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TALL WOOD BUILDINGS
DESIGN, CONSTRUCTION AND PERFORMANCE

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FOREWORD

We are living in an age which will come to be dominated by our relationship with the planet. As the changes to our climate become ever more apparent, the way we live and inhabit the earth will, by necessity, be transformed.

A fundamental change in the way in which we build our cities is imperative, re-learning how to build in timber and how to build tall with the new engineered timbers that the 21st century technologies allow will be fundamental to our future. This new age of architecture takes us beyond the notions of modernism and concrete construction to a new timber age.

Timber is the only construction material that can be grown and as it grows it consumes carbon. Using timber not only reduces our impact on the planet but will also help to reverse some of the effects of 20th century industrialization. Timber construction is not only healthy for our planet but is also healthy for humans. Living and working in timber buildings is good for the soul and good for health. The time has come again to leave behind inhospitable concrete caves and embrace the timber age.

A new architecture will emerge as we learn how to build in timber. We are the very beginning of this new and exciting era, this book marks the beginning of this new age and will help to provide the inspiration and momentum for the exciting new architecture to come.

Andrew Waugh
Waugh Thistleton Architects, London
August 2016

WOOD, A MATERIAL FOR OUR TIME

As the 21st century unfolds, architecture stands at a crossroads. Until now there has been no reason to challenge the supremacy of concrete and steel as the materials of choice for high-rise buildings, but in the past decade our evaluation criteria have become more complex. The core tenets of 'commodity, firmness and delight', first proposed by the Roman architect Vitruvius 2000 years ago as the prerequisites for a fine building, now fall within a framework of pressing global imperatives that are daunting in both scale and scope. The practice of architecture must now encompass the issues of climate change, population growth, and a global housing shortage.

In the spring of 2015, the National Oceanic and Atmospheric Administration (NOAA), a scientific agency based in Washington, DC, announced that changes in the Earth's climate system had reached a significant and disturbing milestone. For the first time since the NOAA began measuring the concentration of carbon dioxide in the atmosphere at 40 sites around the globe, the average of those monthly measurements exceeded 400 parts per million (ppm).

According to the NOAA, this represents an increase of approximately 120ppm since industrialization began about 200 years ago. As we know, the rapid rise in CO_2 emissions has been driven by technological development, population growth and the commensurate increase in fossil fuel consumption. However, the accumulation of CO_2 and other greenhouse gases in the atmosphere has not been linear, as 60ppm of the increase has occurred in the last 50 years, and 7.5ppm in the last three years alone.

At 400ppm, the atmospheric concentration of CO_2 is at a level not seen on Earth for millions of years and the implications are significant. In the words of Dr. Erika Podest, carbon and water cycle research scientist with NASA: 'This milestone is a wakeup call that our actions in response to climate change need to match the persistent rise in CO_2. Climate change is a threat to life on Earth and we can no longer afford to be spectators.'[1]

Implicit in Dr. Podest's statement is the assertion that we cannot manifest the changes that are necessary to stabilize the climate system simply by fine-tuning our current way of doing things – rather we must completely transform our commercial and industrial practices to radically reduce, and ultimately eliminate, their carbon footprint.

Also in the spring of 2015, two devastating earthquakes in Nepal, resulting in the collapse of hundreds of buildings and the loss of more than 8000 lives, came as a tragic reminder of the substandard conditions in which far too many people in the developing world live and work. As with climate change, the statistics are alarming. UN Habitat has estimated that 1 billion people (one in seven of the world's population) currently live in slums, and a further 100 million are homeless.[2]

As the world population continues to increase, it is projected that we will need to construct 3 billion units of affordable housing over the next 20 years. The vast majority of these will be required in the cities of the developing world, where population growth is taking place most rapidly.

At first glance the challenges of climate change and world housing might appear to be unrelated. Of the two, climate change receives more attention in the developed world, as its environmental and economic effects are felt directly in the wake of increasingly frequent hurricanes and floods, droughts and forest fires. By contrast, while access to adequate and secure housing is recognized by the United Nations as a universal human right, it is not a daily concern for most people in the West.

The reverse is true in the developing world, where vast numbers of people live at or below the poverty line, and for whom the overriding concern is the day to day search for enough food to eat and a safe place to sleep. Understandably, for those living in such circumstances, the mitigation of climate change may be so far beyond their control that it is nothing more than an abstract concept.

However, leaders in the sustainability movement increasingly believe that the solution to the environmental crisis is inextricably intertwined with issues of equity, democracy and social justice – not just within national boundaries, but across the world. This position was eloquently summarized by Andrew Ross in his 2011 book *Bird on Fire*, when he wrote: 'The task of averting drastic climate change might be described as an experiment – a vast social experiment in decision-making and democratic action. Success in that endeavour will not be determined primarily by large technological fixes, though many will be needed along the way. Just as decisive to the outcome is whether our social relationships, cultural beliefs, and political customs will allow for the kind of changes that are necessary. That is why the climate crisis is as much a social as a biophysical challenge, and why the solutions will have to be driven by a fuller quest for global justice than has hitherto been tolerated or imagined.'[3]

To frame the challenge in architectural terms, approximately one third of global greenhouse gas (GHG) emissions are attributable to the construction and operation of buildings. The Intergovernmental Panel on Climate Change (IPCC) has estimated that these emissions increased at an annual average of more than 2% between 1971 and 2004. Historically the majority of GHG emissions were generated by the highly developed countries of North America, Europe and Central Asia. However by 2030, it is projected that these emissions will be surpassed by those from developing countries, and overall emissions will be almost twice the 2004 levels.[4]

The production of our most widely used construction material, namely concrete, is already responsible for

between 5% and 8% of global GHG Greenhouse emissions. We produce approximately 3 tonnes of concrete per year for every person on the planet. Although this figure also includes concrete used in a variety of infrastructure applications, it nonetheless represents a significant proportion of the emissions attributable to the construction and operation of buildings. As for steel, while it is less carbon-intensive than concrete, and is relatively efficient to recycle, the production of steel accounts for about 4% of global energy use.[5]

To address the housing shortage, construction activity in the developing world will have to increase exponentially, yet our current materials and technologies cannot deliver this increased volume of construction without grave negative consequences for the environment. If we were to proceed with 'business as usual', the increase in construction activity would generate incalculable quantities of greenhouse gases, and a potentially catastrophic acceleration of climate change.

While reducing the operating energy required to heat and cool buildings is dependent on regionally based solutions that respond to the particularities of local climate, reducing the energy intensity of building construction can be achieved using a universal approach. The typologies of mid- and high-rise urban housing are essentially the same everywhere, and currently realized using a combination of load-bearing concrete masonry and concrete or steel frame systems. The only material we have available to us that could deliver housing solutions on the scale required – and at the same time reduce the GHG emissions associated with construction – is wood.

New massive wood products such as cross-laminated timber (CLT), together with computerized design and fabrication techniques, have accelerated the development of new approaches to building with wood. Calculations have indicated that some of these approaches may be applied to structures in excess of 40 storeys. Although research and development of these new approaches is concentrated in Europe and North America, the implications for the global construction industry are profound.

The expansion of wood construction at this scale must be predicated on the exclusive use of material harvested from independently certified, sustainably managed forests. Only third-party certification provides the necessary guarantee that the rate of wood harvest does not exceed the rate of forest regeneration, and will therefore not result in deforestation and further contribute to climate change.

The purpose of this book is to present the arguments in favour of 'Tall Wood' buildings and to showcase completed projects that demonstrate the applicability of this technology to construction across a wide range of building types, and in a variety of physical and cultural contexts.

While Tall Wood construction can only ever be part of the solution to the social and environmental challenges we face, its adoption around the world would represent the kind of transformational thinking and cooperative action that will be essential if we are to restore equilibrium to the world's climate system, and eliminate the inequities that have contributed to our current problems.

Michael Green and Jim Taggart
Vancouver, Canada
May 2016

REFERENCES

1 NASA (2014). *Global Climate Change – Vital Signs of the Planet.* Retrieved from 'NASA scientists react to 400 ppm carbon milestone'. http://climate.nasa.gov/400ppmquotes/

2 UN Habitat (2014). *World Habitat Day Background Paper.* Retrieved from http://unhabitat.org/wp-content/uploads/2014/07/WHD-2014-Background-Paper.pdf

3 Ross, A. (2011). *Bird on Fire: Lessons from the World's Least Sustainable City*. Oxford University Press.

4 United Nations Environmental Program (2013). *Buildings and Climate Change: Summary for Decision Makers.* Retrieved from http://capacity4dev.ec.europa.eu/unep/document/buildings-and-climate-change-summary-decision-makers

5 UN IPCC (2007). *Climate Change 2007 – Mitigation of Climate Change.* Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4_wg3_full_report.pdf

WOOD, SUSTAINABILITY AND CLIMATE CHANGE

At least in theory, wood is the ultimate sustainable building material. It is strong, durable, renewable and, above all, manufactured by the sun. In practice, however, what remains at issue, is whether we can manage our forest resources in a way that meets our needs without reducing their area, or compromising the ecological services they provide as reservoirs of carbon, purifiers of air and water, sanctuaries of biodiversity and providers of animal habitat.

These concerns are legitimate, as deforestation and its negative effects remain a significant problem in some regions of the developing world. While forest certification organizations continue to work with governments and industry in these areas to establish sustainable forest management (SFM) practices and protocols, these are already in place throughout the major wood-producing countries of the developed world. Thus the focus of this book is on those regions; continental Europe, Scandinavia, North America and Australasia.

FORESTS TODAY

As long ago as 2001, the United Nations Food and Agriculture Organization (UNFAO) determined that, in these regions at least, loss of forest cover is no longer a quantitative issue. In parts of Europe, the United States and Canada, the area of forests is actually increasing, with North America now approaching the level of forest cover it had when the first European settlers arrived in the early 17th century.[1]

The nature and make-up of contemporary forests varies significantly from country to country according to local climate, geographical latitude and elevation [ill. p. 14 top]. Forests that are regulated and managed for commercial wood production also vary greatly. In some jurisdictions, such as New Zealand, commercial timber for structural applications comes from plantation forests where a single exotic species, in this case Monterey or radiata pine (*Pinus radiata*), predominates, and native hardwood forests are set aside as reserves. In Tasmania, where growing conditions are very similar, long-established plantations of radiata pine are now being supplemented by stands of native eucalypts on an experimental basis.

In Northern Europe, forests are dominated by two indigenous species, Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), although the forests also contain Central European varieties such as oak (*Quercus robur*) and beech (*Fagus sylvatica*). Central and Eastern Europe have significant areas of broadleaf (hardwood) forests. Approximately 70% of Europe's forest cover is semi-natural, having been modified to some degree by human intervention, yet retaining natural characteristics. Only 8% is plantation forest, found mainly in Denmark, the Netherlands, Portugal, Ireland and the United Kingdom.

In the boreal regions of Canada, black spruce (*Picea mariana*) and white spruce (*Picea glauca*) predominate, while on the west coast (and in the Pacific Northwest region of the United States) forests in wetter regions contain a mixture of Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*). In drier parts of the west coast, a combination of spruce, pine and fir species prevails.[2] In the southeastern United States, the naturally mixed forests consist of a variety of pine species, generally referred to collectively as 'southern yellow pine'.[3] Together, the forests of North America constitute 20% of the world's total.

To a greater or lesser degree, all healthy forests provide the kinds of ecological services mentioned above, and can continue to do so when commercial wood production is properly managed. Even the exotic plantation forests of New Zealand have an under-storey of native shrubs that support a greater degree of biodiversity than would be found in open prairie or agricultural land.

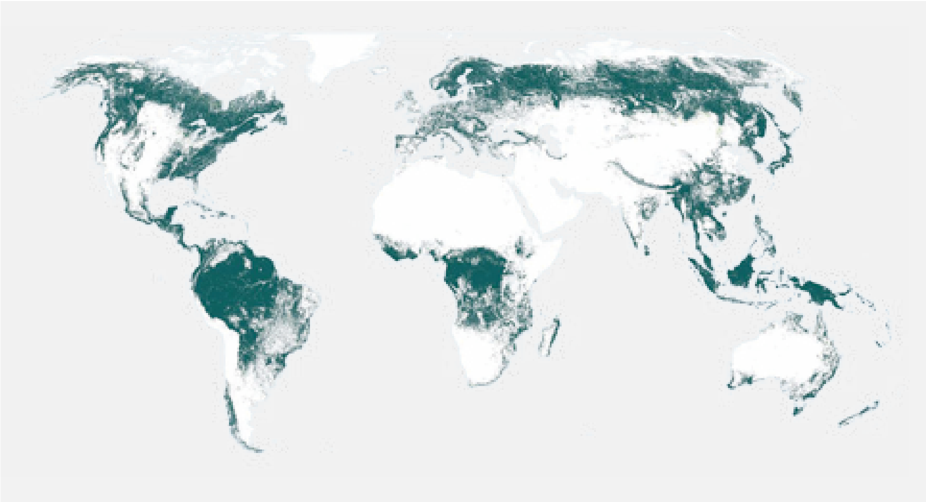
Some countries, such as Estonia and Scotland, are actively reforesting unproductive grassland, recognizing both the economic and environmental benefits this can bring. Overall, the regions that are the primary focus of this book have either stable or increasing areas of forest cover [ill. p. 14 bottom].

SUSTAINABLE FOREST MANAGEMENT

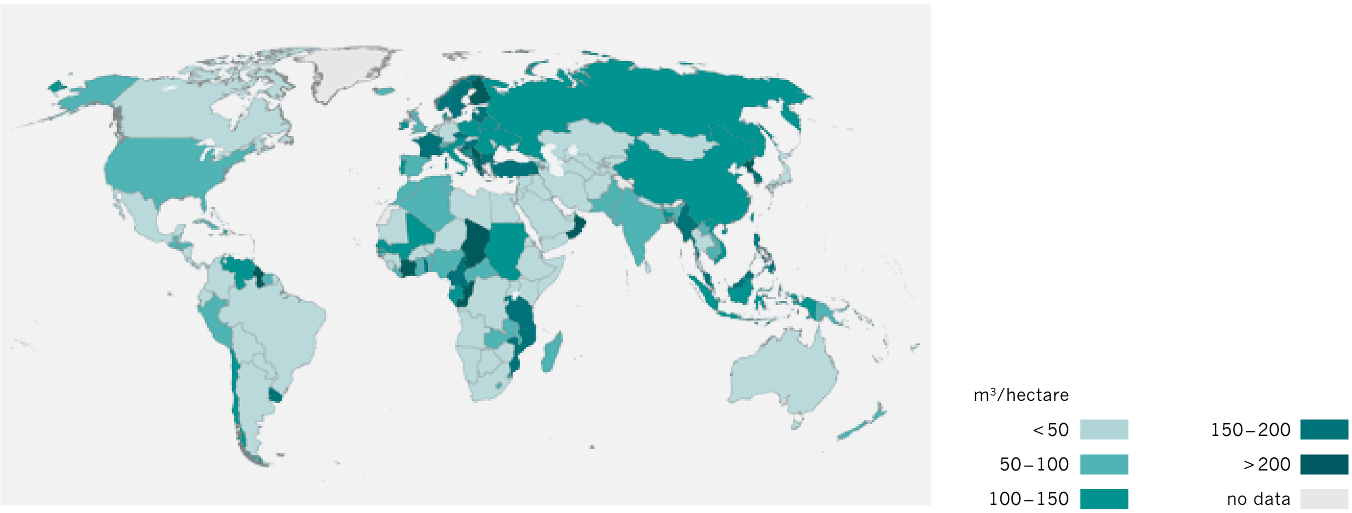
Despite the great variety of natural, semi-natural and plantation forest types, there are third-party administered, internationally recognized sustainable forest management (SFM) protocols applicable to each. These protocols provide assurance to governments, industry, architects and the public alike that the quantity of wood fibre harvested does not exceed the quantity of wood fibre produced by tree growth on an annual basis, nor compromises the ecological services the forest provides. Such protocols are well established in Scandinavia, Western and Central Europe and North America and the area of forests under SFM is increasing rapidly in Eastern Europe, Central America and Asia [ill. p. 15].

Regardless of forest type or jurisdiction, sustainable forest management is typically founded on the following core principles:

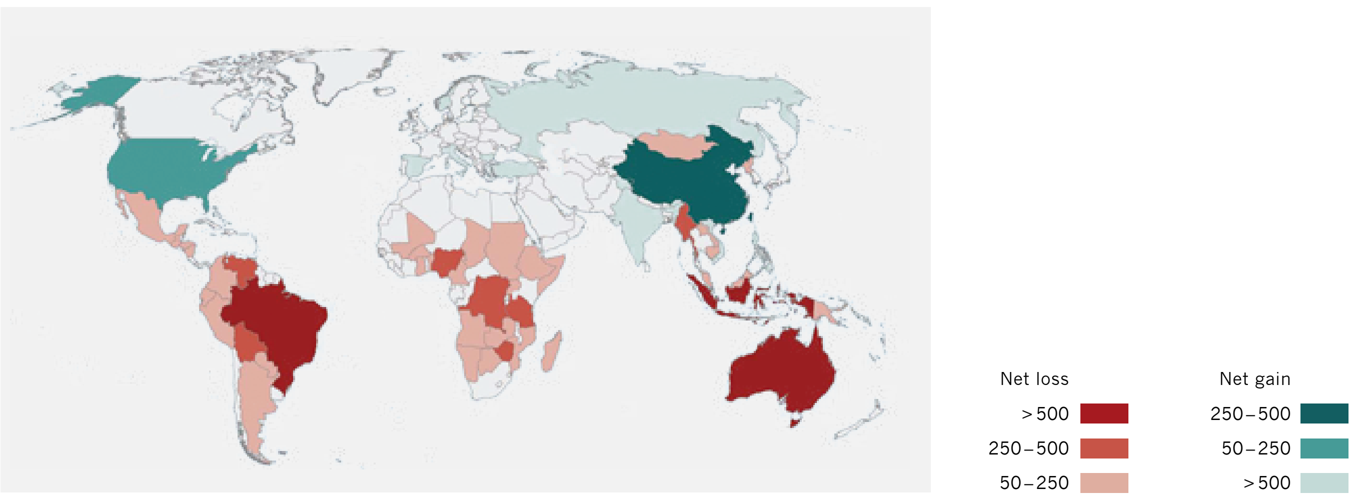
- Conserve biodiversity;
- Maintain the productive capacity of forest ecosystems;
- Maintain the vitality and health of forest ecosystems;
- Conserve and maintain soil and water resources;
- Maintain the forest contribution to global carbon cycles;
- Maintain and enhance long-term, multiple socio-economic benefits to meet the needs of societies; and
- Provide legal, institutional and economic frameworks for forest conservation and sustainable management.



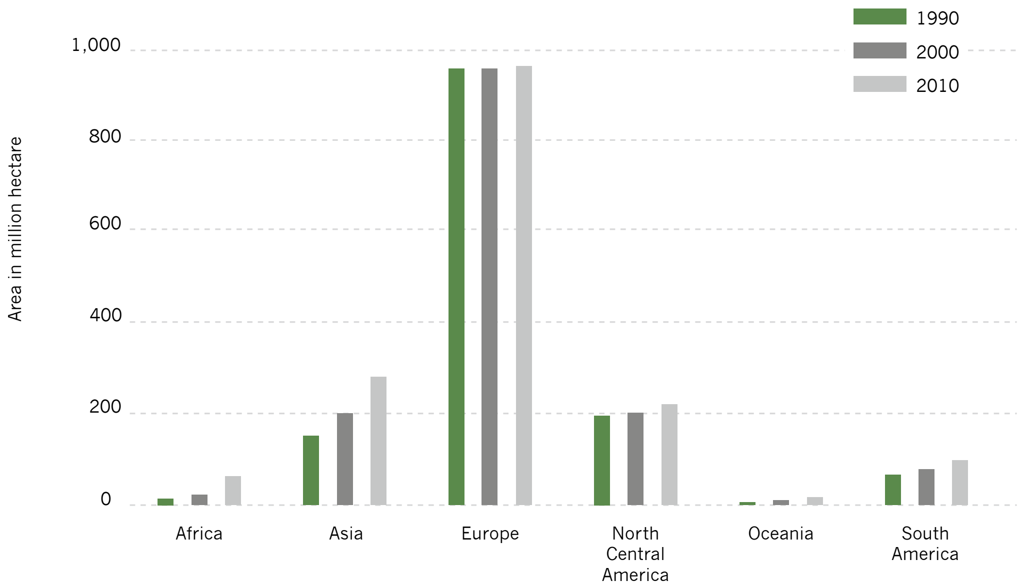
World map depicting overall forest cover



World map depicting percentage of land area dedicated to commercial forestry



World map depicting annual decrease and increase in forest cover



Area of forest certified under sustainable forest management by region

Third-Party Certification

Based on these principles, national and regional standards are developed in consultation with a variety of stakeholders to set parameters for the desired age and density of trees and composition of tree species within individual management areas; and the distribution of forest types and age classes (i.e. stands of trees of similar age) within a region.

Internationally, the efficacy and integrity of the majority of regional and national systems is endorsed by the Programme for the Endorsement of Forest Certification Schemes (PEFC). PEFC is a non-profit, non-governmental organization based in Geneva, Switzerland, that works throughout the entire forest supply chain to promote good forestry practices. Applying the core principles listed above, PEFC certification assures that timber and non-timber forest products have been produced with respect for the highest ecological, social and ethical standards. Forests certified under the umbrella of PEFC constitute approximately 65% of the world's certified forests.

Countries with PEFC-endorsed national certification systems include Australia, Austria, Canada, Finland, France, Germany, Italy, Norway, Sweden, Switzerland, the United Kingdom and the United States. The second-most popular forest certification system is administered by the Forest Stewardship Council (FSC). FSC is also a non-profit, multi-stakeholder organization that sets standards, certifies forests and administers a 'chain of custody' labelling program.

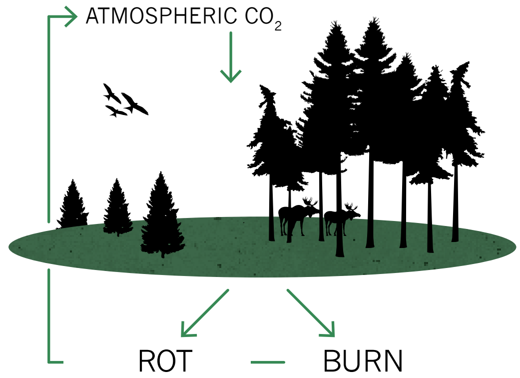
Increasingly, PEFC and FSC are seen by governments and industry as having very similar objectives and standards, although these are realized through different approaches. PEFC is a 'bottom up' organization, as it facilitates mutual recognition between nationally developed standards; whereas FSC is a 'top down' organization, developing its own standards and adapting them to a variety of regional bio-climates and forest types.

In the spring of 2016, the US Green Building Council, which had previously recognized only the FSC standard as eligible for credit under its Leadership in Energy and Environmental Design (LEED) rating system, extended that recognition to include PEFC.

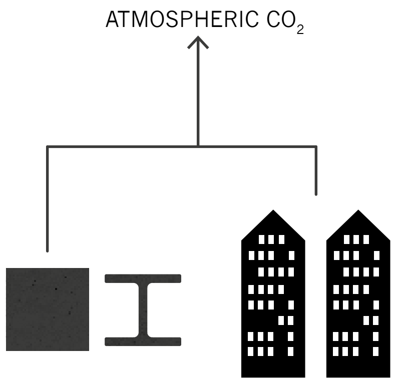
THE ROLE OF FORESTS IN THE CARBON CYCLE

With SFM protocols firmly in place in most developed countries, what makes sustainable forest management of continued interest is the fact that, because growing trees sequester and store carbon dioxide and other greenhouse gases from the atmosphere, increasing the responsible use of wood can actually contribute to the long-term mitigation of climate change.

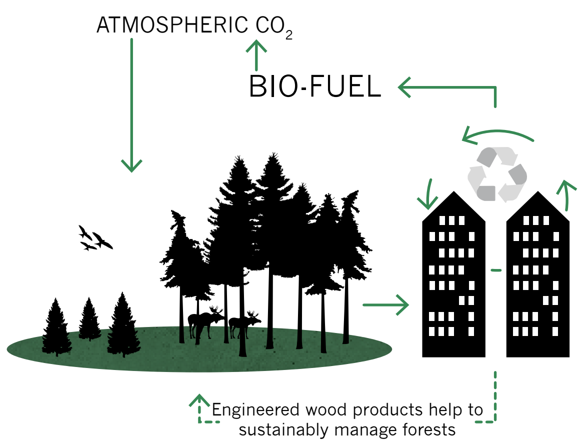
Historically, the composition of the Earth's atmosphere was held in balance in part by the ability of forests to absorb carbon dioxide and release oxygen. For most of its life, a growing tree uses the sunlight it receives to sequester CO_2 and convert the carbon it contains into cellulose, the main component of wood fibre [ill. p. 16]. This carbon remains in the wood until the tree begins to decay or is destroyed by fire, at which point it is released again as CO_2. This process is part of a complex system of global carbon exchange known as the carbon cycle.



Carbon cycle for a natural forest



Carbon cycle for a managed forest yielding traditional solid sawn wood products



Carbon cycle for a managed forest yielding engineered wood products

However, the capacity of this system has been compromised by deforestation, population growth and by the increased per capita impact of human activity dependent on fossil fuel. This process has accelerated rapidly in the last 200 years and we are now entering a period of unprecedented climate instability.

Maintaining Forest Carbon Stocks

Forests and the soils that support them are a major component of the terrestrial biosphere, which, in turn, is one of the five reservoirs in the Earth's carbon storage and exchange system. Across the vast temperate and boreal forests, the proportions of total forest carbon stored in the trees and in the soil varies considerably. In temperate regions the average is believed to be around 65% in the soil and 35% in the vegetation, while in the boreal forests these figures may be as much as 80% in the soil and as little as 20% in the vegetation.

Left undisturbed, the most common mechanism of renewal in forests is fire (although disease, insect attack and windfall also play a part). While fire releases large amounts of carbon from the vegetation it burns, it leaves the carbon in the soil largely intact. By contrast, harvesting has little impact on the carbon in the vegetation, but can release large quantities of carbon from the soil it disturbs. This amount varies considerably with the harvesting method employed.

Over large areas, it is difficult to accurately estimate the volume of wood and other vegetation (and hence the total carbon stored) in a forest. Such calculations must rely on aerial photography and limited field measurements of tree sizes and spacing.

However, within smaller tracts of land where more comprehensive field measurements are achievable, or in plantation forests where tree size and spacing is consistent, it is possible to refine these calculations considerably. Sophisticated computer modelling tools enable forest regulators and forestry companies to compare the environmental impacts of different harvesting methods, and to ensure that (when all impacts and benefits are measured) these activities do

An analysis of the wood structure and finishes of the Eugene Kruger Building, Laval University, Gauthier Gallienne Moisan Architectes, 2005, in Quebec City, Canada demonstrated a significant reduction in embodied energy compared to a steel equivalent.

The imported solid wood structure of the Forte Building, designed by Andrew Nieland/Lend Lease Corporation and built in 2012 in Melbourne, Australia, has a lower carbon footprint than a similar structure built from local concrete.

not diminish overall forest carbon stocks or contribute to climate change.

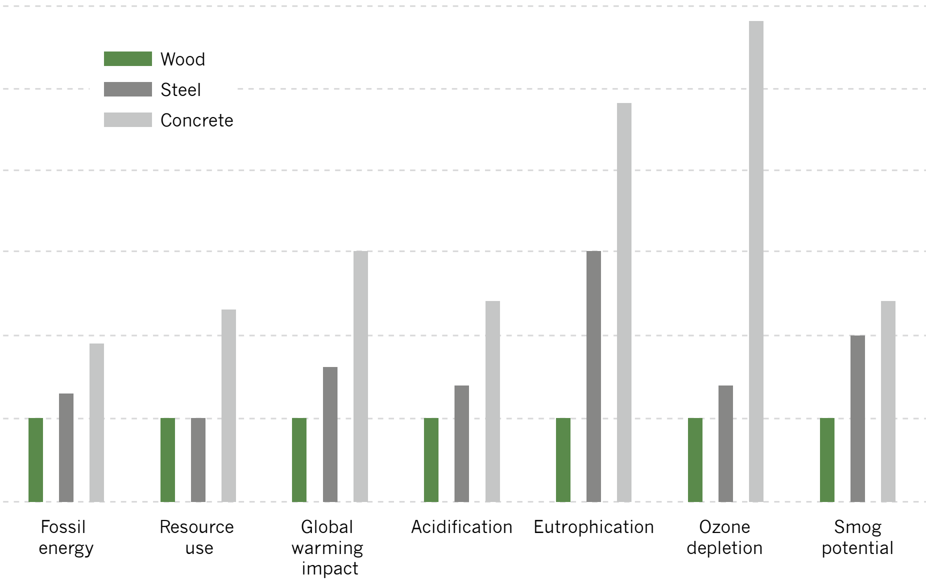
Carbon Sequestration

In addition to measuring forest carbon stocks, sustainable forest management techniques can also enable us to optimize the relationship between forest growth and wood production. The rate at which trees absorb CO_2 varies with species, but in all cases is directly proportional to the rate of growth. Saplings and young trees grow very rapidly, but as trees mature their rate of growth slows, and consequently their rate of CO_2 absorption. In overmature trees CO_2 absorption stops altogether. When trees die and start to decay, they begin to release the CO_2 they contain. Without continuous regeneration, forests can actually become net emitters of CO_2.

SFM can optimize the carbon sequestration rate of forests through a managed process of harvesting and regeneration. For every climate, region and forest type, there is an optimal amount of harvest based on the annual growth rate. This annual increase in wood fibre volume is known as the stem wood increment. Over time, harvesting at a rate less than the stem wood increment will result in an overmature forest, just as surely as harvesting at a rate greater than the stem wood increment will ultimately result in deforestation. While ongoing monitoring through SFM protocols is required, there is a potential benefit to climate change mitigation if we harvest at a rate equal (or close) to the stem wood increment. By optimizing the volume of wood fibre harvested from our forests in this way, we can also optimize carbon sequestration.

CARBON STORAGE, WOOD SUBSTITUTION AND EMBODIED ENERGY

When we transform wood into building products or other durable items (although not pulp and paper), the benefits of carbon storage become longlasting. The carbon in the products made from harvested trees remains encapsulated, while the new trees planted in their place begin to bind new carbon, ensuring that



Comparison of life cycle environmental impact of buildings by primary construction material

the cycle continues. The amount of carbon stored in wood varies with tree species, but for most softwoods used in construction, the rate of storage is approximately 1 tonne of CO_2 per cubic metre.

The environmental benefits of wood are further enhanced when one takes into account that an increase in the use of wood results in a commensurate reduction in the use of other more carbon-intensive materials. Furthermore, the processing of harvested trees into sawn lumber or engineered wood products also takes considerably less input energy than that required to process other common construction materials such as steel and concrete [ill. p. 18 above].

When used in reference to building construction, the term ‘embodied energy’ means the amount of energy required to extract, process, fabricate, transport and install a particular material or product. The amount of embodied energy will be influenced by the energy intensity of the processes used for extraction and production, the distance that raw materials and fabricated components must travel, and the mode of transportation used. In regard to extraction and production processes, there is an assumed relationship between embodied energy and GHG emissions, although this will vary according to the source of energy used – whether hydro-electricity, coal or another fuel. Published data can be confusing, as comparisons of GHG emissions are sometimes presented by volume and sometimes by weight.

Materials such as wood, steel and concrete require different cross sections or dimensions to perform the same functions (whether beams or columns, floors or walls), so the most meaningful method for presenting data is in the form of a whole structure or whole building comparison. Embodied energy and related GHG emissions can then be calculated for identical buildings constructed in each material or combination of materials.

In the last ten years, analysis of wood structures, such as the structure and cladding of the Eugene Kruger Building in Quebec City, Canada [ill. p. 17 left] and many others since, have consistently demonstrated reductions in embodied energy and GHG emissions of 50–90% when compared to steel or concrete systems. One advantage for wood products is that many sawmills and manufacturing plants now generate their electricity using wood waste bio-fuel, which is a carbon-neutral energy source.

With respect to the embodied energy due to transportation, distance is only part of the equation. In the United Kingdom, which does not have sufficient locally grown timber, nor the infrastructure to manufacture massive wood products, cross-laminated timber panels fabricated in Germany and Austria and transported by road are calculated to have a lower carbon footprint (the sum of the GHG emissions related to embodied energy) than locally manufactured concrete. Similarly, and more surprisingly, Australia’s Lend Lease Corporation determined that significant carbon savings are possible with massive timber even when procuring non-local materials. CLT imported from Austria was used in the construction of its Forte Building, a ten-