Introduction to Complexity Science.” In *Managing Forests as Complex Adaptive Systems: Building Resilience to the Challenge of Global Change*, edited by Christian Messier, Klaus J. Puettmann, and K. David Coates, 17–32. Routledge.

Patterson, Murray, Garry McDonald, and Derrylea Hardy. 2017. “Is There More in Common than We Think? Convergence of Ecological Footprinting, Emergy Analysis, Life Cycle Assessment and Other Methods of Environmental Accounting.” *Ecological Modelling* 362 (October):19–36. https://doi.org/10.1016/j.ecolmodel.2017.07.022.

Pavoine, Sandrine, Jeanne Vallet, Anne-Béatrice Dufour, Sophie Gachet, and Hervé Daniel. 2009. “On the Challenge of Treating Various Types of Variables: Application for Improving the Measurement of Functional Diversity.” *Oikos* 118 (3): 391–402. https://doi.org/10.1111/j.1600-0706.2008.16668.x.

Peñaloza, Diego, Martin Erlandsson, and Andreas Falk. 2016. “Exploring the Climate Impact Effects of Increased Use of Bio-Based Materials in Buildings.” *Construction and Building Materials* 125 (October):219–26. https://doi.org/10.1016/j.conbuildmat.2016.08.041.

Perry, Guy, and Michael VanderPol. 2014. “Characterization & Management of Construction, Renovation & Demolition Waste in Canada.” Presented at the Recycling Council of Alberta Conference.

Petchey, Owen L., and Kevin J. Gaston. 2006. “Functional Diversity: Back to Basics and Looking Forward.” *Ecology Letters* 9 (6): 741–58. https://doi.org/10.1111/j.1461-0248.2006.00924.x.

Phillips, Carly A., Brendan M. Rogers, Molly Elder, Sol Cooperdock, Michael Moubarak, James T. Randerson, and Peter C. Frumhoff. 2022. “Escalating Carbon Emissions from North American Boreal Forest Wildfires and the Climate Mitigation Potential of Fire Management.” *Science Advances* 8 (17): eabl7161. https://doi.org/10.1126/sciadv.abl7161.

Pittau, Francesco, Felix Krause, Gabriele Lumia, and Guillaume Habert. 2018. “Fast-Growing Bio-Based Materials as an Opportunity for Storing Carbon in Exterior Walls.” *Building and Environment* 129 (February):117–29. https://doi.org/10.1016/j.buildenv.2017.12.006.

Pizzi, Antonio, and K. L. Mittal. 2010. *Wood Adhesives*. Leiden: VSP.

Pomponi, Francesco, Jim Hart, Jay H. Arehart, and Bernardino D’Amico. 2020. “Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits.” *One Earth* 3 (2): 157–61. https://doi.org/10.1016/j.oneear.2020.07.018.

Pomponi, Francesco, Catherine De Wolf, and Alice Moncaster. 2018. *Embodied Carbon in Buildings: Measurement, Management, and Mitigation*. Springer.

Pope, Jenny, David Annandale, and Angus Morrison-Saunders. 2004. “Conceptualising Sustainability Assessment.” *Environmental Impact Assessment Review* 24 (6): 595–616. https://doi.org/10.1016/j.eiar.2004.03.001.

Preiser, Rika, Reinette Biggs, Alta De Vos, and Carl Folke. 2018. “Social-Ecological Systems as Complex Adaptive Systems: Organizing Principles for Advancing Research Methods and Approaches.” *Ecology and Society* 23 (4). https://doi.org/10.5751/ES-10558-230446.

Proto, Andrea Rosario, Jacopo Bacenetti, Giorgio Macrì, and Giuseppe Zimbalatti. 2017. “Roundwood and Bioenergy Production from Forestry: Environmental Impact Assessment Considering Different Logging Systems.” *Journal of Cleaner Production* 165 (November):1485–98. https://doi.org/10.1016/j.jclepro.2017.07.227.

Puettmann, K. J., K. D. Coates, and C. Messier. 2009. *A Critique of Silviculture: Managing for Complexity*. Washington: Island Press.

Puettmann, Klaus J., K. Dave. Coates, and Christian C. Messier. 2009. *A Critique of Silviculture: Managing for Complexity*. 1 online resource (xvi, 189 pages) : illustrations vols. Washington, DC: Island Press. http://public.eblib.com/choice/publicfullrecord.aspx?p=3317551.

Puhlick, Joshua J., Aaron R. Weiskittel, Laura S. Kenefic, Christopher W. Woodall, and Ivan J. Fernandez. 2020. “Strategies for Enhancing Long-Term Carbon Sequestration in Mixed-Species, Naturally Regenerated Northern Temperate Forests.” *Carbon Management* 11 (4): 381–97. https://doi.org/10.1080/17583004.2020.1795599.

Purba, Citra Yanto Ciki, Guillaume Pot, Robert Collet, Myriam Chaplain, and Jean-Luc Coureau. 2022. “Assessment of Bonding Durability of CLT and Glulam Made from Oak and Mixed Poplar-Oak According to Bonding Pressure and Glue Type.” *Construction and Building Materials* 335 (June):127345. https://doi.org/10.1016/j.conbuildmat.2022.127345.

Raffa, Kenneth F., Brian H. Aukema, Barbara J. Bentz, Allan L. Carroll, Jeffrey A. Hicke, Monica G. Turner, and William H. Romme. 2008. “Cross-Scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions.” *BioScience* 58 (6): 501–17. https://doi.org/10.1641/B580607.

Ramage, Michael H., Henry Burridge, Marta Busse-Wicher, George Fereday, Thomas Reynolds, Darshil U. Shah, Guanglu Wu, et al. 2017. "The Wood from the Trees: The Use of Timber in Construction." *Renewable and Sustainable Energy Reviews* 68 (February):333–59. https://doi.org/10.1016/j.rser.2016.09.107.

Ratcliffe, Sophia, Christian Wirth, Tommaso Jucker, Fons van der Plas, Michael Scherer-Lorenzen, Kris Verheyen, Eric Allan, et al. 2017. "Biodiversity and Ecosystem Functioning Relations in European Forests Depend on Environmental Context." *Ecology Letters* 20 (11): 1414–26. https://doi.org/10.1111/ele.12849.

Ricotta, Carlo, Francesco de Bello, Marco Moretti, Marco Caccianiga, Bruno E. L. Cerabolini, and Sandrine Pavoine. 2016. "Measuring the Functional Redundancy of Biological Communities: A Quantitative Guide." *Methods in Ecology and Evolution* 7 (11): 1386–95. https://doi.org/10.1111/2041-210X.12604.

Rosenfeld, Jordan S. 2002. "Functional Redundancy in Ecology and Conservation." *Oikos* 98 (1): 156–62. https://doi.org/10.1034/j.1600-0706.2002.980116.x.

Ross, Robert. 2022. "Wood Handbook: Wood as an Engineering Material." *FPL-GTR-282*, March. https://research.fs.usda.gov/treesearch/62200.

Sala, Serenella, Biagio Ciuffo, and Peter Nijkamp. 2015. "A Systemic Framework for Sustainability Assessment." *Ecological Economics* 119 (November):314–25. https://doi.org/10.1016/j.ecolecon.2015.09.015.

Sala, Serenella, Francesca Farioli, and Alessandra Zamagni. 2013. "Progress in Sustainability Science: Lessons Learnt from Current Methodologies for Sustainability Assessment: Part 1." *The International Journal of Life Cycle Assessment* 18 (9): 1653–72. https://doi.org/10.1007/s11367-012-0508-6.

Santini Jr., Luiz, Daigard Ricardo Ortega Rodriguez, Manolo Trindade Quintilhan, Sergio Brazolin, and Mario Tommasiello Filho. 2019. "Evidence to Wood Biodeterioration of Tropical Species Revealed by Non-Destructive Techniques." *Science of The Total Environment* 672 (July):357–69. https://doi.org/10.1016/j.scitotenv.2019.03.429.

Saura, S. 2011. "Measuring Connectivity in Habitat Mosaics: The Equivalence of Two Existing Network Indices and Progress beyond Them." *Community Ecology* 11 (2): 217–22. https://doi.org/10.1556/comec.11.2010.2.10.

Scheidel, Arnim, Leah Temper, Federico Demaria, and Joan Martínez-Alier. 2018. "Ecological Distribution Conflicts as Forces for Sustainability: An Overview and Conceptual Framework." *Sustainability Science* 13 (3): 585–98. https://doi.org/10.1007/s11625-017-0519-0.

Scheller, Robert M., James B. Domingo, Brian R. Sturtevant, Jeremy S. Williams, Arnold Rudy, Eric J. Gustafson, and David J. Mladenoff. 2007. "Design, Development, and Application of LANDIS-II, a Spatial Landscape Simulation Model with Flexible Temporal and Spatial Resolution." *Ecological Modelling* 201 (3): 409–19. https://doi.org/10.1016/j.ecolmodel.2006.10.009.

Schlotzhauer, Philipp, Andriy Kovryga, Lukas Emmerich, Susanne Bollmus, Jan-Willem Van de Kuilen, and Holger Militz. 2019. "Analysis of Economic Feasibility of Ash and Maple Lamella Production for Glued Laminated Timber." *Forests* 10 (7): 529. https://doi.org/10.3390/f10070529.

Schweier, Janine, Natascia Magagnotti, Eric R. Labelle, and Dimitris Athanassiadis. 2019. "Sustainability Impact Assessment of Forest Operations: A Review." *Current Forestry Reports* 5 (3): 101–13. https://doi.org/10.1007/s40725-019-00091-6.

Seidl, Rupert, Thomas A. Spies, David L. Peterson, Scott L. Stephens, and Jeffrey A. Hicke. 2016. "REVIEW: Searching for Resilience: Addressing the Impacts of Changing Disturbance Regimes on Forest Ecosystem Services." *Journal of Applied Ecology* 53 (1): 120–29. https://doi.org/10.1111/1365-2664.12511.

Seidl, Rupert, Dominik Thom, Markus Kautz, Dario Martin-Benito, Mikko Peltoniemi, Giorgio Vacchiano, Jan Wild, et al. 2017. "Forest Disturbances under Climate Change." *Nature Climate Change* 7 (6): 395–402. https://doi.org/10.1038/nclimate3303.

Service Canada. 2024. "Opportunities for Circularity of Wood in Construction, Renovation and Demolition in Canada." Readouts. August 12, 2024. https://www.canada.ca/en/services/environment/conservation/sustainability/circular-economy/workshop-report-opportunities-circularity-wood-construction-renovation-demolition.html.

Sheppard, Stephen R. J., and Michael Meitner. 2005. "Using Multi-Criteria Analysis and Visualisation for Sustainable Forest Management Planning with Stakeholder Groups." *Forest Ecology and Management*, Decision Support in Multi Purpose Forestry, 207 (1): 171–87. https://doi.org/10.1016/j.foreco.2004.10.032.

Simard, Suzanne W., W. Jean Roach, Camille E. Defrenne, Brian J. Pickles, Eva N. Snyder, Alyssa Robinson, and Les M. Lavkulich. 2020. "Harvest Intensity Effects on Carbon Stocks and Biodiversity Are Dependent on Regional Climate in Douglas-Fir Forests of British Columbia." *Frontiers in Forests and Global Change* 3. https://www.frontiersin.org/articles/10.3389/ffgc.2020.00088.

Skog, Kenneth E., Theodore H. Wegner, E. M. Bilek, and Charles H. Michler. 2015. "Desirable Properties of Wood for Sustainable Development in the Twenty-First Century." *Annals of Forest Science* 72 (6): 671–78. https://doi.org/10.1007/s13595-014-0406-0.

Smith, Neil. 2008. *Uneven Development: Nature, Capital, and the Production of Space*. Third edition. 1 online resource (xvii, 323 pages) vols. Book Collections on Project MUSE. Athens: University of Georgia Press. http://site.ebrary.com/id/10367034.

Smyth, C. E., B. P. Smiley, M. Magnan, R. Birdsey, A. J. Dugan, M. Olguin, V. S. Mascorro, and W. A. Kurz. 2018. "Climate Change Mitigation in Canada's Forest Sector: A Spatially Explicit Case Study for Two Regions." *Carbon Balance and Management* 13 (1): 11. https://doi.org/10.1186/s13021-018-0099-z.

Sommer, Jamie M. 2019. "Ecologically Unequal Exchange and National Governance: A Cross-National Analysis of Forest Loss." *Environmental Policy and Governance* 29 (6): 422–34. https://doi.org/10.1002/eet.1869.

Soto-Navarro, C., C. Ravilious, A. Arnell, X. de Lamo, M. Harfoot, S. L. L. Hill, O. R. Wearn, et al. 2020. "Mapping Co-Benefits for Carbon Storage and Biodiversity to Inform Conservation Policy and Action." *Philosophical Transactions of the Royal Society B: Biological Sciences* 375 (1794): 20190128. https://doi.org/10.1098/rstb.2019.0128.

Srinivasan, Ravi, and Kiel Moe. 2015. *The Hierarchy of Energy in Architecture : Emergy Analysis*. Routledge. https://doi.org/10.4324/9781315753676.

Stouffer, Daniel B., and Jordi Bascompte. 2011. "Compartmentalization Increases Food-Web Persistence." *Proceedings of the National Academy of Sciences* 108 (9): 3648–52. https://doi.org/10.1073/pnas.1014353108.

Sturrock, R. N., S. J. Frankel, A. V. Brown, P. E. Hennon, J. T. Kliejunas, K. J. Lewis, J. J. Worrall, and A. J. Woods. 2011. "Climate Change and Forest Diseases." *Plant Pathology* 60 (1): 133–49. https://doi.org/10.1111/j.1365-3059.2010.02406.x.

Suding, Katharine N., Sandra Lavorel, F. S. Chapin, Johannes H. C. Cornelissen, Sandra Díaz, Eric Garnier, Deborah Goldberg, David U. Hooper, Stephen T. Jackson, and Marie-Laure Navas. 2008. “Scaling Environmental Change through the Community-Level: A Trait-Based Response-and-Effect Framework for Plants.” *Global Change Biology* 14 (5): 1125–40. https://doi.org/10.1111/j.1365-2486.2008.01557.x.

Swyngedouw, Erik. 2010. “Apocalypse Forever? - Erik Swyngedouw, 2010.” *Theory, Culture & Society*, May. http://journals.sagepub.com/doi/10.1177/0263276409358728.

Thabrew, Lanka, Arnim Wiek, and Robert Ries. 2009. “Environmental Decision Making in Multi-Stakeholder Contexts: Applicability of Life Cycle Thinking in Development Planning and Implementation.” *Journal of Cleaner Production* 17 (1): 67–76. https://doi.org/10.1016/j.jclepro.2008.03.008.

“The Montréal Process: Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests.” 2015. Fifth Edition. https://montreal-process.org/.

Thiffault, Evelyne, Ariane Béchard, David Paré, and Darren Allen. 2015. “Recovery Rate of Harvest Residues for Bioenergy in Boreal and Temperate Forests: A Review.” *WIREs Energy and Environment* 4 (5): 429–51. https://doi.org/10.1002/wene.157.

Thomas, R. Edward, and Urs Buehlmann. 2017. “Using Low-Grade Hardwoods for CLT Production: A Yield Analysis.” *In: Möttönen, V.; Heinonen, E., Eds. Proceedings of the 6th International Scientific Conference on Hardwood Processing; 2017 September 25-28; Lahti, Finland. Helsinki, Findland: Natural Resources Institute of Finland: 199-206.*, 199–206.

Thomasson, G, J Capizzi, F Dost, J Morrell, and D Miller. 2015. “Wood Preservation and Wood Products Treatment.” EM 8403. Oregon State University Extension Service.

Thompson, Ian D. 2009. *Forest Resilience, Biodiversity, and Climate Change: A Synthesis of the Biodiversity / Resiliende / Stability Relationship in Forest Ecosystems*. Montreal: Secretariat of the Convention on Biological Diversity.

Timpane-Padgham, Britta L., Tim Beechie, and Terrie Klinger. 2017. “A Systematic Review of Ecological Attributes That Confer Resilience to Climate Change in Environmental Restoration.” *PLOS ONE* 12 (3): e0173812. https://doi.org/10.1371/journal.pone.0173812.

Turner, Monica G., Daniel C. Donato, and William H. Romme. 2013. “Consequences of Spatial Heterogeneity for Ecosystem Services in Changing Forest Landscapes: Priorities for Future Research.” *Landscape Ecology* 28 (6): 1081–97. https://doi.org/10.1007/s10980-012-9741-4.

“Unraveling the Lumberyard Labyrinth: Your Guide to Lumber Grades.” n.d. Accessed December 16, 2024. https://www.grahamlumber.com/posts/lumber-yard-guides/lumberyard-guide-to-lumber-grades-1654.

Urban, Dean L., Emily S. Minor, Eric A. Treml, and Robert S. Schick. 2009. “Graph Models of Habitat Mosaics.” *Ecology Letters* 12 (3): 260–73. https://doi.org/10.1111/j.1461-0248.2008.01271.x.

Van Elegem, B., T. Embo, B. Muys, and N. Lust. 2002. “A Methodology to Select the Best Locations for New Urban Forests Using Multicriteria Analysis.” *Forestry: An International Journal of Forest Research* 75 (1): 13–23. https://doi.org/10.1093/forestry/75.1.13.

Villeneuve, Claude, David Tremblay, Olivier Riffon, Georges Y. Lanmafankpotin, and Sylvie Bouchard. 2017. “A Systemic Tool and Process for Sustainability Assessment.” *Sustainability* 9 (10): 1909. https://doi.org/10.3390/su9101909.

Violle, Cyrille, Marie-Laure Navas, Denis Vile, Elena Kazakou, Claire Fortunel, Irène Hummel, and Eric Garnier. 2007. “Let the Concept of Trait Be Functional!” *Oikos* 116 (5): 882–92. https://doi.org/10.1111/j.0030-1299.2007.15559.x.

Waas, Tom, Jean Hugé, Thomas Block, Tarah Wright, Francisco Benitez-Capistros, and Aviel Verbruggen. 2014. “Sustainability Assessment and Indicators: Tools in a Decision-Making Strategy for Sustainable Development.” *Sustainability* 6 (9): 5512–34. https://doi.org/10.3390/su6095512.

Walker, Brian H. 1992. “Biodiversity and Ecological Redundancy.” *Conservation Biology* 6 (1): 18–23. https://doi.org/10.1046/j.1523-1739.1992.610018.x.

Walker, Brian, Ann Kinzig, and Jenny Langridge. 1999. “Original Articles: Plant Attribute Diversity, Resilience, and Ecosystem Function: The Nature and Significance of Dominant and Minor Species.” *Ecosystems* 2 (2): 95–113. https://doi.org/10.1007/s100219900062.

Wang, Xiaoming, Jennifer M. Padgett, John S. Powell, and Morton A. Barlaz. 2013. “Decomposition of Forest Products Buried in Landfills.” *Waste Management* 33 (11): 2267–76. https://doi.org/10.1016/j.wasman.2013.07.009.

Webb, Colleen, and Örjan Bodin. 2006. “A Network Perspective on Modularity and Control of Flow in Robust Systems.” In . Columbia University Press. http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-25688.

Wrisberg, Nicoline, Helias A. Udo de Haes, Ursula Triebswetter, Peter Eder, and R. Clift, eds. 2002. *Analytical Tools for Environmental Design and Management in a Systems Perspective: The Combined Use of Analytical Tools*. Eco-Efficiency in Industry and Science. Springer Netherlands. https://doi.org/10.1007/978-94-010-0456-5.

Xie, Sheng H., Werner A. Kurz, and Paul N. McFarlane. 2021. “Inward- versus Outward-Focused Bioeconomy Strategies for British Columbia’s Forest Products Industry: A Harvested Wood Products Carbon Storage and Emission Perspective.” *Carbon Balance and Management* 16 (1): 30. https://doi.org/10.1186/s13021-021-00193-4.

———. 2023. “Substitution Benefits of British Columbia’s Mitigation Strategies in the Bioeconomy.” *Mitigation and Adaptation Strategies for Global Change* 28 (3): 18. https://doi.org/10.1007/s11027-023-10055-8.

Xie, Sheng H., Werner A. Kurz, Carolyn Smyth, Zhen Xu, and Dominik Roeser. 2024. “Forest Products Circular Economy in an Export-Focused Jurisdiction: Can It Fill the Emission Reduction Gap?” *Cleaner and Circular Bioeconomy* 8 (August):100096. https://doi.org/10.1016/j.clcb.2024.100096.

Ximenes, Fabiano, Charlotte Björdal, Annette Cowie, and Morton Barlaz. 2015. “The Decay of Wood in Landfills in Contrasting Climates in Australia.” *Waste Management* 41 (July):101–10. https://doi.org/10.1016/j.wasman.2015.03.032.

Yachi, S., and M. Loreau. 1999. “Biodiversity and Ecosystem Productivity in a Fluctuating Environment: The Insurance Hypothesis.” *Proc Natl Acad Sci U S A* 96. https://doi.org/10.1073/pnas.96.4.1463.