Climate Benefits and Challenges Related to "Mass Timber" Construction: **From Frame to Forest**

BACKGROUND PAPER

Prepared for TFD's Climate Positive Forest Products Scoping Dialogue

29 April, and 3 May 2021

The Forests Dialogue

TFD STEERING COMMITTEE 2021

Chris Buss
International Union for Conservation of Nature (IUCN) – Switzerland

Kerry Cesareo
WWF – United States

Marcus Colchester
Forest Peoples Programme (FPP) – United Kingdom

Crystal Davis
World Resources Institute (WRI) – United States

Minnie Degawan
Conservation International – United States

Gary Dunning
The Forests Dialogue (TFD) – United States

José Carlos Fonseca
Ibá – Indústria Brasileira de Árvores – Brazil

David Ganz
The Center for People and Forests (RECOFTC) – Thailand

Paula Guimarães
The Navigator Company – Portugal

Paul Hartman
The Global Environment Facility (GEF) – United States

Juan Carlos Jintiach
Coordinadora de las Organizaciones Indigenas de la Cuenca Amazónica (COICA) – Ecuador

Victor Lopez
Ford Foundation – Mexico

Antti Marjokorpi
Stora Enso – Finland

Ivone Namikawa, TFD Co-Leader
Klabin – Brazil

Cécile Ndjebet
African Women's Network for Community Management of Forests (REFACOF) – Cameroon

Milagre Nuvunga, TFD Co-Leader
MICAIA Foundation – Mozambique

Sami Oksa
UPM Kymmene Corporation – Finland

Sarah Price
Sappi – Belgium/Switzerland

Kittisak Rattakrajangsri
Asia Indigenous Peoples Pact (AIPP) – Thailand

Fernanda Rodrigues
Diálogo Florestal – Brazilian Forest Dialogue – Brazil

Francisco Rodriguez
CMPC – Chile

Christopher Stewart
Olam – United Kingdom

Ruth Thomas
Global Agribusiness Alliance (GAA) – United Kingdom

Mark Wishnie
BTG Pactual – United States

CLIMATE POSITIVE FOREST PRODUCTS ADVISORY GROUP 2021

Stephanie Burrell
World Economic Forum

Kerry Cesareo
World Wildlife Fund

Gary Dunning
The Forests Dialogue

Ben Kaiser
Kaiser + Path

Jamie Lawrence
Good Energies Foundation

Antti Majorkorpi
Stora Enso

Rachel Pasternack
The Nature Conservancy

Sarah Price
Sappi

Fabrizio Rossi
Climate KIC

Rod Taylor
World Resources Institute

Robyn van den Heuvel
Dalberg Advisors

Mark Wishnie
BTG Pactual

Yuan Yao
Yale University

TFD'S SECRETARIAT

Gary Dunning
Executive Director

Liz Felker
Associate Director

Luca Guadagno
Senior Associate

Eudora Miao
Program Associate

Lisa O'Brien
Program Administrator

ABOUT THIS PAPER

This report was developed to provide a baseline of information on the current state of knowledge related to mass timber construction practices for participants of The Forests Dialogue's Scoping Dialogue on Climate Positive Forest Products, convened virtually on April 26th, 29th, and May 3rd in 2021. During the writing process, an advisory group of representative stakeholders steered the development of the paper, providing feedback and shaping the paper's direction. The advisory group asked for the scoping paper to provide dialogue attendees with a baseline understanding of (i) the current state of mass timber manufacturing and construction globally, (ii) state of knowledge regarding the climate impacts of substituting mass timber for conventional building materials and of storing carbon in mass timber materials, (iii) the state of knowledge of potential end-of-life climate impacts of mass timber utilization, and (iv) potential impacts on forest carbon stock and forest condition of increased demand for wood products from forest harvesting or displacement of wood from other industries. This report synthesizes existing literature on these topics and outlines where the best available research aligns and where there is disagreement. Additionally, a series of informal stakeholder interviews was conducted at the direction of the advisory group to generate a general understanding of where stakeholders agree and disagree on issues related to the potential for mass timber construction to act as a climate solution. During the dialogue, stakeholder feedback was solicited from dialogue participants and incorporated to produce this final version.

ABOUT THE FORESTS DIALOGUE (TFD)

The Forests Dialogue (TFD) is an organization that designs and implements multi-stakeholder dialogues aimed at fostering social learning, building trust, and supporting processes for collaborative and adaptive land management across sectors. TFD believes that structured dialogue is fundamental to breaking deadlocks and creating meaningful change in the forest sector. Housed at Yale School of the Environment (YSE) in The Forest School, TFD's secretariat is directed by a group of 25 steering committee members representing globally significant forest stakeholders. TFD implements its mission through initiatives. Initiatives address a global forest issue identified by TFD's Steering Committee members through a series of dialogues. TFD's process includes mixing international and national perspectives, engaging the private sector in all dialogues, combining field discussions with structured meeting facilitation, and giving participants the mandate to determine outputs and outcomes. Dialogues often occur in countries where the issue is or has historically caused conflict and seek to deliver impact in-country and inform global discourse through grounded examples. Country level dialogue topics and case studies are driven by local priorities, as determined by in-country host organizations and vetted by TFD. The statements, reports, and findings of TFD do not necessarily represent the views of YSE faculty. Learn more about TFD's process, ongoing initiatives, and past work at https://theforestsdialogue.org/.

AUTHOR

Edie Sonne Hall, Ph.D., is Founder of Three Trees Consulting. She has over twenty years of experience working at the intersection of forest science, policy, and management, with a specialty in forest carbon accounting and life cycle assessment.

ACKNOWLEDGEMENTS

The author and organizers would like to thank the advisory group for their comments and suggestions; the dialogue participants for their feedback on the paper; and the individuals who shared their time and perspectives in the stakeholder interview process. The dialogue process and the creation of this publication would not have been possible without leadership and financial support from the Climate Smart Forest Economy Program (CSFEP) that includes the World Resources Institute, World Economic Forum, Climate KIC, and The Nature Conservancy. This report's findings and outputs from the Scoping Dialogue will feed into the larger programmatic work of the CSFEP (more at https://www.csfep.org/), thanks to the many partners and organizations involved in carrying this work forward. Additional thanks to The Forests Dialogue team for facilitating this process.

CITATION

The Forests Dialogue. 2021. Climate Benefits and Challenges Related to "Mass Timber" Construction: From Frame to Forest. TFD, New Haven, CT

The Forests Dialogue

CONTENTS

The Forests Dialogue, Yale University, 360 Prospect Street, New Haven, Connecticut, 06511, USA
O: +1 203 432 5966 T: @forestsdialogue W: www.theforestsdialogue.org E: info@theforestsdialogue.org


Photo © Andrew Pogue (Kaiser + Path)

1. INTRODUCTION: SETTING THE STAGE – WHY DO WE CARE?

In order to keep our climate to under 1.5C warming, the world will have to reduce annual GHG emissions from 52.4 Gigatons (Gt) carbon dioxide equivalent (CO_2e) in 2019 to a mere 6.2 Gt CO_2e in 2050, which constitutes an unprecedented scale of GHG reductions (UNEP 2019). Critical to this goal is the buildings and construction sector, which accounted for 38% of global energy and process-related carbon dioxide emissions in 2019. Of these emissions, 25% were associated with the manufacturing the material used in construction, otherwise known as building embodied carbon. Annually, 6.13 billion square meters of buildings are constructed, and their embodied carbon emits 3.5 Gt CO2e/yr., representing 10% of global energy related CO_2 emissions (UNEP 2020).

The combination of population growth and land-use/climate considerations will put an increasing emphasis on urban multi-story buildings. These new buildings will create over 100 gigatons of embodied carbon emissions by 2060, which is more than 3 years of global CO_2 emissions[1] (Bionova Ltd 2018). Cement alone, with an annual production of 4.2 billion metric tons (mt) in 2016 accounts for 8% of global GHG emissions, with roughly 0.5 mt CO2e released for each mt of cement produced (Pierobon et al 2019). Under business-as-usual projections, global cement production is expected to increase to over 5 billion metric tons/yr. by 2050 (IEA 2018).

Wood products have relatively low embodied carbon and also store carbon while in use; however, traditional stick frame construction has limited application in large and multi-story buildings. Mass timber provides solutions to structural limitations by gluing together smaller pieces of wood in patterns that create strong solid material that does not readily ignite. Currently only 9% of non-residential and multi-story buildings in the United States are framed with wood (Anderson et al 2020).

Though there are many benefits to mass timber construction, including ease of prefabrication and installation, the climate benefits have been loudly touted. There is concern that the existing quantification of these benefits may not be complete. Were all the life cycle stages included? What were the assumptions on end-of-life? How were biogenic carbon emissions and storage treated? Is the data associated with other building materials really accurate? In addition, as with any discussion involving increased demand for a forest product, there is concern about the impact on the forests themselves. Some argue that under the right conditions, expanding climate-positive forest product markets can create incentives for greater investment in reforestation/afforestation and forest landscape restoration. Others worry that increased use of forest products will drive forest degradation or other negative outcomes.

A growing body of literature is laying the foundation for rich discussions. These studies, though all focused on the same topic, can differ in scope, baseline, and assumptions, yielding different, even opposing results. This scoping paper will synthesize existing literature and outline where the best available research aligns and where there is disagreement and why. This will be used to build a dialogue that can address areas of disagreement (fracture lines) and work towards solutions.

The paper is divided into nine sections. Sections 3 - 6 have pulled together the existing literature around four topics: current state and predictions of the global mass timber market, current state of knowledge regarding climate impacts of substituting mass timber for conventional building materials and of storage of carbon in mass timber products, state of knowledge of potential end-of-life impacts of mass timber products, and potential impacts on forest carbon stocks and forest conditions of increasing demand for wood products, with an emphasis on softwood species as these species currently supply the majority of mass timber products. In each of these sections, existing literature was summarized, and areas of agreement and disagreement were surfaced. Areas of disagreement were categorized according to whether there is uncertainty about the data or assumptions or whether there are differences in methodologies. The seventh section summarized inputs from informal stakeholder interviews, who span academia, government, and ENGO across North America and Europe and who represent differing viewpoints about the benefits of mass timber as a climate solution. The eighth section summarizes potential fracture lines that surfaced in the scoping process.

2. ACRONYMS AND CONVERSION FACTORS

Rough conversion: 1 cubic foot lumber requires 2 cubic foot log

Dimension lumber conversion- 0.057 ft^3 = 1 board feet.
Note: conversion from ft^3 log to board feet depends on log size as well as board foot scale (e.g., Scribner)

MBF = 1000 board feet

GWP = Global Warming Potential. A characterization factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to that of carbon dioxide over a given period of time. It is expressed in carbon dioxide equivalents (CO_2e)

Mt= metric ton

Tg = million metric ton = MMT

Gt = gigaton = 1 billion metric ton

3. CURRENT STATE OF MASS TIMBER MANUFACTURING AND CONSTRUCTION, GLOBALLY

3.1 What is Mass Timber?

"Mass timber construction" is the term being used to describe a new **new construction method** that utilizes wood to replace structural function that has long been dominated by concrete and steel such as in commercial or high-rise construction. Mass timber products are generally factory-produced, structural wood panels of two inches or greater thickness and typical widths of four feet or more.

Cross-laminated timber (CLT), Nail-laminated timber (NLT), dowel-laminated timber (DLT), and Glulam are typically sourced from kiln or air-dried softwood lumber. Products such as mass plywood panels

(MPP), laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL) and OSB can be sourced from either softwood or hardwood fiber.

3.2 Market-Share and Growth by Regions

CLT leads the way in mass timber construction and many projections of market share and growth are reported based on CLT manufacturing. Production capacity has increased dramatically in the last decade. Global annual CLT production was expected to reach 1 million m^3 by 2016 (an increase of >60% from a 2014 production capacity of ~600,000 m^3 (Espinoza et al 2016). By 2020, global building mass timber production is expected to reach 2.8 million m^3 (Anderson et al 2020). Though Europe historically has dominated the CLT manufacturing market, North America has increased capacity significantly, especially in the past 5 years. In 2015, central Europe accounted for 80% of CLT production capacity (60% in Austria, 17% in Germany, 3% in Switzerland) (Espinoza et al 2016). In 2020 North America represented over 40% of global CLT capacity (Anderson et al 2020).

As of 2019, North America housed 14 mass timber manufacturing facilities with three more in construction and another three announced. 2019 capacity was 439,000 m^3 (with another 471 m^3 used for industrial matting). The three facilities under construction are expected to add an addition 62,000 m^3 building capacity and the three proposed an additional 182,000 m^3 building capacity, an increase of 55% over 2019 capacity. Most (~70%) of the current capacity is in the northwest United States, with the remainder divided between the southeastern and northeastern United States (Anderson et al 2020).

Other countries are building with mass timber without investing in domestic production capacity. For example, Norway has slowly increased CLT buildings from 2% in 2014 to an expected increase of 6-9%. Less than 3% of CLT used in Norway is domestically produced (900 of the 36,000 m^3 used in 2016) with the rest imported from Austria, Germany, Sweden, Latvia, and Lithuania (Wahlstrom et al 2020).

Global CLT market value was $664 million in 2018 (North America $59.7 million). Both are predicted to have 13-16% yearly growth to $664 and $171 million respectively by 2024.[2] In 2016 only 9% of non-residential and multistory buildings in US were framed with wood. Concrete construction has actually increased market share from 20% in 2009 to 32% in 2016 (with a corresponding reduction in structural steel from 56% market share in 2009 to 49% in 2016 and masonry from 10% to 6%) (Anderson et al 2020). FP Innovations, a Canadian forest research organization suggested that it is plausible for CLT to capture an additional 5-15% of the market share for non-residential and multi-family construction in the United States, which corresponds to 60 – 180 million cubic ft CLT/yr. (The Beck Group 2018).

Less than 10% of global CLT capacity is found in Oceania and Asia and limited production (10,000 m^3) in South America and Africa (Anderson et al 2020). However, current capacity does not necessarily indicate future growth. A London School of Economics capstone project examined three key factors that may be helpful in predicting mass timber growth: 1) the urban score, which encompasses population growth as well as current use of concrete 2) the forest score, which includes availability of forest resources as well as sustainability rating including corruption, traceability, governance, and certification and 3) the infrastructure score, including roads and transportation logistics and ease of import (Kongsgaard et al 2020). Preliminary results indicate that while expected players in Central Europe and the Scandinavian countries yielded high scores in these three factors, countries in Africa such as Zambia, Uganda, Burkina Faso, and Malawi fared well as well as did Asian countries Hong Kong, Vietnam, Japan, South Korea, and Oceania countries of New Zealand and Australia.

3.3 Areas of Uncertainty in Mass Timber Growth Projections

Forest management may play an important role in whether the impact of potential growth in mass timber is positive or negative. Many African countries are rich in forest resources but have pressing problems with sustainability. For example, Zambia has a high deforestation/forest conversion rate, and despite a stated Nationally Determined Contribution (NDC) to use sustainable forest management to reduce country carbon emissions by up to 47% by 2030, lack of enforced forest regulations and unclear governance are hindering progress (Kongsgaard 2020). A key uncertainty is whether increasing demand for these forest resources will increase forest investment and management, creating more stable forests or whether it will further exacerbate exploitation- this fracture line will be discussed more in the demand section.

Tree characteristics may play an important role in potential growth and expansion. For example, currently softwood lumber dominates CLT manufacturing, though other mass timber products such as MPP, LVL, PSL, LSL and OSB can be made from either softwood or hardwood. Within softwoods, there is also a variation in structural characteristics. European blonde spruce has better structural characteristics and aesthetics, e.g., than Radiata pine grown in Australia and New Zealand (Kongsgaard et al 2020), though production technology may overcome species structural characteristics.

As with any new product or system, in addition to supply issues related to new production standardization and logistics, barriers in education and training throughout the entire value chain can lead to higher costs and lower competitiveness. Some countries have instituted specific incentives to reduce building embodied carbon, which can favor mass timber buildings and jumpstart mass timber use. According to a review of Embodied Carbon policy programs, the most effective carbon reduction incentive policies are currently found in Continental Europe, including France, the Netherlands, and Austria. For example, Austria ties housing subsidy and funds to green building methods that use LCA. France’s Energie Positive & Reduction Carbon (E+C-) label program requires all new buildings to calculate and meet embodied carbon performance standards, and the Netherlands has required LCAs for new buildings since 2013. In the Nordic countries, Norway, requires all government projects to use LCA and that has led to a wide consensus on application, development of product information, and training programs (Bionova Ltd 2018). The extent to which other countries will adopt similar policies is uncertain.

4. STATE OF KNOWLEDGE REGARDING THE CLIMATE IMPACTS OF SUBSTITUTING MASS TIMBER FOR CONVENTIONAL BUILDING MATERIALS AND OF STORAGE CARBON IN MASS TIMBER MATERIALS

4.1 What is Substitution?

Substitution typically describes how much greenhouse gas emissions would be avoided if a wood-based product is used instead of another product to provide the same function (Leskinen et al 2018). Substitution replaces the LCI footprint product A with product B and may cause additional indirect impacts as output volumes adjust (Lippke et al 2011).

4.2 Overview of Study Results on Substitution

There is growing body of literature examining wood substitution in general and more specifically CLT as replacement for concrete in buildings. These studies generally are attributional life cycle assessments following ISO 14040 series (ISO 14040, 2006; ISO 14044, 2006) which require four stages 1) goal and scope definition, 2) life cycle inventory analysis, 3) life cycle impact assessment and 4) interpretation of results. Construction specific standards, such as EN 15978 (CEN 2011), *Sustainability of construction works – Assessment of environmental performance of buildings*, ISO 21930 (ISO 2017), and ISO 15392 (ISO 2019), identify the specific life cycle stages associated with a building, including production and construction (A1-A5), building use/operation (B1-B7), end-of-life (C1-C4) and potential net benefits from reuse, recycling and/or energy recovery beyond the system boundary (D).

The term "Building embodied carbon" is an informally defined term to describe the carbon emissions associated with the materials in the building envelope. In LCAs these can include all stages except operating energy (B6) and operating water (B7). However, some analyses just focus on the production and construction phase (A1-A5). Embodied carbon varies by building type and region, as well as by the materials. Simonen et al (2017) benchmarked over 1000 embodied carbon observations by building type and found that almost all buildings have initial embodied carbon <1000 kg CO_2e/m^2, with typically results between 200 and 500 kg CO_2e/m^2 for office buildings.

Though there is some variability in assumptions, studies generally find a reduction in total embodied carbon when comparing building mass timber/CLT vs alternative materials, principally concrete. Several meta-analyses have categorized and summarized various types of wood building comparisons to other materials. Himes and Busby's (2020) meta-analysis examined 11 peer-reviewed publications that compared construction phase (A1-A5 according to EN 15978 life cycle stages, otherwise known as "cradle-to-gate") emissions between mass timber and conventional materials in mid-rise buildings. Average emissions savings with mass timber was 216 kg CO_2e/m^2 (95% confidence interval 146-287 (kg CO_2e/m^2), which is a 69% GHG emission reduction from the conventional material. A subset (3) of the studies did not include transporting building materials to the construction site or emissions associated with on-site construction activities, but these stages were found to not have significant differences by material type.

Leskinen et al (2018) conducted a meta-analysis of 51 studies comparing wood versus non-wood alternatives, with the majority of studies (79%) in the construction sector (e.g., building, internal or external wall, wood frame, beam), though CLT specific studies were NOT included. They derived a "substitution factor" by comparing embodied carbon per unit wood ($GWP_{non\text{-}wood}$ – GWP_{wood}/Wood use $_{wood}$- Wood use$_{non\text{-}wood}$). They found average substitution benefits in structural construction averaged 1.3 kg C/kg C wood product, with 95% confidence range from -0.9 to 5.5 kg C/Kg C wood product. The large variability (with negative number meaning the non-wood alternative had less GWP) was due to differences and assumptions and life cycle stages included. For example, metals and alloys can be recycled at end-of-life, leading to smaller end-of-life emissions than wood. Leskinen et al (2018) also highlighted that more studies are needed in Asia, South America, and Africa, as the meta-analysis was heavily weighted to North America and the Nordic countries.

Sahoo et al (2019) synthesized 96 LCA publications of forest-based products, including 10 on emerging wood building products such as mass timber and tall wood buildings. LCA results ranged from 79-202 kg CO2e per m^3 CLT, with differences due to transportation, species, and electrical grid. For example, US based studies show higher GWP embodied carbon than Canada studies, likely due to higher cumulative energy demand that results from using Douglas fir over lighter species such as Sitka spruce (less resins needed) AND the composition of the electricity grid. Chen et al (2019) found there could be a 14% reduction in CLT GWP embodied carbon when CLT mills source lumber locally and using lighter wood species (e.g., Sitka spruce over Douglas fir).

Other CLT studies have been published since these meta-analyses and many more are in the works. A set of studies, Liang et al (2020) and Chen et al (2020), both which conducted a comparative LCA of a mass timber building and concrete alternative for the same building in Portland, OR, highlight the different results that can be obtained by including different life cycle stages. Liang et al conducted a cradle to gate analysis (A1-A5) and found the 12-story mixed use building had an 18% reduction in GWP compared to a similar concrete building, with much of the embodied carbon of the CLT building resulting from increased use of gypsum board. Chen et al (2020) used the Athena Impact Estimator for Buildings Whole Building LCA (WBLCA) tool to compare the same buildings and a cradle-to-grave analysis and found a 20.6% reduction in embodied carbon in stages A-C (excluding B6). Chen also included wood carbon storage in stage D, which contributed to a 70% savings in GWP. In a separate study, Pierobon et al (2019) compared two types of CLT commercial building against equivalent reinforced concrete: a 'fireproof design' where gypsum board is applied to the structural wood, and a 'charring design', where two extra layers of CLT are added to the panel. The study found that both CLT frames resulted in a 26-27% GWP savings.

While differences in species and electricity composition can vary mass timber embodied carbon, analyses from around the world all seem to show the same directional savings when compared to other materials. Liu et al (2016) conducted a cradle-to-grave comparison of a seven story CLT building with a concrete alternative two northern regions of China (Xi'an and Harbin) and found CO_2 emissions could be reduced by 40% in both regions. This study DID include Stage B (operational energy) and found that the CLT building could provide more insulation and result in operational energy savings. Durlinger et al (2013) found a 13% GWP savings (22% is wood carbon storage included) for a CLT building in Victoria, Australia, compared to a reinforced concrete building.

4.3 Projections for Emissions Reductions at Scale

The substitution studies provide a range of potential GHG savings when building with mass timber; however additional studies have taken these GHG savings and tried to assess potential reductions at scale based on market penetration, both realistic and theoretical. At the theoretical end, Oliver et al (2014) estimated a potential savings of 14%-31% global CO_2 emissions (4.7-10.3 GtCO2 yr^{-1} based on 2019 emissions) by substituting wood for concrete and steel in building and bridge construction. Churkina et al (2020) estimated that a 90% transition to wood buildings could reduce CO_2e emissions from construction by half. Himes and Busby (2020) estimated a savings of 2.84 Gt CO_2e by 2030 by building 50% of new urban construction with mass timber, which could achieve 9% of the 2030 global emissions goals (the 30 Gt reductions needed to meet 1.5 target). D'Amico et al (2021) took a different approach by proposing that a hybrid CLT/steel frame building has a higher likelihood of higher and more immediate market penetration. They found that replacing all steel frame buildings projected to be built globally in the next 30 years at current market share with a hybrid CLT/steel building would lower embodied carbon GHG emissions from 171-303 Mt CO2e to 142-227 Mt CO2e. This average change (52 Mt CO2e) represents a 22% reduction.

Countries have incorporated potential savings of wood substitution in their climate planning. The UK government estimated a potential savings of 836-1245 Kt (0.8-1.2 MMT) CO2e for increasing wood (timber, CLT, and glulam) in non-residential buildings from a 2018 BAU of 3-3.5% to 80-93% by 2050, with an additional 1,680-2,270 mt CO2e stored in the buildings themselves. Such a growth in wood use would require an increase in sawlog inputs of 1.2 million oven dry tons (from 0.952 million in 2018-2022 to 2.546 million oven dry tons from 2048-2050) (Spear et al 2019). A report detailing deep decarbonization pathways for cement and concrete in the U.S., India, and China point to material substitution with mass timber as one of seven potential decarbonization levers (Cao and Masanet 2021).

4.4 Biogenic Carbon Assessments

Biogenic product life cycle assessments have an added complexity that make choices of system boundaries and assumptions difficult- the biogenic carbon cycle. Unlike fossil fuel, biogenic carbon transfers both into and out of the atmosphere (leaving the atmosphere through photosynthesis and returning through combustion or decay), and these processes can be either natural or human induced (IPCC 2019). Life cycle assessments vary in how much they explicitly tackle the biogenic carbon cycle.

Xoxha et al (2020) summarized the range of biogenic accounting methodologies found in 14 peer-reviewed journal articles, 25 EPDs, 12 standards, and 7 research reports. For example, ISO 21930: 2017, which sets the core rules for environmental product declarations of construction products and services, treats carbon in fiber harvested as a full removal and tracks emissions across the life cycle stages (-1/+1) if there is proof the fiber is sourced from either a) a country with stable or increasing carbon stocks or b) wood from a certified sustainable forest management forest. This convention does not incorporate any carbon accrual on the landscape but does track the carbon in the harvested log. EN 15804 conforms with ISO 21930, yet does not allow fiber from "native forests". The International Reference Life Cycle Data System (ILCD) and Publicly Available Specification (PAS) 2050:2008 also follow -1/+1 but allow for the optional reporting of the climate benefit of delayed emissions through dynamic accounting (see below). The European Commission Guidance for the Development of Product Category Rules (EC:2017) follows the 0/0 approach, which assumes that the uptake of biogenic carbon is released and there is no impact (positive or negative) on the atmosphere (Xoxha et al (2020).

Penaloza et al (2019) explicitly tackle the incorporation of biogenic carbon and the influence of system boundaries, baseline, and time by comparing four different bio-based products with different service lives (butanol automatic fuel (0 years), viscose textile fibers (2 years), CLT (50 years), and methanol used to produce both short (0 years) and long-lived (20 years) products) with their respective realistic replacement using five different sets of assumptions spanning spatial and temporal boundaries.

The five different sets of assumptions encompassed combinations of two different methodology choices and variations thereof. These are 1) The scale of assessment, at either the stand level or landscape level, and within a stand level analysis, the study also compared whether the temporal aspect started after harvest or at the start of the forest rotation 2) The "land-use baseline", whether it is compared to a point in time (zero baseline) or a counterfactual. The study illustrates that the methodological choices can influence the result.

Penaloza et al (2019) do not recommend one methodology over another but urge the LCA community to be more explicit with their choices and what they can be used to answer. Incidentally, while there were differences across all methodologies, CLT always delivered better GWP impacts than concrete.

In application, often stand-level analyses focus on the impact of a specific forest operation (e.g., a forest thinning or change in rotation age) and landscape assessments are appropriate where forest managed across a landscape obtains a continuous flow of wood for manufacturing (Cintas et al 2016). The two types of baselines reflect different types of questions asked in studies. In an attributional LCA, a "point-in-time" baseline is appropriate because it incorporates the impact of the specific functional unit, in this case the biogenic impact from which a wood product is sourced. A natural regeneration baseline answers the question of what would have happened had that forest NOT been harvested, which could, but rarely does, include the impact of natural disturbances.

Lan et al (2020) explicitly tackle the impacts of forest productivity on the carbon footprint of CLT manufacturing by conducting a dynamic LCA (to account for the timing of emissions and sequestration over 100 years) that examines different forest productivity regimes in the U.S. South. In contrast to the aforementioned studies that have a functional unit at either the building or product level, Lan et al use a functional unit of one hectare. They modeled two scenarios of productivity for loblolly pine growth and yield at a 25-year rotation age. The different yields of harvest generated saw logs and harvest residues (alternative fates for residues such as pulpwood were not considered). In addition, they examine two scenarios of mill residue utilization (used for energy or sold to market) and two different levels of CLT recycling (0 or 50%). The study found that all scenarios led to a net negative carbon footprint over 100 years, but the scenario derived from the highest productivity management yielded the largest negative net life cycle GHG emissions. Interestingly, when Lan et al examined the same scenarios using a functional unit of 1 m^3 CLT (which is a typical functional unit for other wood product studies) the impacts of forest productivity are muted.

4.5 Storage of Carbon in Building Materials

Harvested wood products (HWP) store carbon, which would otherwise be release as carbon dioxide (or methane under anaerobic conditions). There are two types of questions that are often asked regarding HWP carbon storage: a) is the global accumulation of carbon in wood products increasing or decreasing and by how much? and b) what is the removal value (e.g., GWP_{100}) of carbon storage of a wood product either in a building or other end-use, leaving a production facility (with various end-uses), or from a forest (with various production types and end-uses)? The answers to these questions can use the same data regarding product end-uses and half-lives, but they can differ in results because the first is tracking the change in HWP relative to the year before, and the latter (b) is estimating the climate benefit of temporarily (or permanently) keeping carbon out of the atmosphere.

To answer the first question, Johnson and Radeloff (2019) examined the global mitigation potential of carbon stored in harvested wood products in general by applying the IPCC HWP country level carbon accounting guidance to 180 countries' production data from 1961 to 2065. IPCC HWP country level carbon guidance creates a "virtual" HWP inventory by using past harvest data and tracking inputs to (current year manufacturing) and outputs from (wood products decay from past harvest). They found that the HWP wood product pool continues to increase, but the magnitude of the increase is projected to peak in 2030 between 317 and 415 Mt CO2e yr.[1] In this type of stock change assessment, if there is a significant reduction in harvest, less carbon can enter the product pool than leave it due to decay from products leaving at the end of their service life, resulting in a net release of CO2e into the atmosphere. Such was the case in the collapse of USSR in 1991/1992 and the recession in 2008/2009 in the US, which both saw a sharp drop in HWP production in these countries.

However, product/building LCA studies are not concerned with HWP carbon relative to past harvest and production but rather are concerned with the carbon storage over the life of the specific product; therefore, LCA studies differ in their treatment of wood carbon storage. Most cradle-to-gate LCAs do not account for HWP carbon because they treat biogenic C as an emission as it leaves the gate. Cradle to grave studies track and report carbon to end-of-life, with most carbon ending in landfills. There are wide variations in these end-of-life assumptions, which are discussed in the next section.

To answer question b) methods for calculating the climate impact of carbon storage of varying length have been widely discussed. The Moura-Costa and Lashof accounting methods, and variations thereof quantify the differences in the decay curve (Bern curve) of a pulse of CO_2 molecule in the atmosphere (Levasseur 2012, Ganguly et al 2020). Others have proposed simplified approaches, which have been found to approximate these methods. For example, the California Forest Carbon Offset Protocol averages the proportion of wood product left each year over 100 years (CARB 2015); this method, called the 100-year average is also suggested for entity-level HWP reporting in USFS guidance (Hoover et al 2014). Finally, the International Reference Life Cycle Data System Handbook proposed that the value of keeping a metric ton CO_2 out of the atmosphere has a GWP_{100} equivalency of 0.01 kg CO_2e, meaning one can multiply the average wood product service life by 0.01 to equal the climate "benefit" of HWP carbon storage.

Some assessments focus only on the carbon stored in building stocks. Churkina et al (2020) looked specifically at carbon stored in building materials between now and 2050 and found that new mass timber buildings could store between 0.01-0.68 Gt C yr^{-1} depending on the market penetration of mass timber construction (BAU = 0.5% timber building to 90% timber buildings).

4.6 Areas of Uncertainty/Disagreement

Figure 1 attempts to categorize areas of disagreement in methodology vs uncertainty in assumptions in the quantification of mass timber climate benefits and impacts. Across the various life cycle stages, there seems to be consensus in both methodology and assumptions in quantifying emissions from manufacturing, construction, and building use. Some parts of the life cycle stages contain uncertainty in assumptions but general agreement on methodology- these include assumptions about end-of-life and the choice of a comparable function unit. The assessment of the biogenic carbon cycle, denoted in red, draws both differences in methodology and differences in assumptions. These are discussed in more detail below.

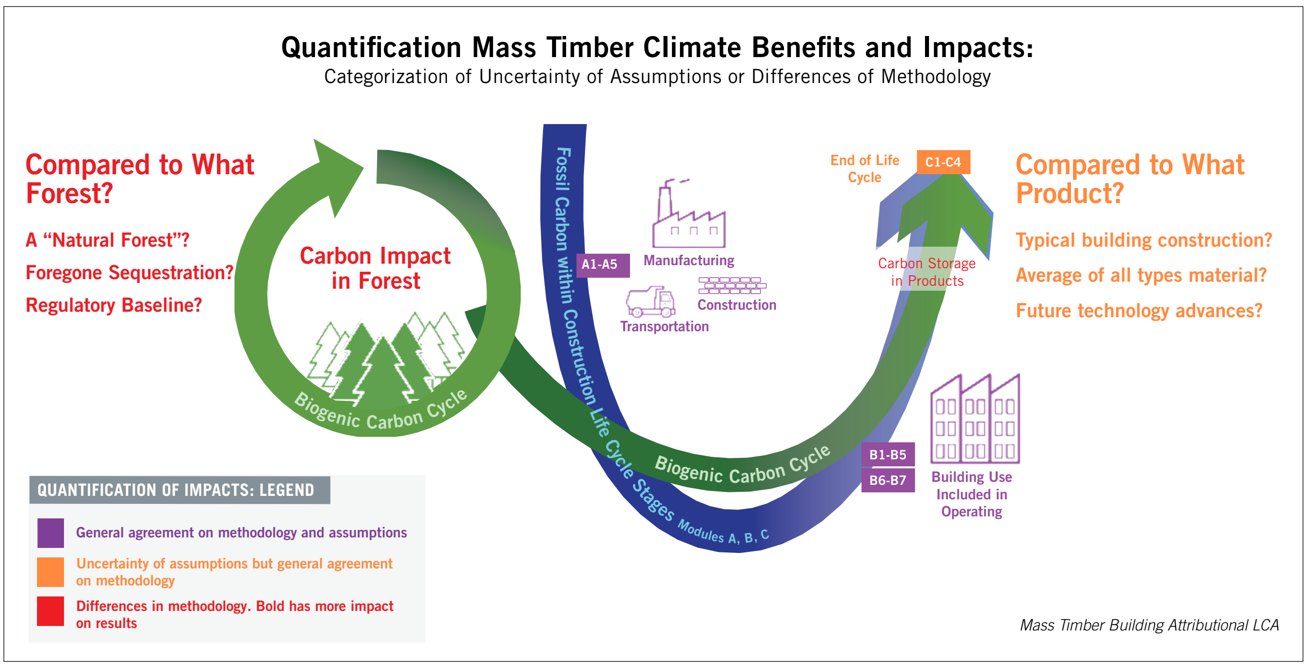

Figure 1: Categorization of uncertainty of assumptions or differences of methodology in the quantification mass timber climate benefits and impacts.

The Middle Part of Figure 1

An attributional life cycle assessment quantifies the environmental impacts, across the life cycle, of a particular product or service, for example, an 8-story building framed with mass timber. Generally speaking, there is agreement on how to calculate emissions associated with manufacturing, construction, transportation (the A1-A5 stages). There ARE some differences in assumptions about end-of-life scenarios, meaning the assumption of how much of the building product will be recycled versus incinerated versus landfilled, and this is described in more detail in Section 5 of this paper. End-of-life assumptions can impact the total emissions but not enough to change a favorable comparison with an alternative material.

The biggest differences in literature are in different methodologies to account for the biogenic carbon cycle, both in products and in the forest. Product carbon storage methodologies differ in how they assign climate values to temporary storage and what assumptions are used for service life longevity. Forest carbon assessments differ in scale (e.g., stand-level or landscape level). These biogenic carbon accounting methodologies are discussed in detail in the *biogenic carbon assessment section.*

The Right Side of Figure 1: Functional Unit Comparison – Compared to What Product?

A comparative LCA must include information about both the subject of interest (e.g., mass timber building) and the material to which it is being compared (e.g., concrete or steel building). There is agreement that the functional unit (a building of the same size and function) needs to be the same, but studies can differ on what the "compared to" building should be. Is it the typical building construction for that area? Is it the average across all building types in the areas? Is it against future technical advances?

One study (Harmon 2019), which has been cited subsequently (Hudiberg et al 2019, Moomaw et al 2020) has questioned whether the assumptions that are made in the substitution studies may over-estimate substitution benefits. He argues that if the materials to which wood is compared reduce their embodied carbon in the future, then these substitution benefits will be overstated. Indeed, there may be a lot of opportunity for reducing GHG emissions in concrete manufacturing, both in more energy efficient processing and in material substitution (e.g., fly ash) and this would lower the potential substitution benefit of mass timber, though these savings would only be against future substitution studies, not against today. Furthermore, eliminating GHG emissions from energy-intensive materials such as concrete and steel will require technical advances (e.g., carbon capture and storage) that are not available today (D'Amico et al 2021), and mass timber production can also have future efficiency gains. Harmon also argued that no leakage is accounted for in most substitution studies. In other words, if the building is not made of concrete, will that amount of concrete be used elsewhere? Leakage has also been pointed out as a potential issue in Leturcq (2020), and although neither Harmon nor Leturcq assess the elasticity of demand for concrete (the degree to which if demand for concrete falls, concrete prices will fall and the now-cheaper material will be used in new applications), future research in this area might better address how large-scale changes in demand for concrete in construction might impact overall usage. Finally, Harmon argued that wood buildings may have different service lives than their substitution counterparts leading to needing to replace the wood building prior to its substituted counterpart. However, comparative LCAs assess against the same functional unit, which is a product that delivers the same service over the same period of time, rendering this concern irrelevant. Furthermore, there is no indication that wood would have lower service lives than concrete and steel. In fact, in a survey of building demolitions between 2000 and 2003 in Minneapolis/St. Paul, wood buildings' median service lives almost 3 times longer than concrete and steel (80-90 years vs 25-30) (O'Connor et al 2005).

The Left Side of Figure 1: Functional Unit Comparison – Compared to What Forest?

On the upstream side, there is no agreement about how to account for the "what-if" scenario had the forest NOT been harvested to make the mass timber product. How does one type of management style compare to another in terms of forest carbon and harvest output? Methodologies differ in terms of baseline (e.g., regulatory, a "natural/historic" forest) as well as functional unit (e.g., an acre of land, a unit of wood). Examples of studies that look at different pathways for forest carbon mitigation include Law et al (2018), Smyth et al (2020), Hudiberg et al (2019), Oliver et al (2014), and these are discussed the *potential impact on forest* discussion section of this paper (see pages 17-18).

Finally, not depicted in this chart is how the impact may change if there are significant increases or decreases in production- this will be discussed in Section 6 (the impact of demand on forest quantity and quality).

5. STATE OF KNOWLEDGE OF POTENTIAL END-OF-LIFE IMPACTS OF MASS TIMBER UTILIZATION

Across all material categories, end-of-life impacts are less often included and methods for assessment vary (Pomponi and Moncaster 2018). Because it is a relatively new product, even less is known about end-of-life impacts of mass timber utilization specifically, except that in general service life of a building does impact overall climate benefit. At the end of a building's service life, mass timber products can be recycled/reused, incinerated in a power plant, or disposed in landfills.

Reuse has often been found to have the biggest carbon benefit because it extends the storage life of a product and reduces the amount of new production/virgin fiber. Liu et al (2016) found that increasing the assumption of end-of-life reuse from 55% to 90% could increase total cradle-to-grave CO_2 savings about 6% (from ~40-46%).

Sandin et al (2014) examined the relative impacts of different end-of-life assumptions comparing a glulam truss roof with a steel truss roof system. They found that relatively speaking the different end-of-life assumptions did not impact the outcome; glulam always showed better environmental benefits than steel, including GWP, except when there was 100% recycling of steel with today's average steel embodied carbon, which had similar results to glulam. However, choice of method (i.e., attribution or consequential), and choice of end-of-life scenario (i.e., incineration or recycling) did influence absolute savings, with recycling yielding the most benefits.

Studies have suggestions for how to improve the ease of recycling. Passarelli (2019) explored the possibility of designing modular CLT buildings in Japan that can easily be taken apart and reused. He found there was a 7%- 21% reduction in GWP under a 90% recycling scenario relative to no recycling depending on whether the wood fiber came from forests with stable or increasing carbon or decreasing carbon.

In general, the longer the service length of a building the greater the climate benefit. In terms of scale, 82 billion square feet of existing space will be demolished and replaced in the United States between 2005 and 2030, which is roughly 25% of the U.S. building stock in 2011 (National Trust for Historic Preservation 2011). One study estimates a savings of 4-46% in environmental impacts by retrofitting instead of demolishing buildings- this scaled up to a savings of 231,000 metric tons CO_2e over 10 years (National Trust for Historic Preservation 2011).

5.1 Areas of Uncertainty in End-of-Life Assumptions

Because mass timber buildings are relatively new, there is large uncertainty about the end-of-life fate (whether recycled, landfilled, or incinerated). Not only is there uncertainty in the amount of material that will be landfilled, but there are also different assumptions about landfill decay for wood products.[3] For example, the widely use US EPA WARM model assumes 88% of carbon disposed in landfill remains permanently and of the 12% that is emitted, 50% is released as methane. ATHENA whole building LCA impact estimator assumes that 23% of wood in a landfill decomposes. Tally, another WBLCA tool assume a decomposition amount 50%. Finally, the IPCC uses a First Order Decay Model to simulate landfill GHG emissions (Lan et al 2020).

6. POTENTIAL IMPACTS ON FOREST CARBON STOCKS AND FOREST CONDITION OF INCREASED DEMAND FOR WOOD PRODUCTS

Of great interest to policy makers and users of mass timber is the potential impacts that increasing demand for mass timber products could have on forest carbon stocks and forest quality. There are several ways to investigate this topic, including looking at demand relative to existing supply, examining empirical studies showing past demand impact on forest supply, and consequential LCA that incorporate economic-ecological feedback models.

6.1 Demand Relative to Current Supply Analyses

Some studies look at project demand relative to current harvest or current supply. Beyreuther et al (2016) conducted a CLT demand study for the Pacific Northwest (WA, OR, ID, MT) between 2016 and 2025 and predicted that demand for CLT panels could range from 6-12 million ft^3 annually, which represent <5% of current harvest for lumber production (1,000 million ft^3). The Beck Group (2018) expanded to include 17 Western States and predicted CLT demand to be 18 million cubic ft in 2025, translating to 200 million Scribner board feet increased log demand. At the high end, if CLT were to capture an additional 5-15% market share of non-residential construction in the US, 60 to 180 million cubic ft CLT would be needed, which translates into 660 million– 2 billion Scribner board feet lumber demand, roughly 1-3% of current softwood harvest, which is roughly 60 billion board ft. The North American State of Mass Timber Market 2020 suggested that the number of buildings made from mass timber could double every 2 years between 2020 and 2034, which would equate to an increase in lumber demand of 12.9 billion board ft by 2034 (assumes average building size of 25,000 square ft), which would be a 21.5% increase in softwood lumber demand over 2019 (Anderson et al 2020). Churkina et al (2020) suggested that increased use of timber in construction could require harvesting 0.2-0.15 Gt C per year in the 10% timber scenario, 0.08-0.75 Gt C per year in the 50% scenario and 0.15-1.36 Gt C per year in the 90% timber scenario over the next 30 years (which is roughly twice as much as the carbon that will be stored). They suggested that this increased harvest could be met with the current projected increase in sustainable forest harvest yields, which is expected to increase by 3.6 to 4.9 GtC globally by 2050. In addition, increased demand could be met with a combination of a) shifting some existing harvest (global harvest in 2015 was ~1.3 Gt C) away from shorter lived products (including fuelwood) to mass timber b) planted forests, whose wood production is expected to reach 0.4-1.75 Gt C in 2050.

6.2 Empirical Studies on Demand and Forest Impacts

Another way is to look at empirical evidence of what has happened to forest supply with increasing forest products demand in the past. In 2010, Peter Ince of the USFS conducted a global analysis using FAO data to overlap industrial roundwood harvest with forest carbon stocks and land-use change. He found that the countries with the highest levels of industrial roundwood harvest in fact had the lowest levels of land-use change and most stable carbon stocks, and vice versa (Ince 2010), demonstrating that wood can be sourced without reducing carbon stocks. Empirical evidence in specific countries have shown that significant increases in harvest and standing inventory can happen concurrently. Sweden almost doubled harvest between 1955 and 2005 and increased standing inventory by 60% in the same time-period (Royal Swedish Academy of Agriculture and Forestry 2010). The US increased growing stock volume by 60% since 1953 with harvest roughly the same (incidentally, in the last 20 years, mortality has increased 90% while harvest has been reduced by 20%) (Oswalt et al 2018). Lubowski et al (2008) examined the drivers for land-use change (to and from forests) in the U.S. between 1982 and 1997 and found that a rise in timber net returns was the most important factor driving increase in forest areas in that time.

6.3 Consequential LCAs and Economic-Ecologic Models

Consequential LCAs incorporate economic models to understand the environmental impact of increasing or decreasing production of a product or service (Earles and Halog 2011) and can be used to help predict impacts of increased demand for wood products on forest landowners' responses in different regions, given a set of assumptions. Economic and global trade models are used for forest market predictions and national forest planning analyses, such as the US Resource Planning Act assessments (Wear 2013). In the 2010 RPA assessment, a forest scenario forecast for the US South found that a higher forest product price (demand) would keep 9 million more acres in forest compared to a lower price (demand) (Wear 2013).

Nepal et al (2016) used a consequential LCA to understand potential carbon impacts of increased softwood lumber and structural panel use in non-residential construction in the U.S, including changes in forest carbon, HWP C storage, substitution, and logging slash pools. They modeled two scenarios for projected wood use of US softwood lumber to 2060: a baseline scenario representing current market penetration of wood, and a high wood use scenario, which increased demands for US softwood lumber and structural panels for an additional 5.3 million m^3 of softwood lumber and 2.3 million m^3 structural panels for use in low-rise non-residential buildings, based off a market analysis study by Adair et al (2013). They found that the high wood use scenario would yield an additional 870 million metric tons CO_2e by 2060, with the most benefit coming from avoided emissions in substitution, followed by additional carbon storage in wood products. Demand projection impacts on forest carbon stocks were simulated for the south, west, and northern regions. The study found that forest carbon stocks will INCREASE relative to the baseline scenario in the Southeast, accounting for an additional 182 million metric tons CO_2e sequestration in SE forests. Past research (Wear 2011) found that changes in timber prices can predict changes in timberland area in the South, but not the north and west. Therefore, forest investment was not modeled in the West and North in this study so the carbon stock losses that are predicted may be overestimated in these areas.[4]

Eriksson et al (2012) integrated a wood product substitution model, a global partial equilibrium model, a regional forest model, and a stand-level model to compare three scenarios over a BAU case in Europe. Two scenarios assumed building 1 million additional apartment flats per year of wood by 2030, which would have little impact on markets and forest management and would reduce GHG emissions by 0.2-0.5% of total 1990 European GHG emissions. The scenario of a very high increase in wood consumption (7% increase per year from 2012-2030) had large impacts on carbon, volumes, trade and potentially forest management. The study examined the forest management impacts further through a stand level model that found that increasing demand for sawlogs could result in relatively little change in carbon stocks in the forest, even with high levels of harvest because there would be a shift away from pulp rotations to longer rotations and perhaps more emphasis on thinning.

Mendelsohn and Sohngen (2019) attempted to describe the impacts of past land-use change and forest management versus a scenario with no harvest using an economic-ecological model of global forests, the Global Timber Model. They modeled impacts of historical harvest and land-use change from 1900 – 2012 and compared against a scenario in which the forests were not harvested. They found that despite extensive land-use change and draw-down of primary forests, the combination of forest investment, regrowth and carbon fertilization has meant that global forest biomass (including HWP) has increased by 94 $GtCO_2$ between 1900 and 2010. However, under the Natural Forest Scenario, the model predicts that global forest biomass would have increased by 194 Gt CO_2 in that same period. Incidentally, in both the US and Europe, the Natural Forest Scenario was predicted to yield LESS increase in forest biomass than what the Historical Market Scenario achieved. The US had substantially more forest biomass compared to the Natural Forest Scenario, largely due to wide-scale replanting after 1950 as well as the impact of fire suppression, which has caused less land burned over the last century relative to ecological models.

Mendelsohn and Sohngen describe this global outcome as the sum of three major impacts on land use and land use change over the 20th century: substantial conversion of forestland into farmland, extensive harvest of the world's "accessible" primary forest, and subsequent investment to renew the forest. They predict that harvest in the future will largely depend on secondary and managed forests, and forest investment will be positively influenced by increasing demand.

Tian et al (2018), applied The Global Timber Model to predict forest outcomes for the US over the next 100 years. They found that if no new land or management is allowed, net forest sequestration will decline (14% over next 30 years and 30% over next 100 years) but the forests will still remain a net sink. However, if a high demand (in this case a doubling of demand from the baseline) for forest products is implemented, the forests will increase net sequestration by 14% MORE than the baseline, yielding 6,220 Tg[5] C (22,807 Tg CO_2) MORE carbon sequestered by 2100.

6.4 Different Strategies for Forest Management

Consequential LCAs that include impact of demand on forest supply can answer the impact that using wood as a building material can have throughout the entire value chain (from forest through to end-of-life). However, it does not answer the question from the forest perspective. It does not answer the question, "Is it more efficient to store carbon in forests instead of using forests for products and energy?" (Leskinen et al 2018).

Smyth et al (2020) examined six regions in North America with different starting growth rates, land-use change rates, and afforestation rates (Western BC- pine and fir; Ontario (spruce and poplar) (Northern US- maple and birch, SE US- pine and oak, Northern Mexico- coniferous and broadleaf, SE Mexico- semi-deciduous, semi-evergreen). They modelled different strategies, such as decreasing harvest, using residues for bioenergy, increasing long lived wood product (LLP), increasing productivity, increasing afforestation, reducing deforestation, and examined their net climate impact. Different mitigation pathways rose to the top depending on the region and current practices, e.g., reducing deforestation yielded the most benefit in the Mexico regions while afforestation and reduce deforestation yielded the most benefit in the US SE. However, across all regions, increasing the proportion of LLP provided a climate benefit because it enhanced carbon storage in HWPs and provided increased substitution benefits.

Oliver et al (2014) highlighted two different pathways proposed for carbon sequestration and protection of forest biodiversity: to minimize harvest and store more carbon in the forest or to actively manage forests to produce solid wood products and wood energy that avoid CO_2 emissions. Using global calculations Oliver et al estimated that 0.9 m^3/ha wood is being harvested, which is less than the average forest growth, suggesting there is room to increase harvest without reducing forest carbon stocks. In addition, over half of global harvest is still fuelwood harvest, often resulting in efficient open fire burning. Oliver et al look at biodiversity impacts of increased harvest by suggesting that more active management with set-aside areas in each forest-type may, in fact, better provide the range of biodiversity that is needed. In their words "the present fragmentation, reduction in forest area, and imbalance of structure may mean that it is prudent for active management to provide the diversity of structures rather than anticipate that natural processes will return the diversity" (Oliver et al 2014).

Law et al (2018) examined different strategies for forest management in the Pacific Northwest (Oregon), including afforestation, reforestation, forest management changes and harvest residue bioenergy use. The study did not include carbon stored in buildings or substitution, citing the temporary nature of products in use and uncertainty around substitution factors as the reason for omission. Law et al modeled different strategies until 2100 and found the most gains in forest carbon if harvest cycles were lengthened to 80 years on private lands and harvested areas were reduced 50% on public lands, though leakage from short-term harvest reduction was not incorporated. The study also reported current net sequestration in Oregon's forests, with net sequestration (growth minus fire minus harvest) referred to as "Net ecosystem carbon budget" (NECB) and emissions from fire and harvest (not the growth of the trees) referred to as "forest sector", leading many readers to believe that the forest sector is one of the largest sources of GHG emissions from the state. This characterization is considered incomplete by some (can only the harvest be attributed to the forest sector and not the tree growth?). In a follow-up study, Hudiberg et al (2019) included NECB in the forest sector and expanded to include harvest, transportation, and manufacturing emissions, wood product and landfill inputs and decay, as well as substitution estimates. They found that "Combined, the US west coast state forest sector (cradle-to-grave) is a net carbon sink, removing ~187 MMT CO_2e annually from the atmosphere and potentially reducing fossil fuel emissions by up to another 20 MMT CO_2e through product and energy substitution" (Hudiberg et al 2019).

While there can be agreement that the forest and wood product system, even without substitution benefits, can be net sinks, a fracture line surfaces on whether the strategy of harvesting for wood products yields the most climate benefits. Smyth et al found a decreased harvest pathway dependent on two things 1) the substitution factor of the foregone harvest (the smaller the factor the better it is to keep in forest) and 2) the disturbance rate of the forest. Smyth points out that it is becoming ever more important to consider climate change in consideration of disturbance rates.

7. STAKEHOLDER FEEDBACK

As part of the process for uncovering areas of agreement and disagreement, six stakeholders, representing a wide range of viewpoints, offered feedback on how they felt about using mass timber as a climate solution. These stakeholders represented government, academia, consultants, and ENGOs in the US and Europe (though heavily weighted to Europe).

The lower embodied carbon in wood buildings compared with concrete or steel was not an area of dispute. Furthermore, even those who were worried about forest product demand on forests believed that the best use of wood (if it had to be harvested) was in long-lived products, such as buildings.

The tension was found in differences of opinions of how forest product demand would impact forests. For those who worried that the impact of increasing demand for wood on forests would negatively impact forests, a few key pieces of literature popped out as being especially influential: Law et al (2018), which is described above and examines different scenarios for forest management in the state of Oregon; and Ceccherini et al (2020), which suggests an abrupt increase in harvested forest area in Europe since 2015.[6] These helped form an opinion that increase demand for wood will decrease the forest sink relative to "what could happen if forests were left to grow".

Others believe that, in fact, forest product demand could have a positive impact on forests. They cite the U.S. RPA assessment (USFS 2010) as predicting more forests with a higher demand for forest products than fewer and empirical studies showing positive correlation between harvest and forest area/carbon stocks (Ince 2010). They also feel that there can be many improvements in forest harvest efficiency, citing the fact that currently 50% of global harvest is still used for fuelwood (mainly open fire cooking) (FAO 2020). One stakeholder felt that mass timber could be a great use for wood in the southeast, which is currently over-supplied.

Some stakeholders felt strongly that not all forests are the same and that biodiversity should be considered. They felt it was important to protect both the "quantity and quality" of forests. There was particular concern over the best strategy for European forests going forward, but one stakeholder pointed out that reducing harvest in a relatively well managed/regulated area may only put more pressure on global forest resources with less regulation.

Finally, there was recognition that end-of-life assumptions were uncertain but those who discussed this felt that storage should, in fact, be longer than current assessments. They felt that mass timber would have a better ease of deconstruction and reuse relative to light framing, where removal of nails can be cumbersome. In addition, many countries may enact regulations for better product reuse. For example, Austria has already banned landfilling wood.

8. FRACTURE LINES

Fracture Line 1: Uncertainty of Future and Assumptions

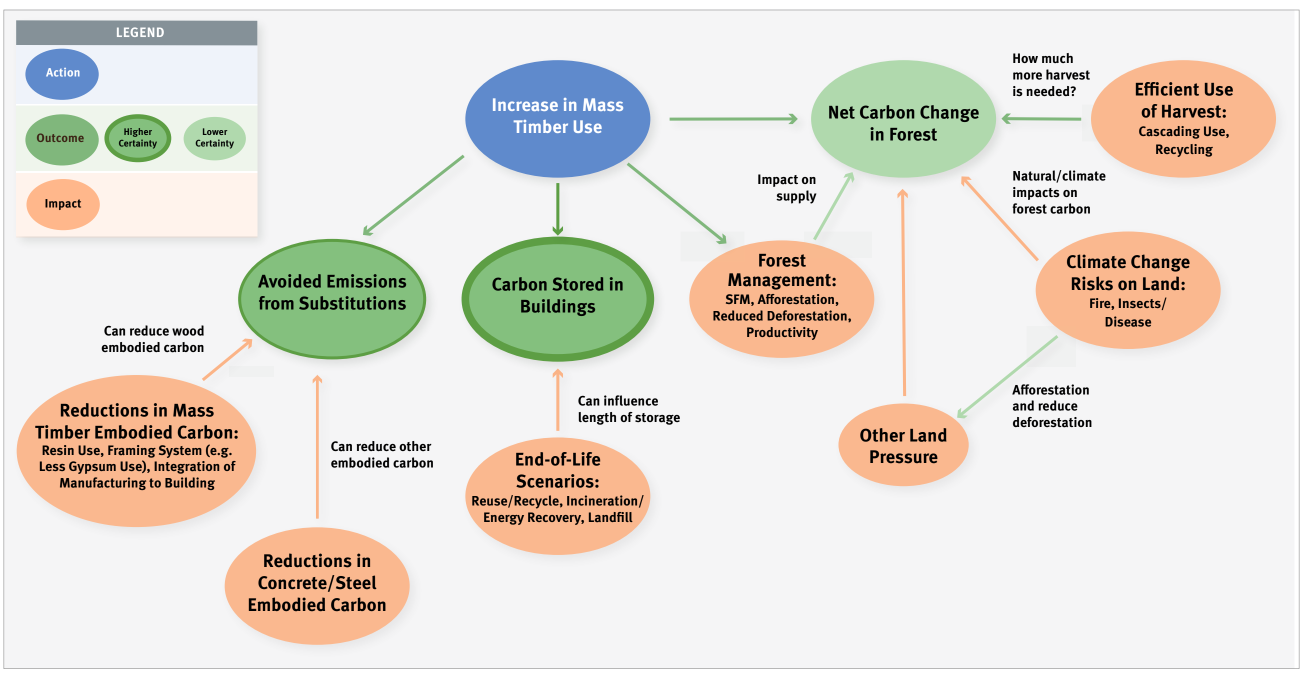

Figure 2: Systems Map Representing Potential Changes in Carbon with Increased Use of Mass Timber in Buildings

Figure 2 attempts to distill potential outcomes from a future with increased mass timber use relative to current practices and categorize areas of disagreement. These all assume equal building demand and size. Generally speaking, no matter what assumptions are made, solid wood construction products generate less GWP than alternative materials. The magnitude may change in the future as renewable energy sources lower embodied carbon for all products, but it should not reverse the results. Furthermore, there is general agreement that more mass timber use means more carbon stored in buildings, making the magnitude of GWP savings/benefit even greater, and improvements in end-of-life actions can improve the length of time of storage.

The biggest uncertainty, however, lies in the impact on the forest.

There are four major impacts that can influence forest carbon outcomes:

- **Harvest efficiency:** Increasing demand for mass timber products does not necessitate a 1:1 increase in wood harvest. Could forest degradation issues be ameliorated with increasing value of wood or will increasing demand for wood cause more forest degradation? Currently wood harvested for wood fuel (e.g., majority still open cook fire), accounts for ~50% of total global roundwood harvest (1.95 billion m^3 of total 3.97 m^3 harvested in 2019) (FAO 2020).
- **Natural/Climate impacts on forest carbon:** Disturbances, such as fire, hurricanes, windstorms, and drought are expected to increase in frequency and intensity with a changing climate (IPCC 2019). In addition, warmer temperatures can increase the likelihood of over-winter pest survival and drought-induced stress can reduce tree resilience. The US Forest Services predicts that 81 million acres of U.S. forests are at risk of losing at least 25% of their basal area in the next 15 years due to insects or disease without management intervention (Krist et al 2014). However, specific impacts are contextual. Are there forests better suited for forest carbon storage than others? Will increasing demand for wood lead to better forest management and increased forest resilience or will it exacerbate existing stresses? Simpson et al (2021) recently introduced a risk assessment framework with which to map out the role of mitigation and adaptation with increasingly complex interactions between multiple risk drivers.
- **Forest management strategies:** There is consensus that increasing forest area, reducing deforestation, and focusing on sustainable and productive forestry can all increase global forest carbon stocks (IPCC 2019, FAO 2016). There is disagreement as to 1) Does increasing harvest drive to or from these outcomes- what is the best climate strategy for the forest? 2) Is there enough land available? There is uncertainty on competition for land-use as well as impacts on biodiversity and other ecosystem services.
- **Other land-use pressure:** There are 13 billion hectares (36.4 billion acres) of land in the world (33% dessert) and 4.06 billion hectares (10 billion acres) of forest. How can we thoughtfully reimagine landscapes where forests, ag, and grazing are in places most suited for these activities? Can we address this fracture line with landscape planning strategies? A lot of work is being done in carefully mapping out reforestation potential- these could be helpful for future harvest demand. See the website: Reforestation Hub – Reforestation Opportunities for Climate Change Mitigation

FRACTURE LINE 2: DIFFERENCES IN QUESTIONS (WHICH INFLUENCES METHODOLOGY CHOICES)

There is consensus that forests are sustainable net sinks as long as forest carbon uptake from the atmosphere exceeds emissions from harvests, wood product use and decomposition, and wildfire (Hudiberg et al 2019). However, the fracture line is formed around whether being a net sink is adequate. Such a fracture line results from two different questions.

The forest level studies are designed to compare different scenarios of forest management, for example, was there more harvest than growth or a counter-factual of what would have happened in absence of harvest. Oliver et al (2014) examined both these questions and determined that, as long as harvest does not exceed forest growth, there is a climate benefit of using wood, though the benefit depends on the what the harvest is being used for. However, when foregone sequestration (i.e., letting the forest grow) is considered, the climate savings depends on a) the growth curve and risk of disturbance of the forest and b) the use (and substitution benefit) of the harvested wood. Can we align mass timber demand to forests with the best potential gains? Do we need to align, or will the market adjust?

FRACTURE LINE 3: FOREST QUALITY VERSUS FOREST QUANTITY

Though mentioned as a consideration in many studies, forest quality, meaning the full suite of ecosystem services, is rarely compared. Life cycle assessments are hardly equipped to incorporate biogenic impacts that have different temporal and spatial dynamics, much less impacts on biodiversity water quality, habitat etc. However, stakeholders felt strongly that not all forests should be managed intensively and there was a difference of opinion on the impacts of intensive management, ranging from always negative in comparison with the natural state of the forest (see e.g., de Warnaffe and Angerand 2020) to providing important habitat for different age class structures (see e.g., Confor 2020). Such a fracture line is not unique to this topic and has been addressed in many past Forest Dialogues.

9. CONCLUSION

Mass timber as a building material has garnered a lot of attention and is being touted as potential improvement for ease of construction and pre-fabrication as well as carbon reductions. The market is expected to grow in value by 13-16% per year through at least 2024, with the largest increases in new capacity in North America. The market is still in its infancy and there is a potential for growth globally, especially where there is an overlap of population and high-density building need, forest resource, and basic infrastructure for ease of transport.

Substitution

Studies that compare a mass timber framed building embodied carbon with a conventional alternative generally follow standard ISO life cycle assessment guidance. Some analyses include all life cycle stages except operating energy and operating water, while others focus on the upfront emissions associated with the production and construction phase (Stages A1-A5 according to ISO 15392). Though there are differences and uncertainty in assumptions, especially in end-of-life, studies almost universally show a savings in GWP emissions building with mass timber compared with a conventional alternative.

Because there are assumptions associated with the choice of the comparable building (do you compare against an average building type, a particular material, future efficiency predictions?), some have identified this as a source of uncertainty. However, the directional result (a favorable outcome with mass timber) is unlikely to change.

The biggest area of disagreement is in how biogenic carbon is treated, both in the forest and in wood product storage. The first life cycle assessments modeled growth at a stand level as that was a logical outcome of tracking a carbon atom through a product. However, forest systems do not operate at a stand level; landscape level analyses have been found to be more appropriate where a continuous flow of wood is needed for manufactured. Other types of baselines include a comparison to a "natural forest" (how close is the forest to what it was 300 years ago), or comparison to what would have happened in the forest without the harvest (e.g., foregone sequestration), or a comparison to common practice or regulatory guidelines. Regardless of methodological choice, the outcome of these analyses also depends on the location and status of the forest sourcing the mass timber used in substitution.

Storage

Though there is currently no standardize method for quantifying carbon storage in HWP, there is agreement there IS some storage. Efforts are underway to align different methodologies, including the in-progress GHG Protocol guidance on land use and removals, which will help address the need for standards for corporate quantification of carbon storage in HWP.

Demand Impacts on Forests

Predicting how potential increases in demand could impact *forest carbon stocks* and *conditions* requires expanding methodologies to include economic and ecological models. These types of analyses generally show that demand can and will likely increase investment in forest area and productivity and result in more carbon in forests, though likely there are different feedbacks at smaller scales. Studies that examine different forest scenarios are usually place specific and can identify important feedback of forest growth, disturbances, and harvest use. The greatest climate benefit gain compared to a no-harvest scenario would be from harvest for long-lived wood products from forests prone to natural disturbances.

There is general agreement that forest quality and biodiversity are important factors to consider and that LCAs generally are not equipped to assess these. However, there is disagreement on how to separately account for forest quality and how to characterize the impacts of intensive management.

Out of these conclusions three broad fracture line topics were surfaced:

- **Uncertainty of feedback loops:** Future impacts are influenced by multiple external factors and feedback loops (see Figure 2). Predicting future outcomes necessitates assumptions of future conditions (e.g., disturbance frequency, harvest efficiency, land-use conditions, management, end-of-life scenarios, energy sources….). Are we able to identify the key feedback loops and nudge them in the right direction?
- **Differences in questions:** Much of the variability in study outcomes, especially in biogenic carbon accounting, can be explained by differences in study questions. The two clearest differences are: 1) What is the impact of wood use on the forest (either today or in the future) versus 2) What is the best use of this forest for climate mitigation? Are we able to answer both questions?
- **Forest quantity vs. forest quality:** Though rarely addressed in LCA studies, there is general agreement that forests have more value than carbon alone. The importance of forest quality and biodiversity is an important fracture line that has and will continue to be discussed across all Forest Dialogues. Are there ways to further specify what the fracture line is beyond forest quantity vs. forest quality?

10. REFERENCES

Anderson R, Atkins D, Beck B, Dawson E, Gale CB, Hammond H, Kaiser B, Rawlings C. 2020. North American mass timber: State of the industry 2020. Missoula, MT: Forest Business Network.

Beyreuther, Todd; Ganguly, Indroneil; Hoffman, Matt; Swenson, Skip; CLT Demand Study for the Pacific Northwest, 2017, https://forterra.org/wp-content/uploads/2017/02/Pacific-NW-CLT-Demand-Study-December-2016.pdf

Bionova Ltd. 2018. The Embodied Carbon Review: Embodied Carbon Reduction in 100+ Regulations & Rating Systems Globally. www.embodiedcarbonreview.com.

Cao, Z. E. Masanet, A. Tiwari, and S. Akolawala. 2021. Decarbonizing concrete: deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China. Industrial Sustainability Analysis Laboratory, Northwestern University, Evanston, IL.

Ceccherini, G., G. Duveiller, G. Grassi, G. Lemoine, V. Avitabile, R. Pilli, A. Cescatti. 2020. Abrupt increase in harvested forest area over Europe after 2015. *Nature* 583: 72-77.

CEN. 2011. Sustainability of construction works – Assessment of environmental performance of buildings- Calculation method. EN 15987:2011.

Chen Z, Gu H, Bergman R, Liang S. 2020. Comparative Life cycle assessment of a high-rise mass timber building with an equivalent reinforced concrete alternative using the Athena Impact Estimator for Buildings. J of Sustainability Special Issue 12(11) 4708. https://doi.org/10.3390/su12114708

Chen, C., F. Pierobon, and I. Ganguly. 2019. Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) Produced in Western Washington: The Role of Logistics and Wood Species Mix. *Sustainability*. 11: 1278, doi:10.3390/su11051278

Churkina, G. A. Organschi, C. Reyer, A. Ruff, K. Vinke, Z Liu, B. Reck, T. Graedel, H. Schellnhuber. 2020. Buildings as a global carbon sink. *Nature Sustainability*. 3: 269-276.

Cintas, O. G. Berndes, A. Cowie, G. Egnell, H. Holmström, G. Marland, G. Agren. 2016. Carbon balances of bioenergy systems using biomass from forests managed with long rotations: bridging the gap between stand and landscape assessments. *Global Change Biology*. 9:1238-1251. doi: 10.1111/gcbb.12425

Confor. 2020. Biodiversity, forestry, and wood: an analysis of the biodiversity benefits of modern forestry and wood production. A Confor Special Report. confor-biodiversity-forestry-report.pdf.

De Warnaffe, G. and S. Angerand. 2020. Forest Management and Climate Change: A new approach to the French mitigation strategy. Report produced in partnership with Fern, Canopee and Friends of the Earth France. Study-Forest-Management_Climate-Change.pdf (fern.org)

D'Amico, B., F. Pomponi, and Jim Hart. 2021. Global potential for material substitution in building construction: The case of cross laminated timber. *Journal of Cleaner Production*. Vol 279. https://doi.org/10.1016/j.jclepro.2020.123487.

Durlinger, B. E. Crossin, J. Wong. 2013. Life Cycle Assessment of a Cross Laminated Timber Building. Forest & Wood Products Australia. Project No: PRA282-1112.

Earles, J.M. and A. Halog. 2011. Consequential life cycle assessment: a review. *International Journal of Life Cycle Assessment*. 16:445-453.

Ericksson, L.O., L. Gustavsson, R. Hänninen, M. Kallio, H. Lyhykäinen, K. Pingoud, J. Pohjola, R. Sathre, B. Solberg, J. Svanaes, L. Valsta. Climate change mitigation through increased wood use in the European construction sector- toward an integrated modelling framework. *European Journal of Forest Research* 131:131-144.

Espinoza, O., V.R. Trujillo. M.F.L. Mallo, U. Buehlmann. 2016. Cross-Laminated Timber: Status and Research Needs in Europe. *Bioresources* 11(1): 281-295.

FAO. 1999. Forest Product Market Development: The Outlook for Forest Product Markets to 2010 and the Implications for Improving Management of the Global Forest Estate. Chapter 2: Factors Influencing the Supply and Demand for Wood and Wood Products. 2.2 Factors likely to affect the supply of wood and other fibre. Written by Whiteman, A., C. Brown, and G. Bull. x4108e.pdf (fao.org).

FAO. 2016. Forestry for a low-carbon future: Integrating forests and wood product in climate change strategies. Food and Agriculture Organization of the United Nations. Cover--I+IV final (fao.org).

FAO. 2020. Forest Product Statistics Facts and Figures. Forest product statistics (fao.org)

Ganguly, I., F. Pierobon, E. Sonne Hall. 2020. Global warming mitigating role of wood products from Washington State's Private Forests. *Forests*. 11(2): 194. https://doi.org/10.3390/f11020194

Harmon, M. 2019. Have product substitution carbon benefits been overestimated? A sensitivity analysis of key assumptions. *Environmental Research Letters 14:* Article 065008.

Himes, A., and G. Busby. 2020. Wood buildings as a climate solution. *Developments in the Built Environment.* (4)

Hudiberg, T., B. Law, W. Moomaw, M. Harmon, J. Stenzel. 2019. Meeting GHG reduction targets requires accounting for all forest sector emissions. *Environmental Research Letters* 14: Article 095005.

Ince, Peter. 2010. Sustainable development in the forest products industry, Chapter 2. Porto, Portugal: Universidade Fernando Pessoa, 2010: p. 29-41. ISBN: 9789896430528. http://www.fpl.fs.fed.us/documnts/pdf2010/fpl_2010_ince001.pdf.

International Energy Association and World Business Council on Sustainable Development. 2018. Cement Technology Roadmap Plots Path to Cutting CO2 Emissions 24% by 2050. Cement technology roadmap plots path to cutting CO2 emissions 24% by 2050 - News - IEA.

International Energy Agency, United Nations Environment Programme 2019 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector (Geneva: United Nations Environment Programme) p 325

IPCC. 2019. IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems.

ISO. 2017. Sustainability in buildings and civil engineering works- Core rules for environmental product declarations of construction products and services. International Organization for Standardization. Second edition (ISO 21930:2017-07) 80pp.

ISO. 2019. Sustainability in buildings and civil engineering works- General principles. International Organization for Standardization. Second edition.

Johnston and Radeloff 2019. Global mitigation potential of carbon stored in harvested wood products. *PNAS*. https://www.pnas.org/content/116/29/14526

Kardung, M., K. Cingiz, O. Costenoble, R. Delahaye, W. Heijman, M. Lovric, M. van Leeuwen, R. M'Barek, H. van Meijl, S. Piotrowski, T. Ronzon, J. Sauer, D. Verhoog, P. Verkerk, M. Vrachioli, J. Wesseler, B Zhu. 2021. Development of the Circular Bioeconomy: Drivers and Indicators. *Sustainability* 13 (1): 413. https://doi.org/10.3390/su13010413

Kongsgaard, A.S., A. Nguyen, K. Arvind, C. Hardman. 2020. Identifying Sustainable Mass Timber Markets. To fulfill GV342M Philosophy, Politics and Economics: Capstone Course at the London School of Economics and Political Science.

Krist, Jr. F.J., J.R. Ellenwood, M.E. Woods, A.J. McMahan, J.P. Cowarding, D.E. Ryerson, F.J. Sapio, M.O. Zweifler, and S.A. Romero. 2014. 2013–2027 National Insect and Disease Forest Risk Assessment. U.S. Forest Service, Forest Health Technology Enterprise Team. FHTET-14-01.

Lan, K., S. Kelley, P. Nepal, and Y. Yao. 2020. Dynamic life cycle carbon and energy analysis for cross-laminated timber in the Southeastern United State. *Environmental Research Letters* 15: 124036.

Law, B. T. Hudiberg, L. Berner, J. Kent, P. Buotte, M. Harmon. 2018. Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences of the United States of America*. 115: 3663-3668.

Leskinen, P., G. Cardellini, S. González-García, E. Hurmekoski, R. Sathre, J. Seppälä, C. Smyth, T. Stern, and P. Verkerk. 2018. Substitution effects of wood-based products in climate change mitigation. From Science to Policy 7. European Forest Institute.

Leturcq, P. 2020. GHG displacement factors of harvested wood products: the myth of substitution. *Scientific Reports*. 10: 20752 (2020). https://doi.org/10.1038/s41598-020-77527-8

Levasseur, A.; Lesage, P.; Margni, M.; Brandão, M.; Samson, R. Assessing temporary carbon sequestration and storage projects through land use, land-use change and forestry: Comparison of dynamic life cycle assessment with ton-year approaches. *Clim. Chang.* 2012, 115, 759–776.

Liang S, Gu H, Bergman R, Kelley S. 2020. Comparative life-cycle assessment of a mass timber building and concrete alternative. Wood and Fiber Science 52(2):217-229. https://www.fs.usda.gov/treesearch/pubs/60137

Liu et al., "Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China—A Life-Cycle Assessment Approach," *Sustainability* 8(10), 2016, https://www.mdpi.com/2071-1050/8/10/1047/htm;

Lippke, B., E. Oneil, R. Harrison, K. Skog, L. Gustavsson, R. Sathre. 2011. Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. *Carbon Management*. 2: 303-333. https://doi.org/10.4155/cmt.11.24

Lomax, G., and J. Laurence. 2019. The Forest Economy and Climate Change: a review of greenhouse gas mitigation in Europe's forests and forest products. A report prepared by TNC for EIT Climate-KIC.

Lubowski, R., A. Plantiga, R. Stavins. 2008. What drives land-use change in the United States? A national analysis of landowner decisions. *Land Economics*. 84(4): 529-550.

Mendelsohn, R., and B. Sohngen. 2019. The net carbon emissions from historic land use and land use change. *Journal of Forest Economics.* 34: 77-97.

Milaj, K, A. Sinha, T. Miller, and J. Tokarczyk. 2017. Environmental Utility of wood substitution in commercial buildings using life-cycle analysis. *Wood and Fiber Science*. 49(3)

Moomaw, W., C. Hanson, D. DellaSala. 2020. Over 200 Top U.S. Climate and Forest Scientists Urge Congress: Protect Forests to Mitigate Climate Crisis. PressReleaseANDClimateANDForestScientistLetterMay2020.pdf (johnmuirproject.org).

National Trust for Historic Preservation. 2011. The Greenest Building: Quantifying the Environmental Value of Building Reuse. A report by: Preservation Green Lab for the National Trust for Historic Preservation. The_Greenest_Building_Exec_Summary-ilovepdf-compressed.pdf (bostonpreservation.org)

Nepal, P., K. Skog, D. McKeever, R. Bergman, K. Abt, R. Abt. 2016. Carbon Mitigation Impacts of Increased Softwood Lumber and Structural Panel Use for Nonresidential Construction in the United States. *Forest Products Journal* 66(1/2): 77-87.

O'Connor J., S. Horst, C. Argeles. 2005. Survey on Actual Service Lives for North American Buildings presented at 10DBMC International Conference on Durability of Building Materials and Components.

Oliver, C., N. Nassar, B. Lippke, and J. McCarter. Carbon, Fossil Fuel, and Biodiversity Mitigation with Wood and Forests. *Journal of Sustainable Forestry*. 33:3, 248-275. https://doi.org/10.1080/10549811.2013.839386

Oswalt, Sonja N.; Miles, Patrick D.; Pugh, Scott A.; Smith, W. Brad. 2018. Forest Resources of the United States, 2017: a technical document supporting the Forest Service 2020 update of the RPA Assessment. Gen. Tech. Rep. WO-xxx. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office.

Palahi, M., R. Valbuena, C. Senf, N. Acil, T. Pugh, J. Sadler, R. Seidl, P. Potapov, B. Gardiner, L. Hetemäki, G. Chirici, S. Francini, T. Hlásny, B. Lerink, H. Olsson, J. Olabarria, D. Ascoli, A. Asikainen, J. Bauhus, G. Berndes, J. Donis, J. Fridman, M. Hanewinkel, H. Jactel, M. Lindner, M. Marchetti, R. Marušák. D. Sheil, M. Tomé, A. Trasobares, P. Verkerk, M. Korhonen, G. Nabuurs. 2021. Concerns about reported harvests in European forests. *Nature* 592: E15-E17.

Passerelli, R.N. 2019. Environmental benefits of reusable modular mass timber construction for residential use in Japan: an LCA approach. Modular and Offset Construction Summit. Banff, Canada.

Peñaloza, D., F. Røyne; G. Sandin; M. Svanström, M Erlandsson. 2019. The influence of system boundaries and baseline in climate impact assessment of forest products. *The International Journal of Life Cycle Assessment* 24: 160-176. https://doi.org/10.1007/s11367-018-1495-z

Pierobon, F., M. Huang, K. Simonen, I. Ganguly. 2019. Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest. *Journal of Building Engineering 26*, 100862. https://doi.org/10.1016/j.jobe.2019.100862

Pomponi, F. and A. Moncaster. 2018. Scrutinising embodied carbon in buildings: The next performance gap manifest. *Renewable and Sustainable Energy Reviews*. 81(2): 2431-2442.

Royal Swedish Academy of Agriculture and Forestry (KSLA). 2010. *The Swedish Model.* The-Swedish-Forestry-Model.pdf (ksla.se). accessed 2/9/21.

Sahoo, K., R. Bergman, S. Alanya-Rosenbaum, H. Gu. 2019 Life cycle assessment of forest-based products: a review. *Sustainability*. Vol 11. https://doi.org/10.3390/su11174722

Sandin, G., G. Peters, M. Svanstrom. 2014. Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling. *International Journal of Life Cycle Assessment.* 19: 723-731.

Simonen, K., B. Rodriguez, C. De Wolf. 2017. Benchmarking the embodied carbon of buildings. *Technology Architecture + Design.* 1(2). Doi: 10.1080/24751448.2017.1354623

Simpson, N., K. Mach, A. Constable, J. Hess, R. Hogarth, M. Howden, J. Lawrence, R. Lempert, V. Muccione, B. Mackey, M. New, B. O'Neill, F. Otto, H-O. Pörtner, A. Reisinger, D. Roberts, D. Schmidt, S. Seneviratne, S. Strongin, M. van Aalst, E. Totin, C. Trison. 2021. A framework for complex climate change risk assessment. *One Earth.* 4(4): 489-501.

Smyth, C.E., A. J. Dugan, M. Olguin, R. Birdsey, C. Wayson, A. Alanis, and W.A. Kurz. 2020. A synthesis of climate change mitigation options based on regional case studies of the North American forest sector using a harmonized modeling approach. *Canadian Forest Service Pacific Forestry Centre Information Report.* BC-X-445.

Spear, M, C. Hill, A. Norton, C. Price. 2019. Wood in Construction in the UK: An Analysis of Carbon Abatement Potential. Report: BC-1383-2018-ES. Commissioned for the Committee on Climate Change. The Bio-Composites Centre.

Tian, X., B. Sohngen, J. Baker, S. Ohrel, A. Fawcett. 2018. Will U.S. forests continue to be a carbon sink? *Land Economics*. 94(1): 97-113.

The Beck Group. 2018. Mass Timber Market Analysis. Completed for: Council of Western State Foresters.

UN Environment Programme. 2020. Emissions Gap Report 2020. https://www.unep.org/emissions-gap-report-2020

United Nations Environment Programme (2020). 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi.

Vogtländer, J., N. van der Velden, P. van der Lugt. 2014. Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; cases on wood and on bamboo. *International Journal of Life Cycle Assessment*. 19: 13-23.

Wahlstrom, S. L. Gullbrekken, K. Elvebakk, T. Kvande. 2020. Experience with CLT Construction in Norway. *E3S Web of Conferences* 172. http://doi.org/10.1051/e3sconf/2020172 0 10 08

Wear, D., R. Huggett, R. Li, B. Perryman, and S. Liu. 2013. Forecasts of Forest Conditions in U.S. Regions Under Future Scenarios: a technical document supporting the Forest Service 2012 RPA Assessment. Gen. Tech. Rep. SRS-170. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 101 p.

Xoxha, E., A. Passer, M. R. M. Saade, D. Trigaux, A. Shuttleworth, F. Pittau, K. Allacker, G. Habert. 2020. Biogenic carbon in buildings: a critical overview of LCA methods. *Buildings and Cities*. 1(1), 504-524. DOI: http://doi.org/10.5334/bc.46

11. ENDNOTES

1 Total GHG emissions in 2019 were GHG emissions in 2019 were 54 gigatons CO2e; of that 33 gigatons were carbon dioxide emissions. Global CO2 emissions in 2019 – Analysis - IEA

2 Info Sheets_Final_200616.pdf (tallwoodinstitute.org)- Data source: Imarc Group. 2019. Press release: cross-laminated timber market: Global industry trends, share, size, growth, opportunity and forecast 2019-2024. Retrieved May 23, 2019, from https://www.imarcgroup.com/cross-laminated-timber-manufacturing-plant

3 Info Sheets_Final_200616.pdf (tallwoodinstitute.org)

4 "Note that the forest investment effect was not modeled in the North and the West. Wear (2011) found that changes in timber prices were not significant in predicting changes in timberland area in these regions. The higher loss of forest inventory in the West could be an overestimate, to the extent that timber harvest would selectively come from faster growing forest areas and to the extent that the production increase is more evenly distributed across plywood, lumber, and OSB." Nepal et al 2016.

5 Teragram = million metric ton

6 Note: a follow-up study (Palahi et al 2021) confirms that forest harvest is increasing in Europe but by 6%, not 69% as stated in the Ceccherini article.

TFD OVERVIEW

The Forests Dialogue (TFD), formed in 2000, is an outgrowth of dialogues and activities that began separately under the auspices of the World Business Council for Sustainable Development, The World Bank, the International Institute for Environment and Development, and the World Resources Institute. These initiatives converged to create TFD when these leaders agreed that there needed to be a unique, civil society driven, on-going, international multi-stakeholder dialogue forum to address important global forestry issues.

TFD's mission is to address significant obstacles to sustainable forest and landscape management through a constructive dialogue process among all key stakeholders. TFD's approach is based on mutual trust, enhanced understanding, and commitment to change. Dialogue initiatives are designed to build relationships and to spur collaborative action on the highest priority issues facing the world's forests.

TFD is developing and conducting international multi-stakeholder dialogues on the following issues:

- Climate Positive Forest Products
- Forests and Climate Change
- Land Use Dialogues
- Tree Plantations in the Landscape

There are currently 24 members of the TFD Steering Committee. The Steering Committee is responsible for the governance and oversight of TFD's activities. It includes representatives of indigenous peoples, the forest products industry, ENGOs, retailers, unions, and academia.

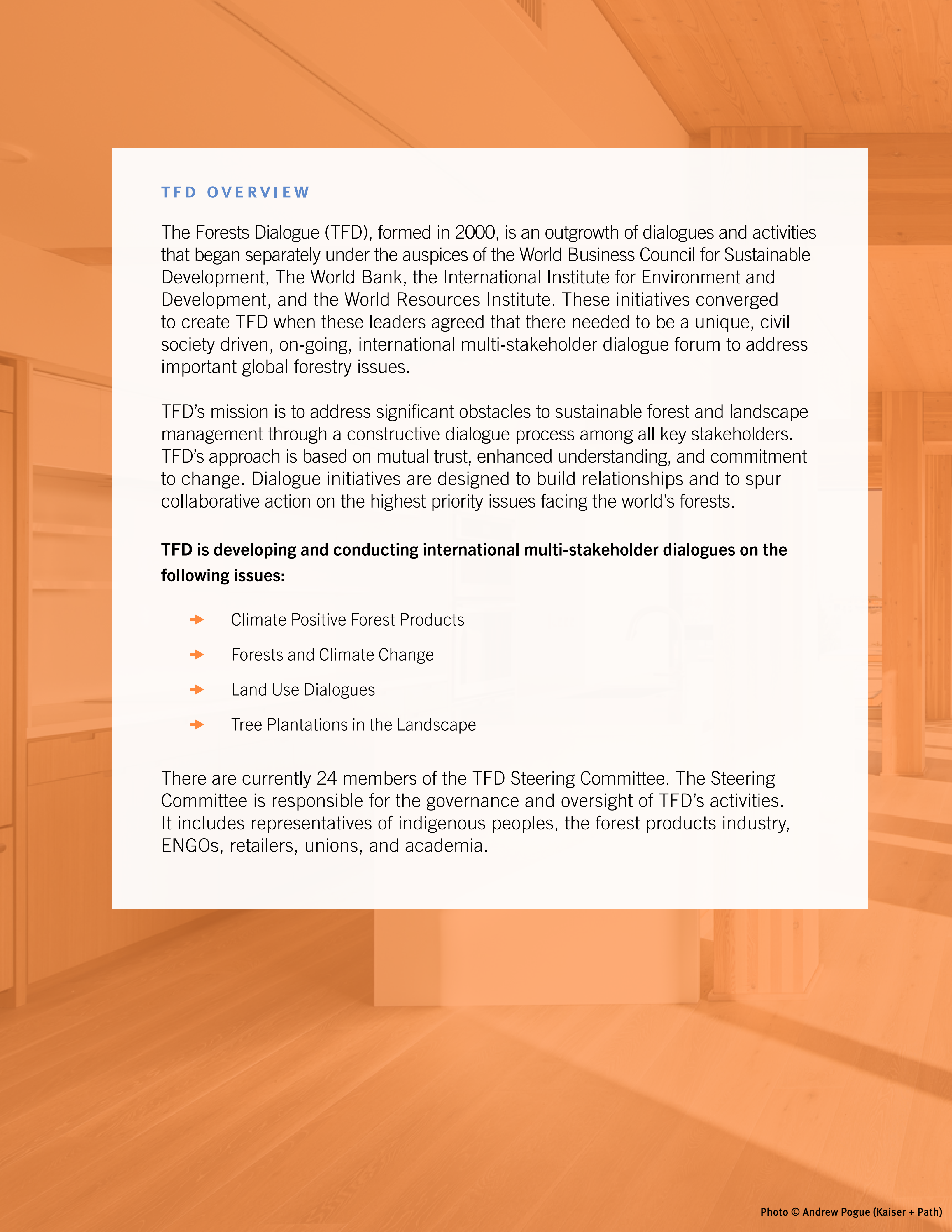

Photo © Andrew Pogue (Kaiser + Path)