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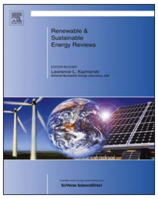

The wood from the trees: The use of timber in construction

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ABSTRACT

Trees, and their derivative products, have been used by societies around the world for thousands of years. Contemporary construction of tall buildings from timber, in whole or in part, suggests a growing interest in the potential for building with wood at a scale not previously attainable. As wood is the only significant building material that is grown, we have a natural inclination that building in wood is good for the environment. But under what conditions is this really the case? The environmental benefits of using timber are not straightforward; although it is a natural product, a large amount of energy is used to dry and process it. Much of this can come from the biomass of the tree itself, but that requires investment in plant, which is not always possible in an industry that is widely distributed among many small producers. And what should we build with wood? Are skyscrapers in timber a good use of this natural resource, or are there other aspects of civil and structural engineering, or large-scale infrastructure, that would be a better use of wood? Here, we consider a holistic picture ranging in scale from the science of the cell wall to the engineering and global policies that could maximise forestry and timber construction as a boon to both people and the planet.

1. Introduction

Timber for construction is one of the many forest products used around the world. It is used in buildings both large and small; here we consider timber for the construction of buildings of six or more storeys, and the biochemistry and chemistry of wood modification that could enable much larger buildings. There is ample global supply for the foreseeable future, and although there is a worldwide trend towards deforestation, it is generally due to clearing land for agriculture rather than logging for timber. Nevertheless illegal logging remains a concern.

How should one use timber? While there are limitless possible designs, and construction is based in both engineering and cultural practice, timber has a high strength to weight ratio, and is used most efficiently in structures where it is carrying a lot of its own self-weight. In many areas of the world building codes trump engineering, so heights are limited well below what is possible in timber. We also address important questions relating to the service life of timber structures, affected predominantly by their fire performance and moisture sensitivity, and how this can be extended through the modification of the natural material, and using effective design details. While such modifications may increase the carbon sequestration period due to prolonged life, there may be however detrimental implications to end-of-life scenarios.

Why should one use timber? Construction-grade timber and

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engineered forest products are some of the highest value products from trees. This suggests that structural use is important for economies that rely on forestry. Furthermore, following primary use as structure, there are many secondary or tertiary uses for timber construction waste that retain its value.

When should one use timber? Timber can have economic benefits for construction, as modern timber is largely factory prepared and brought to site for rapid assembly. Both local and global markets exist for timber, so each could be important in assessing the value of using timber at a large scale. The environmental benefits have been demonstrated on some projects, but are not always easy to quantify or generalise.

This review article aims to provide a big-picture view of the environmental impacts of using timber in construction, and the choices that influence this. The novelty of this article is that it succinctly covers current knowledge and provides important insights at multiple scales across a range of disciplines, all of which contribute to the environmental impact of timber use: trees as a resource, wood cell biology and molecular structure, forestry and management practices, processing into products, modification for durability, design and engineering for full-scale applications, end-of-life considerations, and global use, trade and policies. Following this assessment, we also highlight directions for future research that will shape environmental outcomes for constructing with such natural materials.

2. Trees

2.1. Tree variation

The ability to become a "tree" has been acquired many times during the evolution of plants, and so there can be great variability between tree species. In our era, the most abundant tree forming groups are within the angiosperms (group of plants producing flowers and enclosed seeds), but almost all gymnosperms (plants producing uncovered seeds such as spruce, pine, fir) are also trees. Industrially, wood obtained from angiosperms (dicots, often deciduous broad-leaved, including oak, birch, beech, ash) is called hardwood, and that from gymnosperms, softwood (Fig. 1). Notably, this nomenclature does not necessarily reflect the actual wood properties; balsa (a hardwood) is much softer than average softwood.

2.2. Trees – the biggest organisms on earth

Different species grow at different rates. Examples of the fast growing trees are Trema micrantha, which is used for site amelioration of deforested land and can reach 20 m after seven years [1], Royal Empress Trees, eucalyptus (three m per year), and willow and poplar. The studies on the possible maximum height of trees consider various issues like hydraulic requirements [2,3] or limited leaf expansion and photosynthesis on the top of the tree [4]. Despite such constraints, the tallest living trees on Earth, Sequoia sempervirens, found in California Redwood National Park (Fig. 2), can reach well over 100 m, with the tallest measuring 115.7 m. The tallest tree ever reported was Eucalyptus regans in Australia, reaching at least 143 m. The biggest trees (by volume) are Sequoiadendron giganteum, with estimated trunk volume of nearly 1500 m^3. Trees of the same species grown in diverse conditions may grow very differently. The increase in girth of a tree grown in the open is twice as much as one grown in woodland. An average free-standing tree would add 2.5 cm per year to its girth, with fast trees (like giant sequoia, coastal redwood, Sitka spruce and Douglas fir) reaching 5–7.5 cm. Some trees, for example Scots pine, grow more slowly [5,6]. Matching optimised growth and usefulness of trees for construction is not an easy task. For example, the main tree grown for construction in the UK is Sitka spruce, an imported conifer from the Pacific Northwest of North America. It can reach 40–70 m height, but in the UK, where conditions are milder than its native

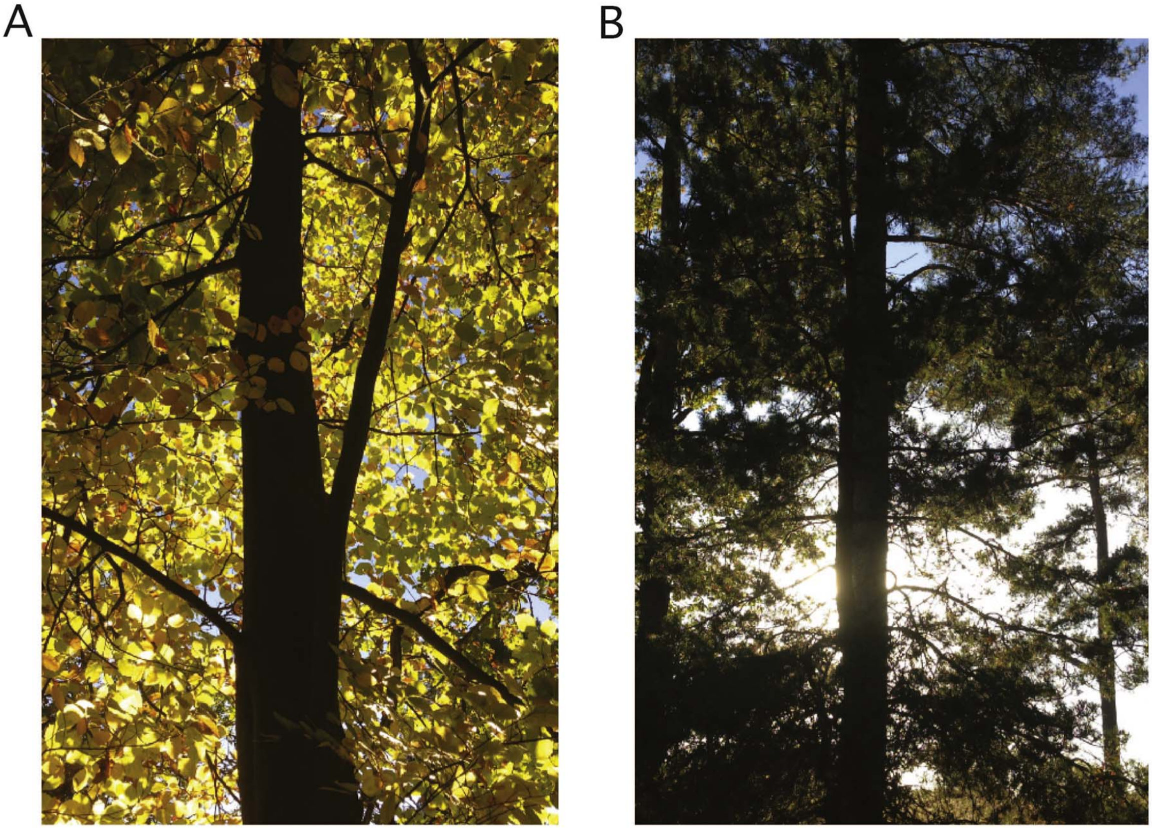


Fig. 1. Trees. (A) Beech, a hardwood. (B) Pine, a softwood.

Fig. 2. California Redwood National Park. Photo courtesy of C. Feijao.

environment, its growth rate is faster but the resulting density of wood is lower. For typical harvesting it is grown for 35–45 years, reaching a height of 16–23 m, with trunk diameter 25–40 cm (measured 1.3 m above ground). Longer rotation times (as measured on 80 year old trees) may provide timber with improved structural properties [7]. The yield (annual volume increment per hectare) for Sitka spruce in the UK is 14 $m^3 ha^{-1} year^{-1}$ [8]. Research on a forest in southern Sweden measured total yield of approximately 10 $m^3 ha^{-1} year^{-1}$ for an established forest of Norway Spruce, and 7 $m^3 ha^{-1} year^{-1}$ in the first rotation of a newly planted forest [9].

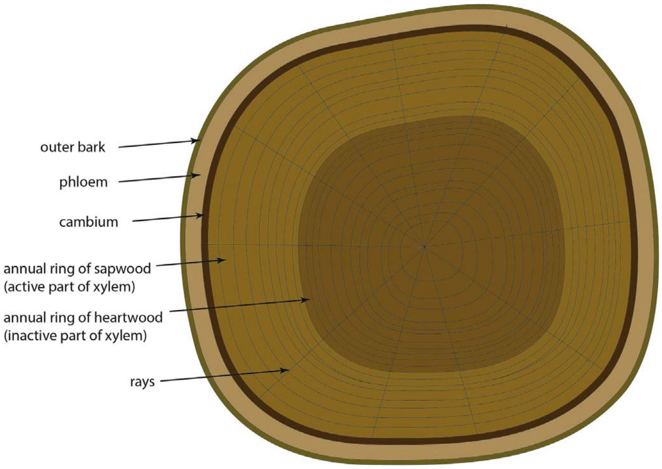


Fig. 3. Tree cross-section. Vascular cambium is producing new cells of phloem and xylem (wood).

2.3. Tree growth and structure

The growth of a trunk is achieved by two kinds of events, each controlled by specialised parts of the plant. The first is mediated by the shoot (apical meristem) located on the top of the tree and is responsible for predominantly upward primary growth. This growth is common for all vascular plants. Trees also have the ability of secondary growth (In contrast to non-tree plants), which means that their stems can get thicker. This growth is determined by the proliferative activity of vascular cambium, a group of dividing cells located between, and giving rise to xylem (water-conducting tissue positioned on the inside of the trunk) and to phloem (tissue responsible for transfer of nutrients and situated on the outside of the trunk) (Fig. 3). The molecular mechanisms regulating wood formation are the subject of intensive research [10].

Because of the mechanisms of secondary growth, the oldest part of the tree is in the center of the trunk. Young xylem is the water-conducting tissue (sapwood), and if the tissue dies and wood cells become hollow it forms heartwood. Resinous materials and polyphenols subsequently protect these dead cells from fungal attack [11]. Importantly for construction, heartwood and sapwood have different properties.

Wood is nonuniform within heartwood and sapwood layers. In general, trees produce annual rings. Such rings reflect the changing environment. Rapid growth during the spring produces “earlywood” which is less dense and composed of large cells with thinner walls allowing for efficient water transport to support intense photosynthesis. This period is followed by slower growth, yielding “latewood”, characterised by more densely packed, smaller cells, production of which stops for winter. Each annual ring consists of both early and latewood. In softwoods, the transition can be gradual, distinct, or a combination of each. In hardwoods, vessels may have a different size in early- and latewood (big vessels in earlywood of ring-porous wood such as oak, elm) or be of more uniform appearance (diffuse-porous wood of beech and alder) (Fig. 4) [12].

Some tropical trees may not produce annual growth rings due to their constant growth. In places where conditions change drastically from favorable to harsh several times per year, growth can be restarted, leading to the appearance of more than one growth ring per year.

2.4. Cellular structure of wood

Despite similar growth patterns, there are significant cellular

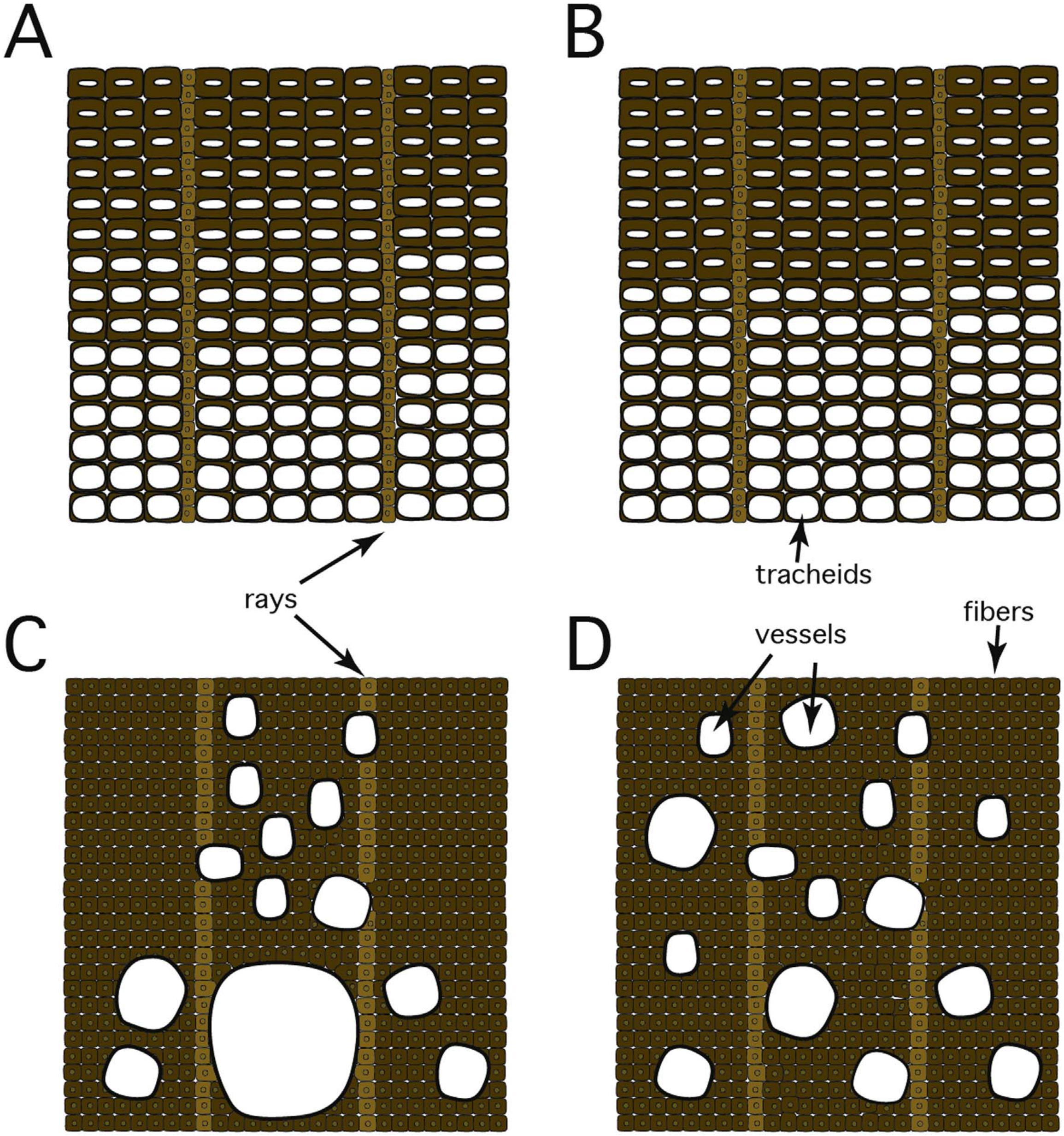


Fig. 4. Different structures of wood. Sections of annual ring of (A) gradual transition conifer, (B) abrupt transition conifer, (C) ring porous hardwood, (D) diffuse porous hardwood. Picture courtesy of Dr. Krzysztof Wicher.

differences between angiosperms and gymnosperms. In softwoods, tracheids are the predominant wood cell. They are longitudinally positioned within the trunk and constitute the majority of the woody mass. Their functions are both to conduct water and to provide structural support to the tree. They are approximately 2–4 mm long and roughly 30 µm wide and joined top-to-bottom via pits to allow water to pass upward. In addition to tracheids, parenchymal cells are also present in wood tissue. These are part of the rays, positioned radially within the trunk and may carry various substances (like resins); they make up approximately 6–10% wood volume.

In hardwood, there are two primary types of wood cell: fibers (constituting 50% of the wood volume) providing structural support, and water conducting vessels (30% of wood). The fibers are approximately 1–2 mm long and 15 µm wide. The vessel elements are on average 0.2–1.2 mm long, 0.05–0.8 mm in diameter, open-ended and stacked vertically to be later fused into long structures that can be meters in length. Their joining points are called perforation plates, which are openings that allow for high water conductance. In addition, the parenchymal cells also present in rays and they play a similar function as in softwoods [6,11].

3. Molecular structure and mechanical properties

As described in Section 2, during the secondary growth of trees, vascular cambium is differentiated into phloem (outside of the cambium) and xylem (inside the cambium layer to the center of the tree). Wood is sometimes defined as only the secondary xylem in the stems of trees and almost entirely composed of cell wall material [13]. Wood properties are derived from the cell wall structures and wood polymer compositions. This section will demonstrate how wood properties originate from the cellular microstructure of trees, and how those properties can be influenced by modification.

3.1. Molecular structure

Wood is essentially composed of cellulose, hemicellulose, lignin,

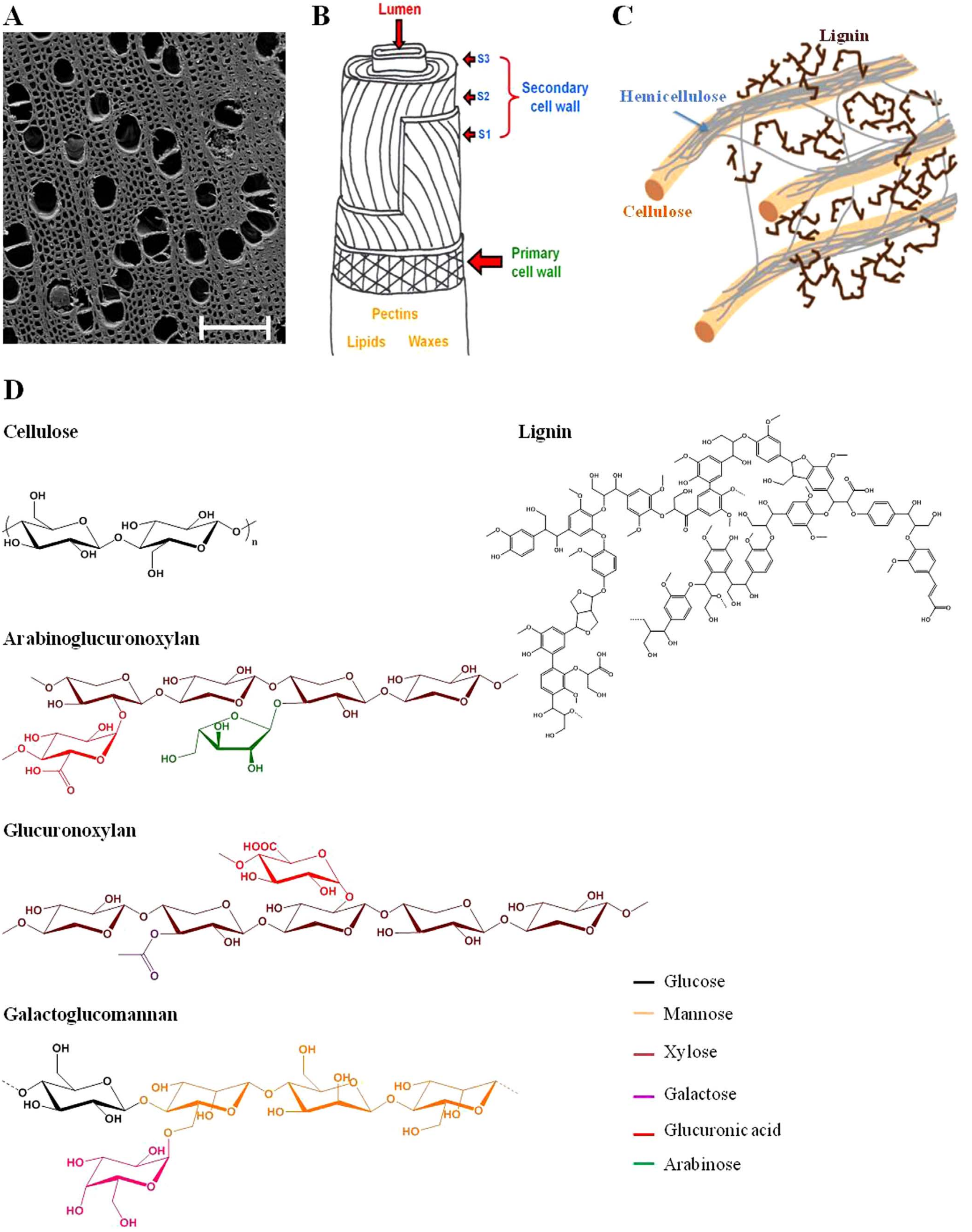


Fig. 5. Diagrammatic illustration of the framework of wood cell wall. A, Anatomical structure of willow wood (Scale bar=100 μm); B, Cell wall structural organization; C, Cell wall polymer interactions in secondary cell wall of hardwood; D, Secondary cell wall polysaccharide structures different colors show different sugars.

and extractives. Cellulose is composed of very long linear chains of D-glucose linked by β-1,4-glycosidic bonds. These glucan chains are held together by hydrogen bonds to form cellulose microfibrils of a diameter of 3–5 nm [14]. Hemicellulose is a class of structurally diverse polysaccharides consisting of β-1,4 linked glycans with various substitutes. Hemicellulose structures differ between hardwood and softwood. The main hemicelluloses of softwood are galactoglucomannan and arabinoglucuronoxylan, while in hardwood it is glucuronoxylan. Galactoglucomannan from softwood and glucuronoxylan from hardwood are decorated with acety groups (Fig. 5). Although it is unknown how different hemicelluloses impart properties to the cell walls, hemicelluloses are proposed to crosslink with cellulose by hydrogen bonds, which may influence the ability of the microfibrils to slip past one another [15]. Wood cell walls (fibers, tracheids, etc) may be impregnated with lignin, making these walls impervious to water. Lignin is also often regarded as the cementing agent that provides the cell wall with rigidity and compressive strength. Extractives are a collective term for a series of organic compounds present in certain timbers in relatively small amounts, which include coloring matter, phenolics, turpentine, fatty acids, resin, and simple metabolic intermediates. Extractives impart colouration to the wood and give it its natural durability, as most of these compounds are toxic to both fungi and insects [16].

The layered structure of the wood cell wall is a major determinant of strength and mechanical properties. The structure of a wood cell wall is that of a multilayered composite as shown in Fig. 5. The xylem tracheid (softwood) or fiber (hardwood) cell wall has four distinct cell wall layers (primary, S1–S3) [17]. Between two adjacent cells lies a highly lignified region called the middle lamella. The middle lamella, a lignin-pectin complex, is responsible for cementing the cell walls of two adjoining cells together. The primary cell wall is a thin layer and the microfibrils are deposited in a random fashion. Both the middle lamella and adjoining primary walls are sometimes referred to as the primary layer [18].

In the secondary cell wall layers the microfibrils are closely packed and parallel to each other. In addition to the cell lumen, the secondary cell wall is subdivided into three layers: S1, S2, and S3. Wood is highly anisotropic, meaning that its physical properties differ along different axes. The angle between the cellulose microfibrils and the longitudinal cell axis, the microfibril angle, is found to be a critical factor in determining the structural and mechanical properties. The varying fibril orientation in the particular layers (50°–70° in S1, 5–15° in S2,

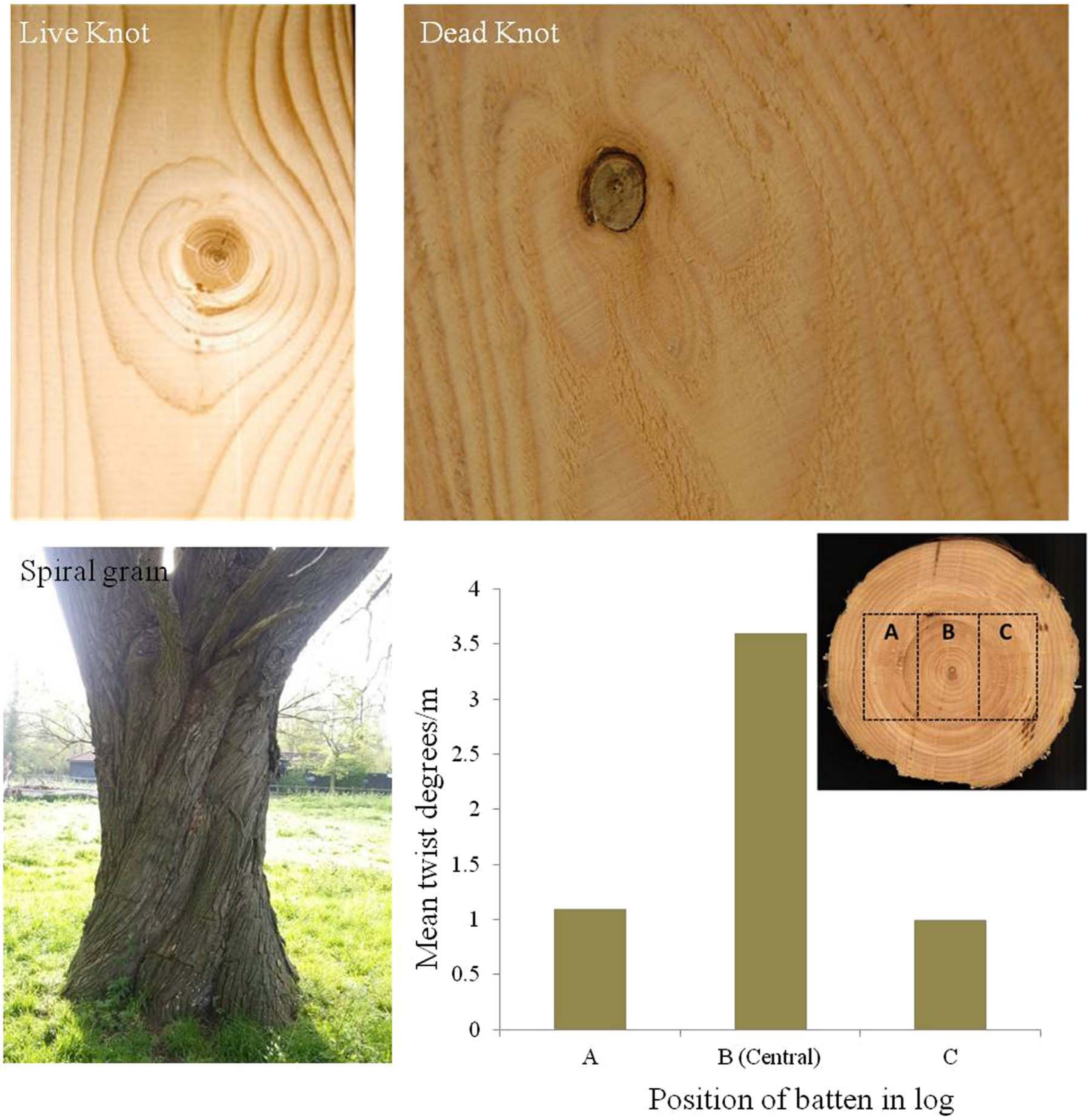


Fig. 6. Knots and twist on timbers.

and 60–90° in S3) causes a mechanical locking effect, leading to a very high stiffness of the overall cell [15,19]. Due to its thickness (90% of the secondary cell wall) and low value of microfibril angle, the S2 layer is responsible for the high tensile strength and stiffness and low shrinkage of wood in the longitudinal direction. Increased microfibril angle in the S2 layer decreases cell wall tensile strength and stiffness but increases the durability. This enables trees to adjust both stiffness and toughness of the tissue by shifting the cellulose fibril orientation of the cell wall. The S1 and S3 layers are thin and the microfibrils of each alternating between left- and right-hand spirals. The fibril angle and thickness of the S1 and S3 layers are believed to be of significance to mechanical properties in the transverse direction [15].

3.2. Knots and twists

During normal tree growth, several visual characteristics, such as knots and spiral grain, affect the mechanical properties and the use of wood. Fig. 6 shows the dead and green knots, spiral grain, and twist in wood.

As the trees grow in height, branching is initiated by lateral bud development. With increasing radial growth of the trunk, the branch bud is surrounded by a knot. If the branch is still alive when the trunk grows, the wood growth is continuous and the knot fits tightly. If the branch dies when the trunk grows, there will be a discontinuity within the stem wood and the knot will be non-adhesive and may fall out of the wood during processing [15]. Most mechanical properties are lower in sections containing knots than in knot-free clear wood because the grain direction in the vicinity of knots is frequently distorted, the interruption of continuity leads to stress concentrations, and clear wood is replaced by a knot. The influence of knots on mechanical properties is difficult to quantify, because it depends not only on the amount and size, but also the distribution along the length of a piece of timber and across its section. During processing, especially thermal modification, knots fall out because the knots and clear wood surrounding have different shrinkage properties [20]. Some wood processing removes knots, while other processing randomly distributes them.

Wood cells are aligned in the grain direction. In many trees, especially in softwood, the grain direction is rarely truly vertical but instead shows a distinct spiral mode which may be either left- or right-handed. There is a connection between spiral grain and how twisted the timber will be. Timber twist is due to the fact that wood does not shrink uniformly in all directions when dried. In general, cells get slimmer, but not much shorter, when they lose moisture. Therefore, timber shrinks least in the grain direction and more in radial and tangential directions. Rays act as restraining rods to reduce radial shrinkage, so most shrinkage is tangential. With knowledge of the size and direction of the grain angle under bark, and the diameter of the log, calculations can be made that show how twisted the sawn timber will be after it is dried [20]. Timber also expands and contracts with seasonal changes in moisture, which must be accommodated in construction details.

3.3. Reaction wood

Reaction wood forms in place of typical wood as a response to a non-vertical orientation of the stem caused by prevailing winds, snow, slope, or asymmetric crown shape. This abnormal type of wood forms as part of a developmental process, which is an example of self optimisation and the axiom of uniform stress in trees [21]. In softwood, the reaction wood is called compression wood and is produced on the lower (compression) side of the leaning part of the tree, with a higher proportion of lignin and lower proportion of cellulose. In hardwood, reaction wood is called tension wood and is produced in the upper (tensile) side of the leaning part of the tree. It has a higher proportion of cellulose than normal wood. A high proportion of reaction wood in a trunk is considered to be undesirable in any structural application, primarily as its mechanical properties are different from normal wood. Reaction wood alters the uniform structural properties of timber and can twist, cup or warp dramatically during machining. Another important factor affecting the properties of wood is the change of microfibril angle. Compression wood has higher microfibril angles, and consequently, lumber with compression wood is more likely to warp during drying. Compared to normal wood, tension wood has higher longitudinal, radial, and tangential shrinkage during the drying process [22].

3.4. Property changes during modification

Hydroxyl groups in wood are responsible for water absorption and dehydration that leads to swelling and shrinkage. Nonuniform dimensional changes restricts the use of wood for certain exterior applications. Furthermore, when the moisture content is above 20%, wood is susceptible to attack by fungi and bacteria, which can release cellulase or hemicellulase to degrade the cell wall polysaccharides. Such biodegradation results in an unacceptable loss of mechanical properties.

During the wood processing (see Section 5), several modification methods are available to increase wood stability and durability.

- Impregnation: Lumina and cavities in the cell walls are filled with bulking chemicals (e.g. monomers, polymers, resins, and waxes). These bulking chemicals hardly react with the wood polymers. This method does not alter the molecular structure of cell wall polymers but can increase the wood density and block pathways for water.
- Chemical Modification: Externally applied chemical reagents react with the hydroxyl and phenyl groups of the cell wall polymers. The chemical reaction can block these hydroxyl groups, which will reduce the hygroscopicity.
- Thermal modification: Thermal modification has been found to be an effective way to improve wood dimensional stability and durability against biodegradation [23,24]. Industrial heat treatment is usually performed in a nitrogen atmosphere, aqueous or dry environment.

For chemical and thermal modification processes, the chemical composition and structure of the wood cell wall is altered, which can modify the stability, durability, and mechanical properties. Details of modification are discussed in Section 6.

3.5. Research questions

Sections 2 and 3 show that the mollecular and cellular structure of wood is fundamental to its use as a construction material. There are several open research questions regarding the structure-property relations at this scale, which could change the way we grow, harvest, grade and treat wood:

- How do molecular and cellular wood architecture influence its properties? In particular, what are the specific roles of the components of the cell wall?
- Can biophysical characteristics of wood be predicted by studying biochemical properties of the plant cell wall?
- Is it possible to modify growing trees to produce wood with desired properties, either by choosing favorable conditions, or by altering the biosynthesis of wood molecules?

4. Forests as part of the supply chain for timber

The potential for more widespread use of timber as a construction material is significant (see Section 1). The increased use of timber need not raise concerns regarding deforestation; various initiatives seek to regulate the provenance of timber to ensure that it is sourced from responsibly managed forests (see Section 5). Furthermore, the area of

Europe's forests has increased by approximately 10^7 hectares (or about 6%) since 1990 [25] (for a discussion of the global trends see Section 9.1).

Forests form part of the supply chain for the softwood and hardwood timbers used in the construction industry. The supply chain for each major construction material (e.g. steel, concrete, brick, timber, cement, sand and aggregate) is quite distinct. However, the supply chain for timber is unique. All other construction materials require rocks, ores or soils to be mechanically removed from the ground. Timber, in contrast, requires that topsoil remains intact, seedlings are allowed to germinate and forests are nurtured before any timber can be harvested.

Forests are long lived in terms of human time scales, with recommended rotations for forestry harvests ranging from 35 to 70 years [8,26] depending on species and location (cf. one or two rotations per year for most cereal crops). As such, changes to our forests can impact society, ecology and the environment. Yet, one must keep in mind that even the longest forestry rotations are just a blink on any geological time scale, i.e. the time scale for the replenishment of the Earth's resources (rocks, ores and soils) required in the supply chain of other construction materials. In that regard, timber is the only widely used building material that can be considered to be truly sustainable.

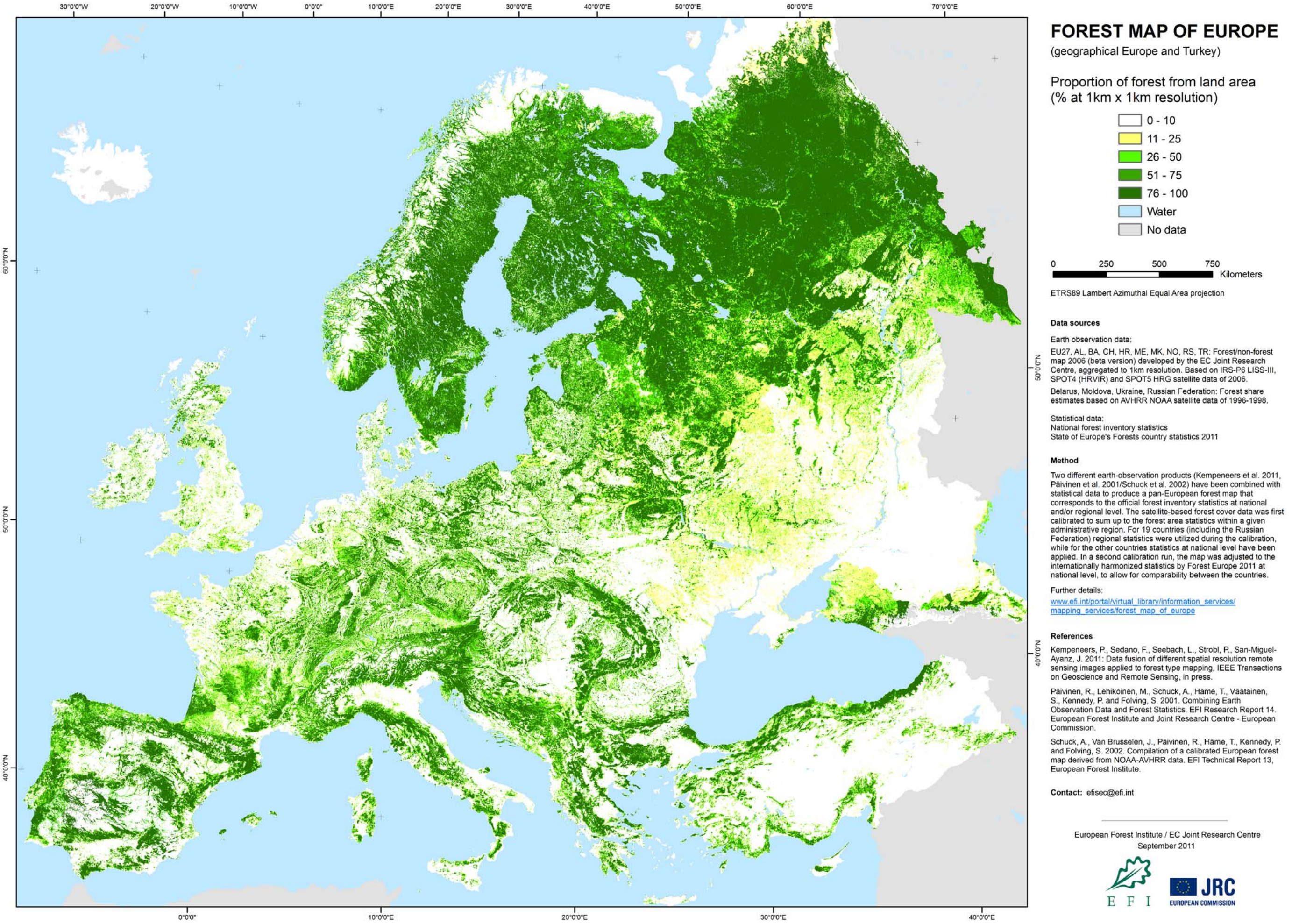
4.1. The use of land, nutrients and water for forestry

Any change of land use impacts our use of the Earth's natural resources. Moderate increases in timber demand from construction may be met, at least in part, by more efficient management of the existing forests [27] and processing of timber (see Section 5) without any change of land use. Should further land be required for forestry it is logical (due to efficiencies in transport and use of existing infrastructure) to meet much of this demand through the extension of current forest stands. Much of Europe's forests lie predominately in the northern latitudes or on the periphery of the mountainous regions of central and southern Europe (Fig. 7). Such mountainous, often harsh, conditions offer little opportunity for the production of food crops and hence extension of Europe's existing forests presents little challenge to food security. Rainfall in these regions is typically high and so the increased uptake of water by trees (often from the deep soil, inaccessible to other vegetation, [28]) within the extended forests does not present any fundamental concerns.

Due to the extremely low nutrient mineral content of harvested timber, its removal from the forest presents no significant nutrient loss to the forest [29]. Moreover, much of the nutrient rich biomass of trees (for example, foliage and roots) remain within the forest to rot and provide a major pathway for returning nutrients to the soil [30].

4.2. An assesment of the environmental impact of forests

Within Europe forest plantations are typically neither mechanically watered nor fertilised. As such, the energy input for forestry growth is almost entirely solar, harnessed naturally by photosynthesis within the tree's foliage. This natural conversion of the sun's energy into a usable material occurs over a time scale which makes it sustainable for human



Data sources

Earth observation data:

EU27, AL, BA, CH, HR, ME, MK, NO, RS, TR: Forest/non-forest map 2006 (beta version) developed by the EC Joint Research Centre, aggregated to 1km resolution. Based on IRS-P6 LISS-III, SPOT4 (HRVIR) and SPOT5 HRG satellite data of 2006.

Belarus, Moldova, Ukraine, Russian Federation: Forest share estimates based on AVHRR NOAA satellite data of 1996-1998.

Statistical data:
National forest inventory statistics
State of Europe's Forests country statistics 2011

Method

Two different earth-observation products (Kempeneers et al. 2011, Päivinen et al. 2001/Schuck et al. 2002) have been combined with statistical data to produce a pan-European forest map that corresponds to the official forest inventory statistics at national and/or regional level. The satellite-based forest cover data was first calibrated to sum up to the forest area statistics within a given administrative region. For 19 countries (including the Russian Federation) regional statistics were utilized during the calibration, while for the other countries statistics at national level have been applied. In a second calibration run, the map was adjusted to the internationally harmonized statistics by Forest Europe 2011 at national level, to allow for comparability between the countries.

Further details:
www.efi.int/portal/virtual_library/information_services/mapping_services/forest_map_of_europe

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Contact: efisec@efi.int

European Forest Institute / EC Joint Research Centre
September 2011

Fig. 7. Map showing the distribution of forests within Europe. Much of the most dense forestry is concentrated at high latitudes and around the more mountainous regions of central and southern Europe. The map is reproduced with the kind permission of the European Forestry Institute (see figure for further information).

needs and is a significant benefit, unique to wood within major construction materials. We consider the energy usage in the harvesting and processing of wood in Section 5.

Assessment of carbon cycles for complex systems like forests is challenging. Estimates of the quantities of carbon exchanged by forests vary, as do the actual exchanges which depend on species and, in particular, latitude [32]. Indeed, one can draw a distinction between the uptake and storage of carbon by a forest. The uptake of carbon primarily occurs during the processing of carbon dioxide, within the forest's canopy, during photosynthesis and may occur to a lesser extent through the root system's uptake of minerals from the soil. The storage (or sequestration) of carbon by a forest occurs through the accumulation of biomass within the trees and potentially within the soil. Whilst the uptake of carbon may be maximised with suitably mature forests, the sustainable harvest of timber in managed forests enables the benefits arising from the carbon sequestered during the trees growth to be maximised, provided that the harvested timber is used in long life-cycle products, for example in the construction of buildings. As such, the sustainable harvest of timber from well-managed forests for use in construction presents a real opportunity to sequester more carbon than might be achieved by allowing the forest to mature naturally. Fig. 8 presents a schematic illustration of the carbon cycle for an unmanaged mature forest. This simplified diagram highlights the scale of uncertainty within quantitative measurements, for example, the carbon exchanged between trees and the soil is unknown and may or may not be significant. Based on data collected across Europe from 15 different mature forests the study of Valentini et al. [32] concludes that European forests act as carbon sinks even in the absence of significant timber harvesting — with the annual balance varying between an uptake of 6.6 tonnes of carbon per hectare to a release of 1.1 t C $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$. Other estimates lie within this range, for example, Broadmeadow and Matthews [31] provide a value of approximately 4 t C $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ for the uptake by a forest in southern England.

Such statistics must be seen in the context of the global carbon budget (the net accumulation of carbon in the atmosphere), generally accepted to be approximately 3.2 Gt C yr^{-1} (e.g. [33]). By way of crude illustration, accepting the value of Broadmeadow and Matthews [31] as indicative provides that the carbon budget could be balanced by the global forests increasing in area by 800 MHa — this equates to an approximate 20% increase in the existing area of forests worldwide (http://data.worldbank.org/). Such a dramatic increase seems unlikely but increasing forest area by just a few percent could make a meaningful contribution towards reducing the global carbon budget especially if more forests are sustainably harvested and the carbon effectively sequestered by using the timber in construction.

4.3. The social and ecological impact of monoculture and multi-species forests

Forests host a number of (typically non-priced) recreation activities, e.g. walking or bird watching, thereby providing benefits for society. These benefits are typically hard to quantify but may be significant, for example Willis et al. [34] estimate the social and environmental benefits of forests in Great Britain at approximately £30 billion. They also note that the social benefits are greatly enhanced for multi-species plantations, relative to monoculture forests (see Fig. 9). Indeed, the benefits of multi-species plantations are broad; including reducing the propagation of and susceptibility to disease and pests [35] and benefits to the forest's ecology, for example to wildlife and biodiversity [36]. Brockerhoff et al. [37] argue that plantations can make an important contribution to biodiversity but only where they replace human-modified ecosystems (e.g. degraded pasture) and not where they replace native ecosystems. In addition, multi-species plantations offer the ability to supply a broader pallet of timber materials, e.g. increased supply of reasonably priced durable timber species (see Sections 2 and 7). All of the benefits associated with multi-species plantations have to be carefully balanced by the efficiencies (both economic and environmental, see Section 5) inherent in monoculture forests — both types of forestry are required in order to make increasing contributions to society and ecology whilst meeting the demand for timber effectively.

Increasing forestry to supply more timber is a long term commitment and as such must be well planned and the forests well managed in order to maximise their broad and far reaching benefits. While meeting the demand for timber, forests can also make an increasingly positive contribution to society, ecology and biodiversity, and even help mitigate climate change by balancing part of the global carbon budget. Within Europe, changing land use to increase forestry should present few significant issues. Further understanding the impact of monoculture forests relative to multi-species forests in terms of pest and disease control, tree species and tree maturity mix, and the impact on regeneration, harvest and processing efficiencies are critical in order to better balance ecological benefits with the needs of efficient timber supply. Furthermore, a more quantitative understanding of the factors affecting the emission and absorption of carbon by forests (including the effects of: geographical location, tree species and species diversification) would provide insight as to the scale of aforestation required to make a meaningful contribution to the global carbon budget and identify whether the increased use of timber in construction might motivate such aforestation, in whole or in part. Such benefits of increased forestry come with the need to use the natural material which forests provide wisely, ensuring that timber in increasingly used in a manner which maximises its lifetime and permits environmentally sound disposal — we examine the scope that the increased use of timber in construction offers for meeting these aims in Section 8.

5. Processing timber products

The global supply chain for wood is a complex network of harvesters, processors, and distributors. Since the 2013 European Union Timber Trade Regulation [38], these parties must meet legal obligations of 'due diligence' in chain of custody and risk-assessed timber

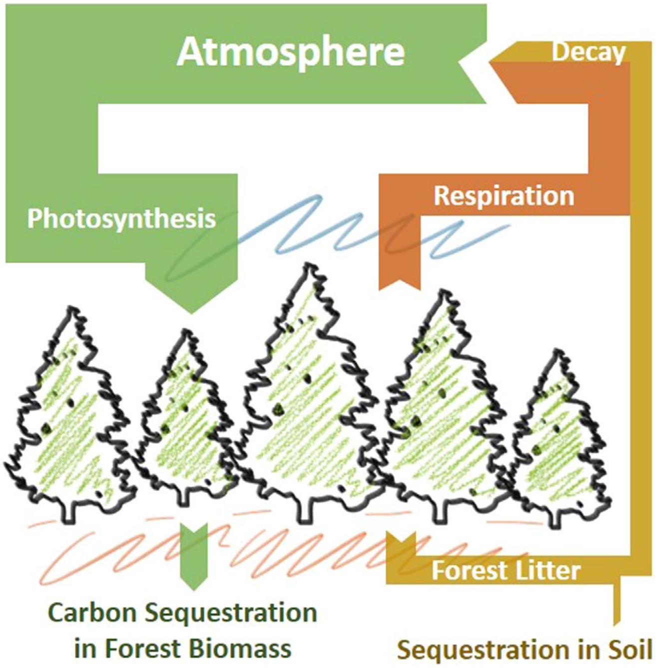


Fig. 8. Schematic illustration of the carbon cycle within a mature unmanaged forest. The width of the arrows indicate the approximate relative scale of the carbon exchanges based on the values of Broadmeadow and Matthews [31]. We note that sustainable harvesting of forestry timber (with suitable usage, e.g. in consturction) would add a significant pathway to carbon sequestration in addition to those shown in the illustration.

Fig. 9. Images of two differently managed woodlands. The images were all taken within a few days of each other in two woodlands located at similar longtidues and lattitudes within Europe to enable comparison of the levels of biodiversity apparent with monoculture and mutli-species forests.

procurement from both EU and non-EU sources for construction grade materials and other timber-derived products. Due to significant concerns about the unsustainable use of tropical hardwoods the use of global certification schemes like the Forest Stewardship Council (FSC) and Programme for Endorsement of Forest Certification (PEFC) is now more prevalent. In Europe the most commonly used structural timbers are derived from sustainably managed coniferous forests [39].

Although typically not as dense as hardwood species, softwoods are cheap, plentiful, available in useful dimensions, and can be easily manipulated into engineered timber products that optimise their structural properties. These enhanced properties equate to high strength-to-weight ratios that allow timber to compete with other more energy- or carbon-intensive construction materials discussed in Section 7. In addition, net area of European forests is rising annually (Section 4), making softwood an attractive choice for efficient and sustainable construction.

5.1. The harvesting of roundwood

The first stage of timber processing is the wood harvest. Felled trees with branches removed and trunks cut to length for transportation are commonly referred to as ‘roundwood’. European forests are some of the most intensively managed in the world. Depending on the topography, common silvicultural practice typically ranges from:

- Clear felling and artificial regeneration of whole stands of plantation trees.
- Natural regeneration under shelterwood.
- Mixed and natural regeneration combined with selective cutting [40].

Clear fell harvesting with specially customised harvester heads (Fig. 10) offers the greatest efficiencies in terms of annual yield due to the regular trunk diameter of consecutive farmed trees. On UK Forestry commission stands, a single machine is capable of harvesting up to 60,000 tonnes of timber per year. It would take 24 chainsaw operators to match this output manually [41].

In northern Europe, output of 18 m^3 per machine hour can be achieved with skilled mechanical operators when cutting softwood trunks of approximately 0.3 m^3 [42].

Thinning and clear-cut harvesting operations are increasingly mechanised for optimum productivity, particularly in Nordic countries where almost 100% of logging is fully mechanized, integrating cut-to-length systems [42]. Mechanized round wood harvesting is carried out by customised cutting heads mounted on a hydraulically controlled harvester vehicle. This ‘head’ is equipped with a gripping mechanism, debarking rollers, a chainsaw and de-limbing knives. These linear harvesting processes can occur at speeds of up to 5 m/s [42].

Within the 1.5 Mha of viable conifer forest in the UK, there is a move away from traditional clear-felling of softwood species in favor of alternative silvicultural management that encourages greater structural diversity within the crop, as seen in other parts of northern Europe [43].

5.2. Why dry timber?

As a natural material, wood is susceptible to fungal degradation (Section 7), but below 20% moisture content, this is not an issue. European standards for structural timber also specify an upper limit of 20% moisture content for ’dry graded‘ timber in order for it to receive a

Fig. 10. Typical mechanical timber harvester head displaying gripper and debarking rollers. Wisconsin Department of Natural Resources.

defined strength grading [44]. Drier timber also provides a more receptive substrate for gluing [45] and is lighter to transport. Timber's durability and environmental resistance can be further enhanced by thermal and chemical treatments discussed in Section 6.

As a hygroscopic material, timber fluctuates in moisture content relative to its surrounding environment. It is therefore important to dry timber prior to use in order to match the anticipated moisture content within a building environment and avoid excess movement as the timber naturally dries to its equilibrium service condition. This embodied moisture is generally represented as a percentage of the dry weight of timber, and the moisture content which wood tends towards in a given temperature and humidity is called the ‘equilibrium moisture content’. Harvested softwood can have a moisture content in excess of 100%, consisting of ‘free water’ held in the cell cavities and chemically ‘bound water’ in the cell walls. Once all free water has been removed from the cell cavities a state known as the ‘fiber saturation point’ (FSP) is reached [46]. Timber at or above the FSP is termed ‘green’ wood, and above the FSP, the mechanical properties of the wood are not seen to vary with moisture content [15]. Below the FSP, there is a strong correlation of mechanical properties with moisture content, with strength and stiffness increasing with decreasing moisture content [15]. Timber also shrinks as it dries below the FSP. Since the equilibrium moisture content in buildings is commonly around 8–12%, well below the FSP of 25–35%, depending on species, drying of the ‘bound water’ is necessary to avoid shrinkage in service [46]. In order to improve the mechanical properties of wood and for dimensional stability in use, it is therefore necessary to reduce the natural moisture content with natural or accelerated drying.

There are many methods of removing moisture from timber including air, solvent, microwave and supercritical CO_2 drying, but the most common in the sawn softwood industry is convective or condensing kiln drying. Convective drying, although energy and equipment intensive, offers the most accelerated means of drying dimensional timber for market. The ‘kiln’ is defined as an enclosed structure, typically 30–100 m^3, that provides controlled heating, air circulation, humidification and ventilation. Heating is achieved by indirect (steam, hot water, thermal liquid, electricity) or direct means (gas/oil burner). It is common for convective kilns to enclose overhead or side fans that circulate warm or dehumidified air through and around an open stack of sawn timber. Equipment factors which can affect efficiency of softwood drying include standards of kiln thermal insulation and the modulation of fan speed speeds during different stages of the drying cycle. Material factors that impact timber drying efficiency include volumetric dimension, porosity and green moisture content of a given timber species. One study has shown that the energy required to kiln dry radiata pine can be 3 GJ/m^3 specific heat, three times that of easier to dry species like mixed spruce at approximately 1 GJ/m^3 [47].

Studies in the Pacific Northwest of the United States have shown that of all the manufacturing processes associated with converting roundwood into dimensional timber, kiln drying of softwood consumes the most energy accounting for up to 92% of total manufacturing energy. By contrast, harvesting and regeneration of forestry has been shown to have a minimal impact, accounting for just 5% cumulative energy use [48]. The typical energy consumption associated with the harvesting and manufacture of softwood construction timber products can be seen in Fig. 11.

Structural timber is most commonly used within a dry building envelope but can be exposed to excess moisture on-site during the construction phase. To ensure equilibrium moisture content relative to its anticipated service environment, structural timber is dried to between a 12–20% moisture content. Sitka and Norway spruce shrink 4–5% tangentially and 2–3% radially when kiln processed from green to 12% moisture content for structural use [45]. These specific moisture percentages are defined in European standards [49] and equate to “service classes” for timber aimed at “assigning strength values and for calculating deformations under defined environmental conditions.”.

Structural timber unprotected on-site is likely to be exposed to elevated levels of moisture. Once the timbers are enclosed within the finished building, the 20% moisture content would then decrease in-situ to 12%. Service class definitions are important as excessive shrinkage in-situ can cause warping and cracking of timber, reducing its mechanical properties.

5.3. Dimensional timber processing

Once harvested, timber is referred to as “roundwood,” which is transported from the forest to a sawmill for further processing in order to remove bark and surface defects. During the processing of roundwood, seen in Fig. 12, approximately 50% is recovered as viable board and plank products, with the remaining dust, shavings and fiber by-products typically used as biomass fuel [50] or as fiber in engineered timber panel products with a market value.

Aggregated data shows that the embodied energy for primary production of dimensional softwoods from sitka spruce is approximately 10.5–11.6 MJ/kg as compared to structural grade steel (S275J2) at approximately 25.2–27.8 MJ/kg [51].

As a natural material, timber exhibits inherent variation of it's properties, even across samples of the same species [52]. This is due to the interaction of characteristics at the molecular and macro scales. In order to ensure that processed timber materials are able to support anticipated maximum loads as part of a structure in service, it is necessary to strength grade each piece of dimensional timber according to BS EN 14081 [53]. This grading standard permits a structural engineer to specify a chosen strength class of timber and use the characteristic strength values of that class in their design calculations [44].

Strength grading consists of two types: visual strength grading (VSG) and machine strength grading (MSG) according to the standard BS EN 14081-3 [54]. VSG is defined by a set of rules describing a series of weakness related features such as knots on the timber surface and any splits or related defects that may occur as a result of drying. MSG tests the characteristic values of stiffness and density for the strength classes by feeding individual timber lengths through a set of calibrated rollers. An additional visual assessment factors in any strength-reducing features that are not automatically sensed by the machine. The wood is then classified ‘C’ (softwoods) or ‘D’ (hardwoods) into various strength classes, each designated by a number indicating the value of bending strength in N/mm^2, e.g. ‘C14’ (weakest) to ‘C50’ (strongest) defined by European standard, BS EN 338. Whilst EN 338 defines a broad range of the most common strength classes in timber, these are not exhaustive. The more mature a conifer tree becomes, the more likely it is to produce stiffer, stronger and less knotty wood. This

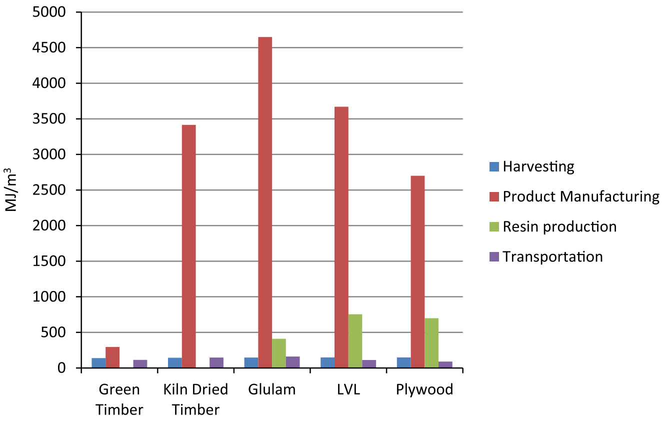


Fig. 11. Typical embodied energy of construction timber products based on data from Puettmann and Wilson [48]. Most energy is consumed in the drying process.

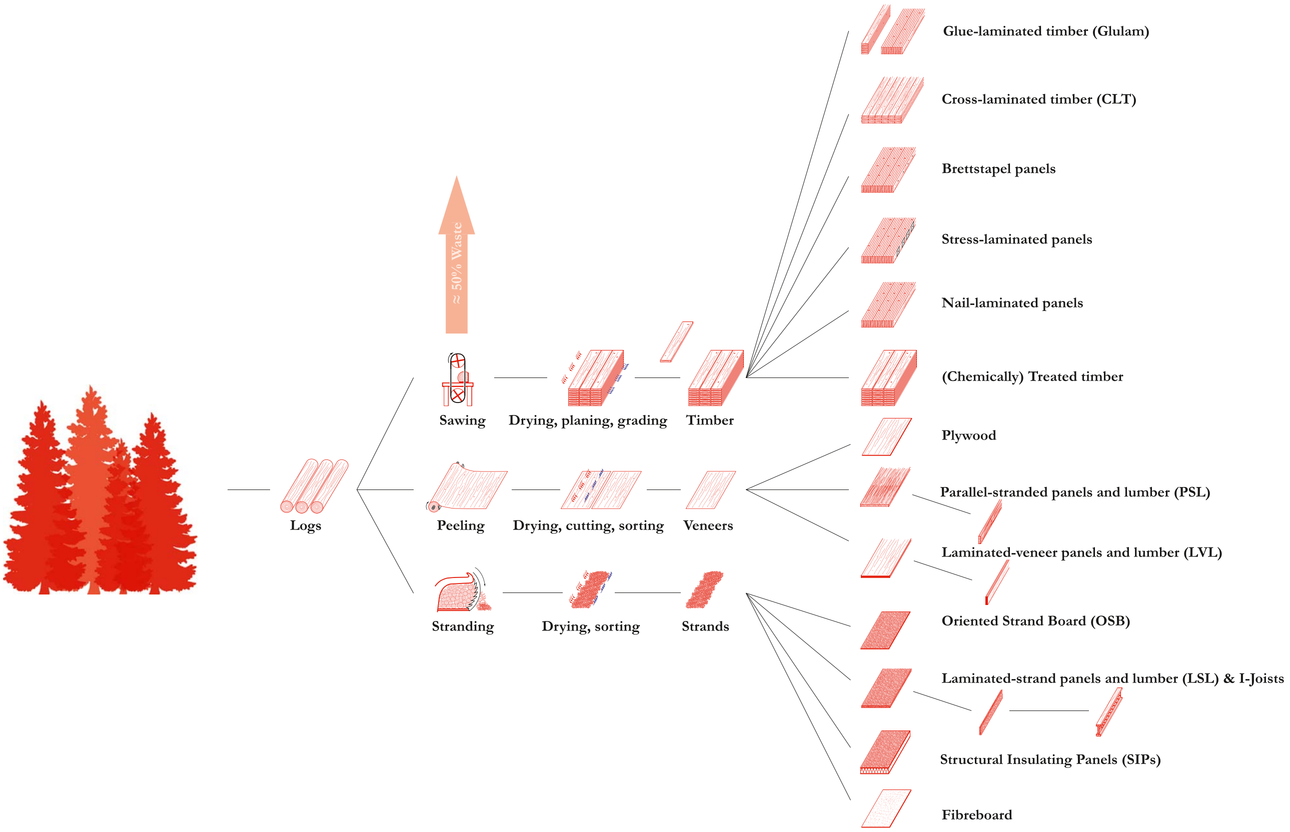


Fig. 12. The processing chain of engineered timber products, P.H. Fleming.

typically results in higher strength grading of softwoods derived from imported Swedish material that is harvested at 90 years of age, approximately twice the harvest age of UK grown timber [52].

Grading checks take place in the timber processing factory where the materials are cut to standardised lengths and dimensions defined by BS EN 336:2013. Anyone trading in construction grade softwood products within the European union is required to supply ‘CE’ marked materials that describe the product properties according to the following European norms:

- Solid construction timber: EN 14081.
- Glued-laminated timber: EN 14080.
- Wall and facade paneling made of solid wood: EN 14915.
- Finger-jointed timber: EN 15497.

Aside from dimensional sawn timber, softwoods are also processed into structurally optimised building materials known as ‘engineered timber’ seen in Fig. 13. The benefits of these wood composites – manufactured from laminated timbers, adhesives and other materials, include increased dimensional stability, more homogenous mechanical properties and greater durability. Families of these materials include:

Glulam: Defined as a structural timber member composed by at least two essentially parallel laminations which may comprise of one or two boards side by side having finished thicknesses from 6 mm up to 45 mm [BS EN 14080:2013]. These are typically used to fabricate curved and long beams limited only by methods of transport. Glulam is allocated to specific strength classes defined in BS EN 14080:2013.

Laminated Veneer Lumber (LVL): A reconstituted dimensional timber that is commonly twice the strength of dimensional timber of the same species manufactured from rotary peeled veneers of spruce, pine or douglas fir of 3 mm thickness [55]. Commonly the veneer grain is oriented in a single direction but cross-grained sections are also manufactured to offer tailored mechanical properties. Lengths of short veneer are jointed end-to-end with a scarf joint allowing limitless dimensional lengths.

Structural Veneer Lumber (SVL): Consists of outer plies of

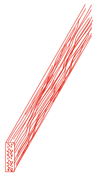
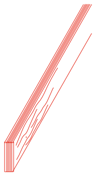
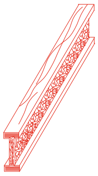
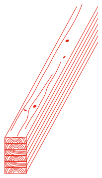
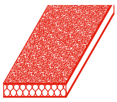
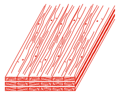
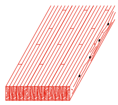
Engineered Timber Product	Parallel Strand Lumber (PSL)	Laminated Veneer Lumber (LVL)	I-Joist	Glulam	Structural Insulating Panel (SIP)	Cross Laminated Timber (CLT)	Brettstappel
Typical Detail							
Application	• Beams • Columns	• Beam • Columns • Cord	• Joist • Beam	• Beam (Long span) • High Loading	• Roof • Wall • Floor	• Roof • Wall • Floor	• Roof • Wall • Floor
Usage	Interior	Interior	Interior	Interior / Exterior	Interior	Interior/ Exterior	Interior/ Exterior

Fig. 13. Common structural engineered timber products in Europe.

LVL laminated together to form linear structural components. Douglas fir veneers of 2.5 mm laminated in the direction of grain parallel to the longitudinal direction of the board or beam is common [56].

Cross-Laminated Timber (CLT): Timber panels that are made of a minimum of three layers of sawn softwood stacked on top of one another at right angles and glued to form a thickness in the range 50–500 mm suitable for floor, wall and roof elements of up to 13.5 m in length [57].

I-Joists: Whilst these are more expensive and deeper than solid timber joists for an equivalent strength and stiffness, composite I-Joists are more dimensionally stable due to their homogeneous OSB web and the relatively small dimension of the solid timber or LVL flanges.

Structural Insulating Panels (SIPs): Structural prefabricated sandwich panels consisting of an insulation layer encased between two skins of fiber or oriented strand board.

Brettstapel: Also known as 'dowellam', these solid wood panels are manufactured from softwood planks connected by hardwood dowels. Hard wood dowels are driven into the panels at 8% moisture content. With the softwood planks at 12–15% moisture content the hardwood dowel swells to find equilibrium, fixing the panels tight without the need for glue [58].

Many engineered panel products are also combined with dimensional timber frame constructions to add bracing and shear strength including Plywood, Oriented Strand Board (OSB, Medium Density Fiber Board (MDF)and Fiberboard.

Although engineered timber products have superior structural properties as compared to dimensional timber, the necessity for adhesives use, seen in Fig. 14, negatively impacts the embodied energy burden of these products, seen in Fig. 15.

In terms of use in UK construction, there is an also additional transportation burden associated with importation and delivery of both kiln dried softwoods and engineered timber products, most of which are currently only manufactured in continental Europe or Scandinavia, as demonstrated in Fig. 16.

5.4. Future trends and innovation in timber construction

In recent studies of the UK construction sector it has been shown that novel off site panellised modular timber frame systems can save up to 50% of embodied carbon and 35% embodied energy when compared to traditional residential building methods and materials [63]. Modular timber construction offers benefits including reduced waste, lower costs, and shorter installation programs, meaning these materials are increasingly prevalent across the European building market.

Other recent innovations include welding of timber via high frequency oscillating or linear friction of adjacent wood surfaces as a replacement for wet adhesives. This joining method is under investigation for moment connections in softwood timber structures [64].

To further improve the stiffness and strength to weight ratios of engineered softwood products some research institutes are also researching the use of performance fiber reinforced timber for more resilient timber structures in seismic zones seen in Fig. 17 [65].

5.5. Research questions

- Given the evidence that approximately 90% of total manufacturing energy can be attributed to timber drying, alternative means of accelerated removal or chemical use of 'bound water' for improved timber properties, could reduce the drying energy burden.
- Stiffer or stronger composite timber materials could provide a route to market for small section timber or wood waste that has a small aspect ratio and is therefore more efficient to dry. Low strength grade wood, otherwise not suitable for structural use, might also be considered by engineers through increased mechanical properties as part of a hybrid composite. Careful consideration will have to be taken of the embodied energy and embodied carbon of the composite materials used however, so as not to outweigh any environmental gains from the use of timber waste streams.
- Timber with a lower moisture content before harvesting could help to reduce the transport weight and drying burdens associate with saturated softwoods. Can bio-chemical interventions yield timber species with naturally lower moisture content?

6. Wood treatments

In addition to drying and dimensional processing (Section 5), wood treatment for increased durability is another important procedure before timber flows into construcion sector. Wood, consisting of cellulose, hemicellulose and lignin, is susceptible to biodegradation by fungi and bacteria, especially under high moisture condition (Section 3.4). It is undesirable for timber to degrade during service in buildings. In addition to using naturally durable timbers (Section 8.2) such as larch or tropical hardwood, the durability of wood products can be improved by physical or chemical treatments.

6.1. An overview of wood treatments

Wood treatment is 'a process that is used to improve the material properties of wood, but produces a material that be disposed of at the end of a product life cycle without presenting an environmental hazard any greater than that associated with the disposal of unmodified wood' [66].

The material properties required to be improved for wood include dimensional stability, resistance to biological degradation, thermal stability or fire resistance, UV resistance, mechanical properties etc [67]. Currently applied physical or chemical treatments usually take effect by:

- Reducing the ingression of water in order to minimize changes in wood volume, and inhibit the growth of fungi and bacteria (indirectly), which can be realized by hydrophobic treatment or filling with blocking agents.
- Quenching chemically-active groups such as hydroxyl groups in order to prevent the attack by fungi, bacteria and insects (indirectly), and also increase fire resistance to some extent.
- Impregnating preservatives to kill fungi, bacteria and insects directly, or impregnating fire retardant for thermal stability.
- Coating moisture-, bio-, fire- or UV-resistant agents on the surface of wood.

Therefore, wood treatments normally use one of three strategies: modification of the cell wall, impregnation, and coating (Fig. 18). Modification of the cell wall can be further divided into thermal

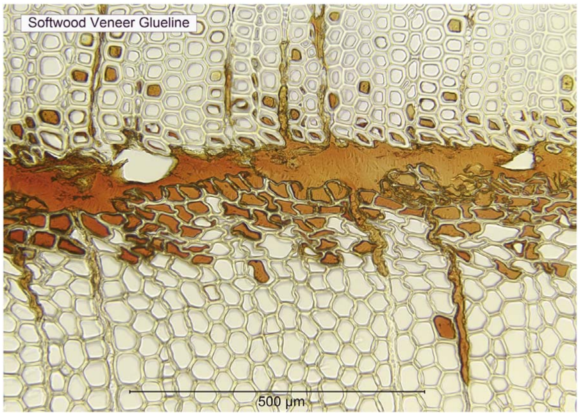


Fig. 14. Micrograph of phenolic resin adhesive line bonding softwood veneer layers, courtesy, American Wood Council, Leesburg, VA, USA.

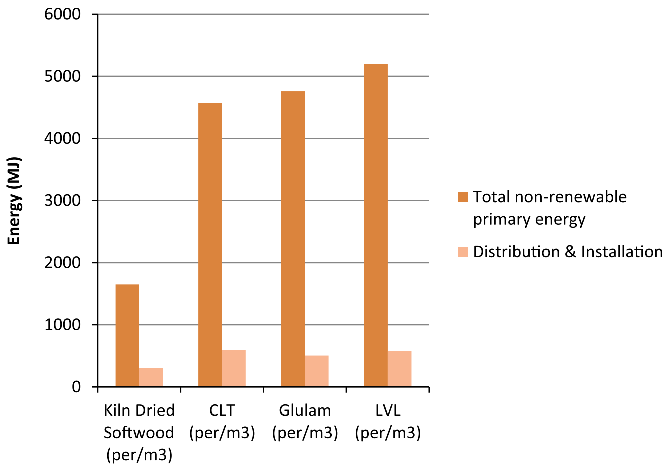


Fig. 15. Total non-renewable primary energy consumption and distribution/installation energy associated with adhesively bonded engineered timber products manufactured in the EU. Data taken from assumptions made in [59–62].

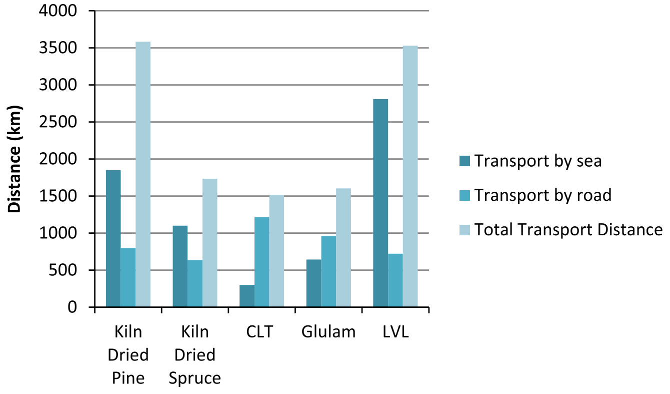


Fig. 16. Predicted transportation distances from European manufacturers to a given UK construction site drawn from assumptions made in [59–62].

Fig. 17. Carbon Fiber Reinforced Wood (CFRW) Beam, Teijin Ltd, 2015.

modification and chemical modification, both of which are active strategies that result in a change to the chemical nature of materials at the molecular level.

6.2. Thermal modification

Thermal modification, having a widespread application in industry due to its feasibility, is an effective way to improve wood dimensional stability and durability against biodegradation [23,24]. Chemical and anatomical properties of timbers are both changed during heat treatment (Fig. 19).

Chemical reactions can be activated within cell walls under high temperature. During the heat treatment, acetic acid is formed from the hydrolysis of acetyl esters in xylan [68,69] (Section 3). Hemicelluloses are depolymerised into oligomeric and monomeric units and further dehydrated to aldehydes under acidic conditions, leading to fewer hydroxyl groups and less hygroscopic. The effect of heat treatment on the depolymerisation of cellulose is rather limited, instead by a small increase of cellulose crystallinity [69,70]. Lignin is the least active component, and can be cleaved to form phenolic groups only at high temperature. However, the resulted reactive lignin derivatives can increase the degree of cross-linking in the cell wall. As a result, the cell wall of treated timbers becomes less elastic and the cellulose microfibrils are less hygroscopic and have less possibility to swell, which leads to improvements in dimensional stability and resistance to biodegradation [71,72].

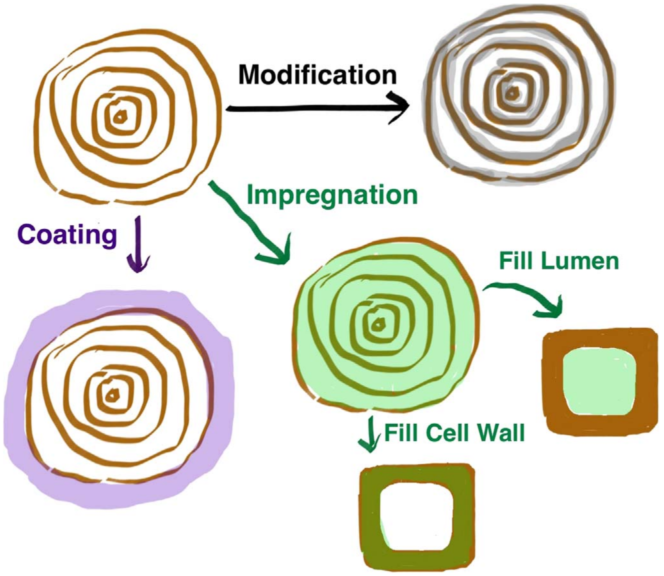


Fig. 18. Illustration of different wood treatments. Wood treatments normally use one of three strategies: modification of the cell wall, impregnation, and coating.

The anatomical structures of wood is also affected by thermal modification. Treated woods exhibit a more porous structure, with a increase of the amount and size of pores [73]. Radial cracks are observed between different cell wall layers and at the corner of cells [74]. No significant changes are observed in the microfibril angle distribution [75].

Compared with untreated wood, thermally modified wood becomes more brittle, showing lower bending and tensile strength. This has been explained by the degradation of hemicelluloses and the large stress caused by the radial crack [76,77]. However, polycondensation reactions of lignin result in higher strength in the longitudinal direction, along with an increase in compressive strength and stiffness [78].

6.3. Chemical modification

Chemical modification makes use of enormous numbers of hydroxyl groups (OH) in wood to react with other chemical reagents, resulting in permanent change to the molecular structure of cellulose, hemicellulose etc. A well-known case is acetylated wood, also known as Accoya® wood, where the hydrophilic OH groups are replaced by more hydrophobic acetyl groups through acetylation with acetic anhydride, as shown in Fig. 20. In addition to good durability and dimensional stability without loss of strength, the acetylated wood shows significant resistant to moisture and fungi, due to the hydrophobic treatment. More importantly, it has the same end-of-life scenarios (Section 8) as untreated woods and can be burned for energy recovery without producing extra hazards [66,79]. Two wooden bridges constructed by Accoya® wood in 2008 and 2010 for heavy road traffic up to 60 tonnes

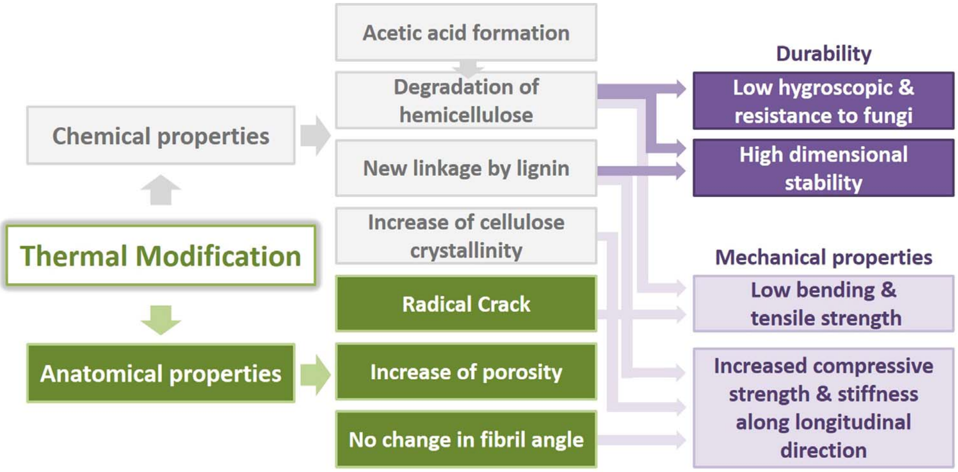


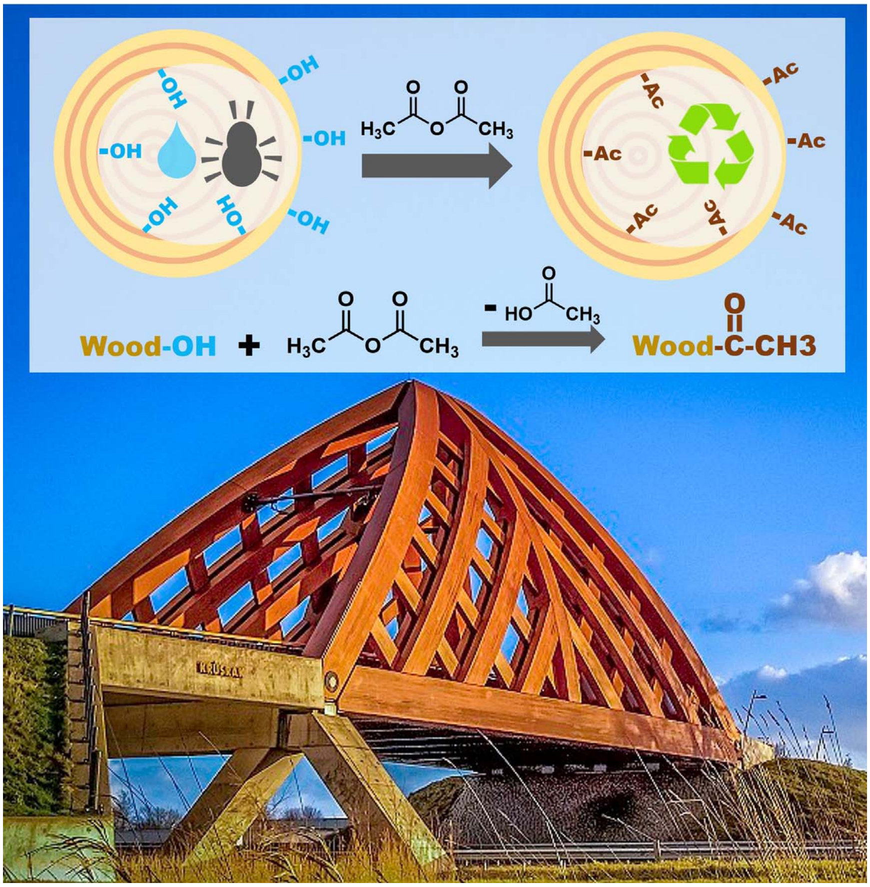
Fig. 19. Property changes involved in the thermal modification.

in Sneek, the Netherlands (Fig. 20) are the first to incorporate laminated softwood elements, without reliance on toxic preservatives or a protective roof [80]. Industrial-scale acetylation processing is currently done primarily on Radiata Pine from New Zealand.

6.4. Impregnation

Impregnation treats wood with chemicals that diffuse into either the cell wall or lumen. Unlike active strategies such as modifications, impregnation is a passive strategy where an improvement in properties occurs without alteration of the chemical nature of materials. The property change primarily comes from the bulking of wood cells by the impregnants [66]. After impregnation, the permeability of timbers decreases, leading to a better resistance to water and fungi. Moreover, the density of timber increases with an improvement in some mechanical properties.

Impregnants can be monomers that are cured into bulk within wood cells after subsequent polymerization. Taking furfurylation treatment as an example, furfuryl alcohol, derived from biowastes such as sugar canes, corn cobs, sunflower and birch chips, fills in wood cells



$$\text{Wood-OH} + H_3C\text{-}C(=O)\text{-}O\text{-}C(=O)\text{-}CH_3 \xrightarrow{-\ HO\text{-}C(=O)\text{-}CH_3} \text{Wood-}C(=O)\text{-}CH_3$$

Fig. 20. Acetylation of wood: a case of chemical modification. The hydrophilic OH groups are replaced by more hydrophobic acetyl groups (Ac) through acetylation with acetic anhydride. In addition to good durability and dimensional stability without loss of strength, the acetylated wood shows significant resistant to moisture and fungi, and has the same end-of-life scenarios as untreated woods. Background is the wooden bridge constructed by Accoya® wood in Sneek, The Netherlands for heavy road traffic up to 60 tonnes. (Photographs courtesy of John Kroes).

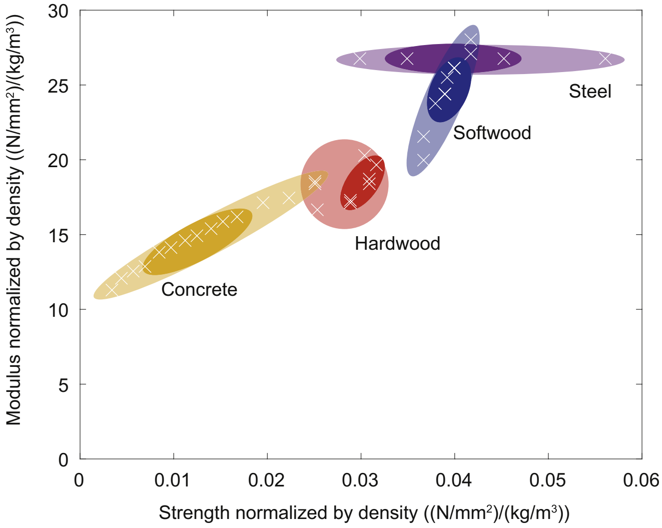


Fig. 21. Compression strength and modulus of construction materials normalised by density, according to the relevant design standards – the dark colors represent the more widely used grades of material. Design values of strength and stiffness, including partial factors, are shown, based on the Eurocode design standards for concrete [90], steel [91] and timber [44].

with ethanol, citric acid (catalyst), and water, which then furfurylates the wood by polymerization under high temperature. Wood after furfurylation treatment exhibits high dimensional stability, good resistant to microbial decay and insect attack, and increase in modulus of rupture as well as modulus of elasticity [81].

Impregnants can also be preservatives such as chromated copper arsenate (CCA) and creosote. However, the use of CCA and creosote has been stopped in Europe because the use of arsenic and chromium is no longer allowed. Alternatives like alkaline copper quat (ACQ), Cu-HDO, and other metal free wood preservatives have been developed. Even so, wood preservatives are still potentially hazardous. At the end of life of these products, potential loss of toxicants into environment may become an issue in recycling or disposal stages [66].

6.5. Coating

A coating or sacrificial layer can be painted on the surface of wood products, supplying a physical barrier against weathering and degradation and presenting the aesthetics of the product as well, which is suitable for many high value exterior wood end uses, such as window joinery and cladding [82]. As a surface treatment rather than homogenous bulky modification, coating usually is the final operation of wood processing.

6.6. Research questions

Wood treatment not only can extend the service life of construction timbers, but can also make them available for extra tasks where untreated ones are not qualified. Herein, the following topics relating to wood treatments are required for further study:

- In order to use wood products for constructing tall timber buildings, wood treated for high strength performance is desirable, but still remains a challenge. The mechanical properties of timbers are rarely increased by most wood treatment technologies. Lignostone, a thermal and pressure treated wood, which has been produced in Germany since the early 1860's and still in use today, is one of the few modified woods that can show significant increase in strength [83].
- Treated wood may produce hazardous chemicals when being burned without special facilities (Section 8.3.2). Exploiting new treating agents from natural materials (e.g resin) as alternatives may be worth investigating so as to reduce the cost and environmental risk at the end-of-life of treated wood.
- No treatment is a good treatment. Genetically creating a fast-growing species with good durability is an ultimate dream worth chasing.

7. Structural use of timber

During the 20th century, public perception and prescriptive regulations limited the structural use of timber in Europe largely to small and low-rise structures [84]. The use of timber as a construction material for domestic dwellings is well established in many parts of Europe and around the world. Roughly 20% of new houses in the United Kingdom and up to 70% in Scotland are timber frame [85]. The move towards performance-based design in the common standards for Europe [86], however, has made it possible to build larger and taller timber buildings more routinely, and timber has the fundamental material properties necessary to form large structures.

This section discusses the use of various structural systems and wood products in these more challenging structures.

7.1. What should we build with timber?

Timber is one of three structural materials currently used in the construction of large structures, along with steel and reinforced concrete. If timber is used in the types of building in which it is most structurally efficient then the timber we harvest can do the most to reduce the environmental impact of construction.

Timber has a strength parallel to grain similar to that of reinforced concrete: hardwood is slightly stronger, and softwood slightly weaker, although timber cannot match modern high-strength concrete in compression. Timber is less stiff than concrete, and both materials are far less stiff and strong than steel. However, timber has a low density compared with these other conventional structural materials. This results in efficiency for long-span or tall structures, in which a significant part of the load to be carried by the structure is its own weight. When those loads are resisted purely in tension or compression, the strength-to-weight or elastic modulus-to-weight ratio are measures of the mass of material required to achieve a structure of a given area, height or span. Fig. 21 shows the strength-to-weight and modulus-to-weight ratios for steel, timber and reinforced concrete, and shows that softwood performs similarly to steel by those measures.

This suggests that timber is particularly structurally efficient material in structures, or parts of structures, in which a high proportion of the load to be resisted is the self weight of the structure itself. Examples are roofs, some bridges and the gravity load resisting system of tall buildings. In structures for which the load to be resisted is largely independent of the weight of the structure – such as the wind load on a tall building – the higher absolute strength of steel or reinforced concrete may make them more efficient, in terms of the amount of material required to achieve the function of the building.

In an earthquake, the force imposed on the structure by shaking depends strongly on its mass, with heavier structures experiencing larger seismic forces. Light timber residential buildings have therefore been seen to perform well in seismic events, such as the 2011 earthquake in Christchurch, New Zealand [87]. The seismic performance of taller timber structures is an active area of research, including full-scale shaking-table tests of multi-storey timber frame [88] and CLT buildings [89].

On the basis of its mechanical properties, timber may be particularly efficient in certain structural forms. Shell structures are efficient for long-span roofs, since they transfer loads purely in compression and shear in the plane of the shell. In timber, it is convenient to concentrate the shell material into a grid of linear members, resulting in a gridded shell. Timber gridded shell structures have been used in roof domes for sports stadia greater than 150 m diameter, and 45 m in height [92]. Gridded shells can be made from small strips, cut from the tree, and connected at their ends by glued finger joints to give continuous strips of any length required [93]. This form has been used to create very large structures without the need for the infrastructure associated with the production of large curved engineered wood products such as glulam.

The energy efficiency of timber is improved if the processing required is reduced. As described in Section 5, a large proportion of the energy expended in processing engineered wood products is in drying and production of adhesives. This energy use may be justifiable in creating large structural elements which shrink very little in service. The need for drying and adhesives can be avoided, however, in small structures by using relatively small cross-sections and traditional connection methods which can accommodate the resulting shrinkage [94]. It has been shown that drying can be avoided in large structures too: green oak was used in the construction of the 15 m by 50 m by 10 m high roof structure of the Downland gridshell [95], where the global structural form and the local detailing are appropriate to accommodate the movement in the timber.

It is also possible to avoid even the use of a sawmill, by using green roundwood in construction [96]. By avoiding cutting the grain, this retains the structure formed by the tree. Keeping the timber closer to its natural form in this way may also reduce the weakening effects of knots, since the tree has naturally formed load paths around them, but connecting these circular cross sections is challenging. In roundwood and green timber construction, traditional methods may hold lessons for large-scale, repeatable engineering of larger structures. Researchers have begin to address some of the obstacles to the widespread use of roundwood construction using local species by investigating their strength and stiffness and suitable connection systems [97]. Small-diameter trees are removed from managed forests to improve the quality of mature trees and to control fire; it has been shown that these are a potential resource for use in structures [98,99].

7.2. Building taller with timber

In the last decade, a handful of timber buildings six storeys and higher have been constructed, and engineers have begun to look at the possibility of building much taller with timber. The complexity of the structure of a tall building increases with the height of the structure. In low-rise buildings, where the forces to be resisted are relatively low, it is possible to resist lateral loads by bending stresses in walls which form a vertical cantilever. This is the approach widely used in cross-laminated timber construction in buildings such as the seven-storey University of East Anglia student residence [100]. Forming some of these walls into a core improves their efficiency by loading the outer walls of the core in tension and compression, as was done in the eight timber storeys of the Stadthaus [101]. Using a frame around the perimeter of the building, rather than a core in the interior, can load all members in uniform tension and compression. Such a glued-laminated timber frame is used for the 14-storey Treet building in Bergen, Norway [102]. A common system for very tall buildings in concrete is a central core coupled with shear walls near the outer edges of the building by stiff link beams, and a timber version of this system is proposed by Skidmore, Owings and Merrill in their theoretical design exercise for a 42-storey building [103].

A selection of structural systems for multi-storey buildings are compared in Fig. 22 on the basis of the number of storeys and their use of timber. For buildings up to about six storeys, CLT uses substantially more timber to achieve the same function as a light timber frame building. For buildings over six stories, the use of CLT together with light timber frame may use less timber than CLT alone, and for buildings taller than ten stories, the only proven system to date is the external glulam frame supporting internal CLT units, constructed in Bergen [102].

Structural material is only part of the material used in a building. Some materials, such as glazing, cladding and mechanical and electrical fittings may be unrelated to the structure. The use of wood as a structural material, however, often has the consequence of introducing other materials to achieve certain performance requirements: concrete is often used to achieve acceptable floor vibration, for example, and gypsum boards for fire resistance [104], or concrete to achieve thermal mass. Efficiencies may be achieved by giving materials multiple function: if concrete is used to add mass in floors to reduce impulse vibration, for example, shear connection to the slab also enables it to contribute to resisting static gravity loads.

Fig. 23 shows the proportions of materials in a series of timber buildings of five, seven, fourteen and forty stories in height. It can be seen that there is often a substantial mass of concrete. In many of these cases, this is primarily due to a concrete screed added to the floors to improve accoustic and impulse vibration behavior. A group of European researchers investigated the use of ‘floating floors’ and walls separated by pads or layers to reduce impact vibration and sound transmission [105]. Attenuation was achieved by using lightweight materials such as polymer foams and wood fiber insulation boards. Such a change could substantially reduce the mass of the building, and therefore the loads on foundations. In the case study buildings, the proportion of materials other than timber and concrete was almost constant, at approximately 30% of the total mass.

Another argument for introducing heavyweight materials into buildings is to increase their thermal mass – to reduce the load on mechanical heating and cooling systems by exposing materials to the indoor environment which absorb and release heat, thus buffering diurnal fluctuations in temperature. Such behavior requires an appropriate combination of heat capacity and thermal conductivity. The ability of timber to perform this function is limited by its low thermal conductivity, which means that it does not absorb and release heat rapidly enough to correspond to daily heating and cooling cycles [106]. Research is ongoing into ways of improving the thermal performance of timber systems.

It is pertinent at this stage to compare the amount of timber used in a building to that which can be produced by a given area of forest. We use the Limnologen building as an example: a 7-storey residential building in Växjö, Sweden. Examining just one type of apartment in that building, it uses approximately 28 m^3 of timber per apartment for apartments approximately 125 m^2 [107]. This may be a relatively efficient building, as approximately 30–40 m^3 of timber would be used for a similar apartment in a multi-storey cross-laminated timber

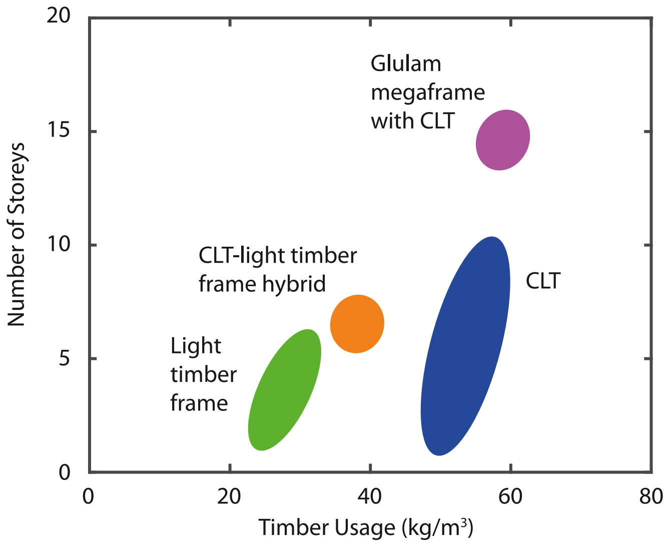


Fig. 22. The density of structural timber used to achieve a given height of building for various structural systems.

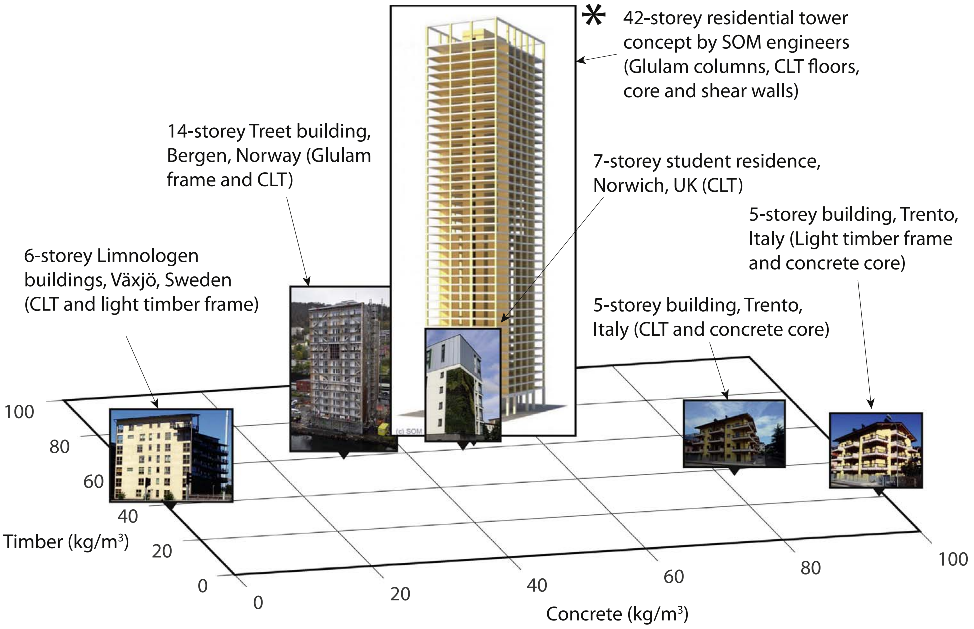


Fig. 23. Material usage, in terms of mass, in multi-storey timber buildings. The horizontal axes show the mass of timber or concrete used per m^3 of each building. The size of the images indicates the height of each of the six case-study buildings investigated – the building indicated by * is a concept, and has not been constructed (image by SOM [103]).

building in the UK [108].

The total yield of a forest of Norway spruce was found to be around 10 m^3 ha^{-1} $year^{-1}$ (Section 2.2), and accounting for the fact that approximately 40% of wood removals from forest go into building and construction (Fig. 27 in Section 9.1), this may be considered to produce at least 4 m^3 ha^{-1} $year^{-1}$ of construction products. Each of the three-bedroom apartments described above therefore represents about a year's growth over 7–10 ha. If the building is replaced after 50 years, and the rotation period for the forest is 50 years, then an area of forest of approximately 0.15 to 0.2 ha – a square with 35 or 45 m sides – is required to sustain that accommodation indefinitely.

Another way of considering amount of wood is to say that if the population of Europe (750 million) lived in this type of apartment, with three people per apartment, then approximately 40–50 million hectares of forest would be required renew those buildings every 50 years. This would represent about 25–30% of Europe's forest, managed, harvested and utilized in the same way it currently is.

7.3. Connection design for efficiency

A critical element of the design of most timber structures is the design of the connections between load-bearing members. The dimension of the member required to accommodate the connection may define the size of the structural member as a whole, since edge-distances from connectors are set to prevent splitting. These requirements have the potential to add material to a structure simply to accommodate connections. The efficiency of a connection is defined as the ratio of the strength of the connection to the strength of the member it connects. Fig. 24 compares connection efficiencies using a range of connection types, and shows that connections using glue give the highest efficiency.

The comparison of connections purely in terms of their structural efficiency doesnot tell the whole story. It is possible to achieve high efficiency with connections using glue, but this comes with the cost of the environmental impact associated with the glue. Glued connections must be performed in a controlled environment, which largely precludes their use on-site, although steel plates glued to timber members may be bolted on site. Mechanical connections using steel fasteners such as screws and dowels achieve efficiencies of approximately 20–30% without the use of glue, and can be installed in-situ.

Traditional pegged mortise and tenon connections have lower efficiency, but have been shown in traditional green oak construction to accommodate the movement associated with drying shrinkage, and may even use the effects of shrinkage and swelling to achieve prestress in the structure, such as in Brettstapel panels, where the swelling of pre-dried hardwood dowels locks together a series of timber boards [110].

7.4. Research questions

For the engineering of larger, more efficient timber structures, several research requirements have become apparent:

- The high strength-to-weight and stiffness-to-weight ratios of timber mean that it can form extremely light structures; research is required to manage the structural dynamics of these structures, from sound transmission to wind-induced and seismic vibration.
- Modern timber engineering has been largely based around a few softwood species, but this report has shown the benefits in durability, energy efficiency and ecology possible by using a greater variety of species; research is required to efficiently assess the

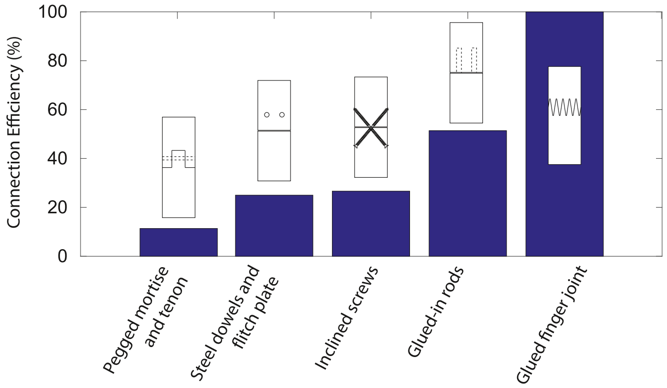


Fig. 24. Efficiency of connections between 100 mm by 200 mm timber members transmitting a tensile axial force – connection efficiency is the ratio of the strength of the connection to the strength of the memebers it connects. These values were calculated based on Eurocode 5 for mechanical connections [49], and research papers for glued and traditional connections [94,109].

properties of lesser-used species for design.

- The use of roundwood and wood with higher moisture content for structures may substantially reduce their embodied energy; research is required into effective connection systems and the effects of changes in moisture content for such structures, as well as grading methods for these materials.

8. Fire resistance, durability and end of life

When timber is used as the primary structure in a building, it is required to have a service life as long as the building itself, and to withstand the environmantal conditions and catastrophes to which it may be exposed. In this section, we explore the factors affecting the lifespan of timber components, whether that is an abrupt end of its service life due to fire, or a more gradual decay due to fungal or insect attack. We then discuss the options for those components at the end of their service life.

8.1. Fire resistance

The use of timber in larger structures relies on fire engineering design to ensure that the building can retain its structural integrity for sufficient time either for building occupants to be evacuated, or for the fire to be extinguished. In construction using large cross-section timber members such as CLT, this may be done by assuming a rate at which the timber chars [111], and therefore the cross-section of timber remaining after a given time [112]. Smaller cross-sections must be encapsulated in non-combustible material such as gypsum boards or concrete [104].

The strength and stiffness of timber both reduce at lower temperatures than steel and concrete. For example, timber's strength is reduced by more than 50% at 100 °C, compared with that at 20 °C [111]. Timber structural members may still perform well at high temperatures in comparison with steel, however [104], since the char layer can act to insulate the material within, whereas the high thermal conductivity of steel means that the complete section quickly heats up. Where steel is used to connect timber elements, heat can be quickly conducted through the connectors, degrading the strength and stiffness of the wood around them.

The behavior of timber in fire is fundamentally different to steel and reinforced concrete, however, since it is combustible, and research groups have identified the key research needs to be addressed for the next generation of large timber buildings [113,114]. They address the performance of systems with various levels of encapsulation, the effect of flame spread due to a combustible structural material and the fire performance of connections.

8.2. Lifespan of construction timber

The potential lifespan of a wood product is described by its durability, and the its natural durability may be enhanced by a variety of treatments (Section 6).

Lifecycle analyses studies include timber buildings assume the same lifespan for timber as other structural materials [115–118]. Although there is little published data addressing the lifespan of construction materials, this assumption appears to be justified by the results of a survey of demolition contractors by the Athena Institute [119], which showed that buildings are rarely demolished due to degradation of their main structure, whatever the structural material. In their survey of 227 buildings demolished in Minnesota, only 8 were demolished because of a specific problem with a structural material. Of the 27 wooden buildings over 100 years old in that study, none were demolished because of a material problem.

As with any building material, some timber components in a building may have a design life shorter than that of the building as a whole, or may require maintenance during the life of the building [120].

Wood properties have an intimate relationship with moisture. The mechanical properties and dimensions of timber vary with moisture content, as described in Section 5.2, and a high moisture content makes the wood vulnerable to attack by fungi or insects, as described in Section 3.4. Design details which limit the exposure of the timber to wetting and direct sunlight, such as columns raised above ground level and overhanging roofs, ensure that timber components can last for centuries, such as the 16th century Spreuer Bridge in Lucerne [121].

Even when timber must be exposed to the weather, the use of durable species can be an alternative to chemical preservative treatments that may limit options for recycling and reuse. Durable species can be used even in marine and freshwater environments [122]. Since European timber production has concentrated on the less durable whitewood species, however, procurement of durable species is often costly. Researchers have been working to obtain the experimental data necessary to permit design with durable hardwood species such as oak and sweet chestnut [97].

European norm EN 350-2 [123] gives guidance on durability of wood species for decay by fungi and for insect attack. Since fungi require moisture to grow, the durability of timber to this form of decay must be considered by looking both at the permeability of the wood and its resistance to the fungus itself. Fig. 25 shows their resistance to decay by fungi and their resistance to ingress of water. Species towards the top right of the graph are most durable. Not all hardwoods are more durable than softwoods. Although the spruce which is widely used in construction is not very durable, there are softwoods which have higher durability.

8.3. End-of-life scenarios for wood

For sustainable use of wood resources, it is ideal to employ wood in products with a design lifespan that (at least) matches timber rotation periods, thereby enabling 'sustainable-yield logging'. Aiming to a prolonged service lifespan, the European Parliament has established a cascade use principle for wood, which suggests wood be used in the following order of priority: wood-based products, re-use, recycling, bioenergy, and disposal [124,125].

Following this principle, it is sensible to use wood resources for construction products whose lifespan is long (>30 years, but even over 100 years [126]). In addition, construction timbers, after one service for previous building projects, can be re-used (as wood plastic

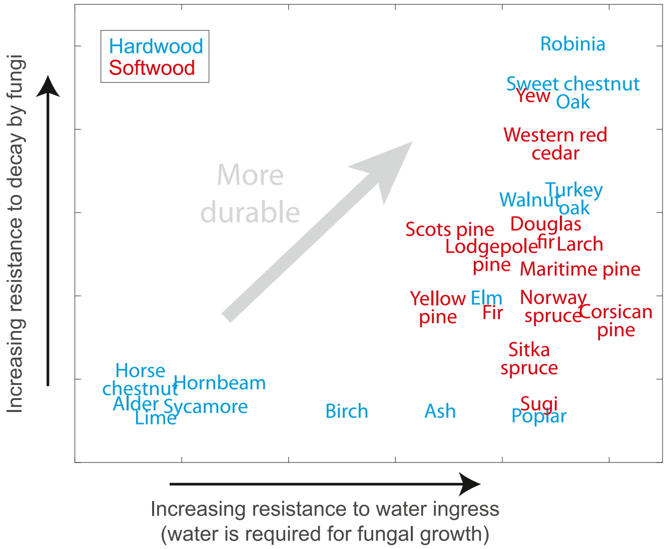


Fig. 25. Durability of heartwood of important species grown in Europe according to EN 350-2 [123]. Species towards the top right of the axes are most durable, with those lower and further to the left less durable.

composites or fibreboard panels, for instance) or down-cycled (into the competing uses for pulp and fuel) at their end-of-life. Fuelwood, by contrast, is a single-use, very short lifespan product [126] that is often burned inefficiently [127], and paper and packaging products have short lifespans (<2 years [126]) with moderate recovery rates (~50%) at their end of life.

According to the cascade principle and referring to a report by Jungmeier [128], an end-of-life scenario for wood is summarized in Fig. 26(right), which is similar to the waste management hierarchy stated earlier by EU waste framework directive in 2008 [129] (Fig. 26, left). There are three main options for wood products after one service unit: re-use, burn, or landfill.

8.3.1. *Re-use: from waste to resource*

Re-use is the priority for wood products after one service unit. They can be re-used as products either for the same purpose as before or for less demanding purposes after simple reshaping (e.g. from structural timbers to flooring). According to the principle of 'preparing for re-use' in the waste framework directive, wood products are encouraged to be designed with ease of disassembly and re-use as a consideration.

Even if wood products after one service unit are not qualified for further use, they can still be reprocessed as fibrous materials for making new wood-based products, corresponding to the 'recycling' phase in the waste framework directive. In 2002, the UK recycled 41% of wood waste, produced from all wood based products including construction, furniture, joinery, packaging, and pulp [130]. If one only considers the wood waste from construction, the largest sector in UK timber industry, the recycling rate is 31% [131]. However, the UK has already made much progress on recycling wood waste, with a current recycling rate of 40–45%, showing a more than tenfold increase since the mid 1990s, when the rate was less than 4% [132]. If including energy recovery, the recycle rate can be as high as 65–70%. Recycled wood can now be considered more as a resource than a waste product.

8.3.2. *Burn: energy recovery and energy supply*

If recycling is not possible, wood products can still produce energy through direct combustion or through conversion to gaseous or liquid fuel before burning [133]. This will not aggravate the climate change due to the carbon neutral feature of wood (Section 4). Clean wood wastes without being contaminated with harmful substances are allowed to be burned in normal power stations or private stoves [134]; while contaminated wood such as treated wood, painted wood, or chipboards containing adhesives (e.g. formaldehyde glue), can only be used for energy generation in special stations equipped with appropriate combustion facilities [128,135].

In addition to using wood waste for energy recovery, some wood is used directly as fuel (or fossil-fuel substitution) for energy supply without serving as wood products (Fig. 26), and is termed 'wood fuel'. The role of wood fuel in the energy system of the EU is increasingly important. From 2009 to 2013, the European wood fuel production had a dramatic rise by 20%, although the global increase is only 2% [136]. This is against the cascade principle, where energy recovery should only take place after exhaustion of product's material value. It is noteworthy, however, that the increase use of wood fuel does not significantly impact the wood supply for construction, because wood fuel normally comes from short-rotation forest or coppice, of which the trees are small and not suitable for structural use [137].

Those against wood fuel [138] point out that wood is a fuel with high 'carbon emission factor' – the amount of carbon (or CO_2) emitted per unit of released energy. For instance, the amount of carbon emitted by natural gas is only 55% of that released by wood fuel. Therefore, they insist wood be used as products, leaving energy production to fossil fuel and carbon-free energy resources in order to mitigate climate change. Another opinion [139] holds that whether or not to use wood as energy should be determined by the market economy. For example, METLA predict the use of wood fuel in Finland in 2015 will not grow due to the low global market price of coal, the low price levels of emissions rights, and cutbacks in subsidies [140].

8.3.3. *Landfill: if no better choice*

Landfill is the least favored end-of-life scenario. It not only fails to recover energy from wood products, but also has to pay for the cost on landfill practices. However, treated wood wastes containing hazardous components and the ash disposed from wood burning have to go to landfill. Landfill restrictions on wood waste in UK are currently not necessary, pointed by DEFRA in 2013, as it can be regulated more properly by the market itself [141]. Many governments (e.g. Sweden, Austria, Germany), however, have already banned landfilling of wood waste, while many others have discouraged landfilling through taxation [142]. The objective is not only to reduce dependency on landfilling, but also to encourage energy recovery (through incineration - although even this may be restricted or taxed), and importantly, to encourage material recovery and recycling. The latter would further extend the life of wood and therefore the carbon sequestration period, but more importantly it would reduce demand for newly-sourced wood and associated emissions in production.

Biodegradation takes place on wood waste in landfills. Most of the cellulose and hemicellulose in wood are biodegradable and quickly decompose to small components; while lignin is resistant to biodegradation in an anaerobic environment and can remain for very long periods (Section 3) [143]. 0–3% of the carbon in wood waste are emitted as landfill gas, containing 56% methane, 31% CO_2, 10% nitrogen, 1% oxygen, 1% trace species, and 1% moisture [144,145]. A large portion of remaining carbon is permanently sequestered in soil. It noteworthy that most of modern landfill sites are required to flare or make use of landfill gas (as energy) [145], because the methane is

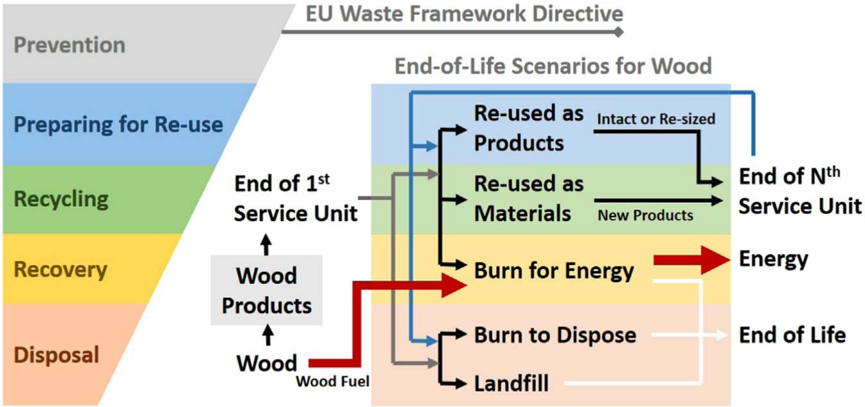


Fig. 26. End-of-life scenarios for wood. The cascade use principle suggests wood be used in the following order of priority: wood-based products, re-use, recycling, bioenergy, and disposal.

estimated to have 34 times the global warming impact of CO$_2$ [146].

8.4. Research questions

Aiming toward wood products and buildings with a lifespan long enough for sustainable use, which may be efficiently reused or recycled at the end of their life, the following research topics are worth investigating:

- Massive timber buildings may behave in a fundamentally different way in fire than non-combustible buildings, and research is required to understand how fire behaves in timber buildings of a different scale, and how they may be best protected.
- Research is required to form the basis for standards or strategies to design wood products according to their further end-of-life scenarios (e.g. design for recycling or design for energy).
- Planning buildings or projects for ease of disassembly and sorting of wood elements after end-of-use, in order to manage wood waste (especially treated wood waste) in an economical and environmentally friendly way.
- Developing techniques to use wood fuel in a high quality and efficient way, associated with proper forest or land management.

9. Wood across the world

We have seen the cradle-to-grave performance, both structural and environmental, of wood and wood products for the EU construction market. The map in Fig. 27 traces the global flow of wood from its source (i.e. forests), through the various processing systems, to the end-use products consumed in various industries. Such a global map of the flow of wood enables us to understand where our wood comes from and therefore what we can do to sustainably manage our forest resources. The map also enable us to assess where wood products are being used and therefore what we can do to sustainably use our wood resources. This section presents a snapshot of the global usage of forests for wood production, and wood for construction against other competing uses. We also discuss current international and local policies that may direct strategies in the production, consumption, and disposal of wood products.

9.1. Global forests for wood production

Forests cover a third of our world's total land area. As illustrated in the first segment of our map in Fig. 27, these forests can be classified as i) pristine primary forests, ii) modified natural forests, where signs of human activity due to forest degradation are apparent, and iii) planted forests [147,148]. Notably, not all our forests are used for production. In fact, a quarter of our world's forest area, of which half is on legally protected land, has protection (of environment and heritage) as the primary objective [147]; even a quarter of planted forests are protected [149]. Just over half of our world's forests contribute to the production of wood and non-wood (50% of which is food) forest products (second segment of our map).

Importantly, substantial amounts of wood can be harvested without depleting or degrading forest resources (Fig. 28). This is exemplified by the fact that Asia and the developed regions (namely, Oceania, North America and Europe) have, combined, extracted over 75000 Mm^3 of roundwood logs since 1990 (which accounts for just under three-

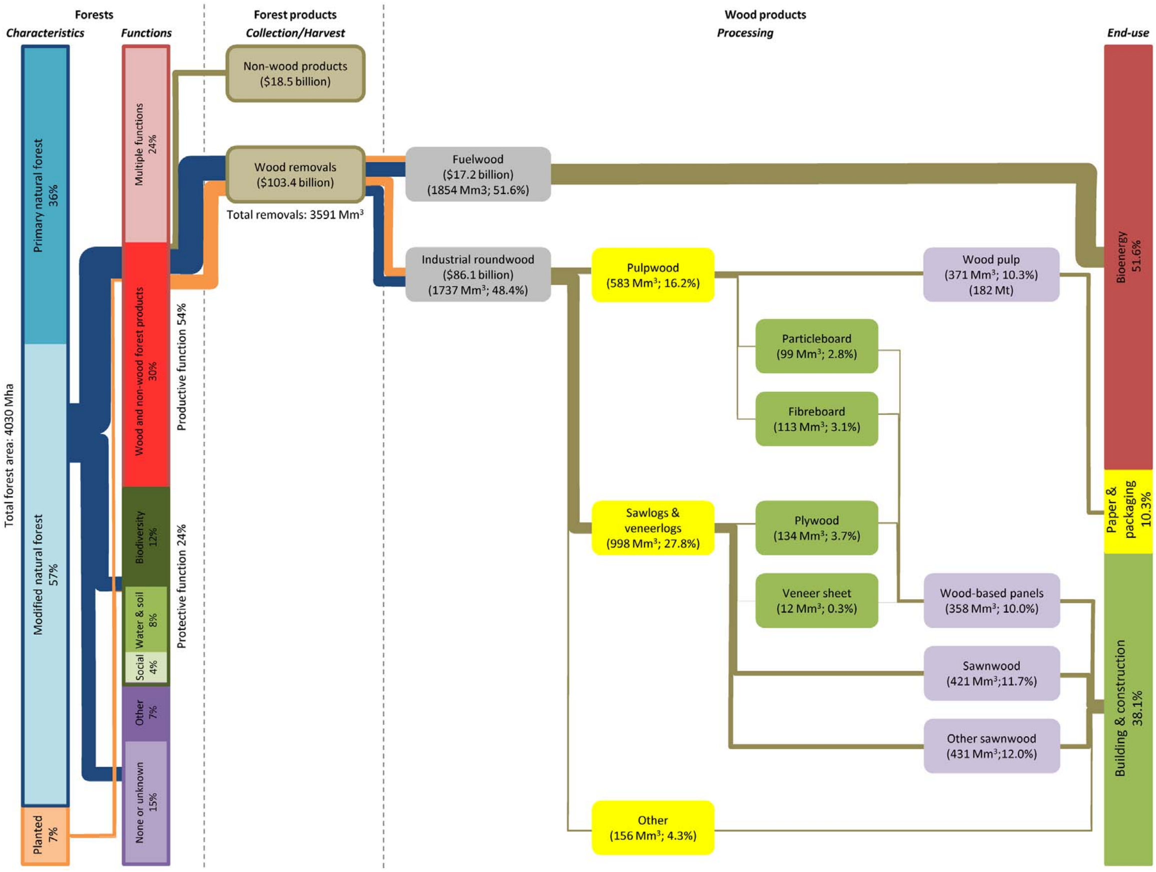


Fig. 27. Sankey map illustrating the global flow of wood, from forests to end-use. The first segment focusses on the source (i.e. forests) where global forests are described by their characteristics, primary designated functions and productivity. The second segment focusses on the collection of primary, wood (i.e. roundwood) and non-wood products from the forest resources. The third segment explores the processing of primary roundwood removals into wood products and their ultimate use in various industries. Data from FAO [147]. Forestry data for 2010. Wood removal data for 2013.

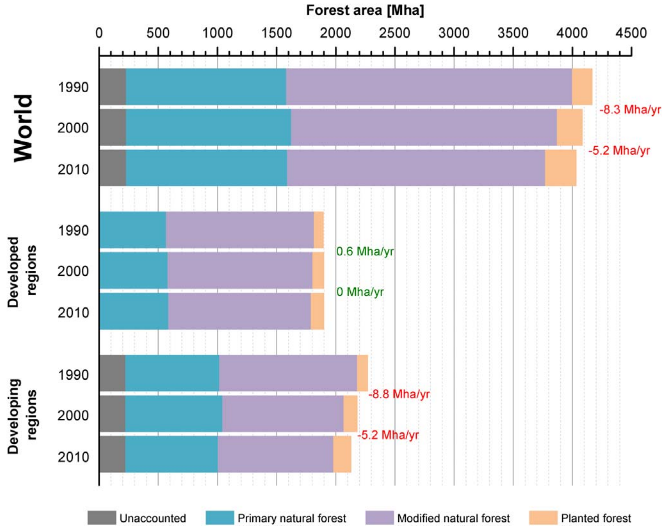


Fig. 28. Trends in forest area and characteristics (in Mha) from 1990 to 2010. Developed regions (Oceania, Europe and North America) have maintained their forest resources well, while developing regions (South America, Africa and Asia) have lost about 135 Mha of forest area. The latter is despite a notable increase in planted forests in developing regions (principally China). Data from FAO [147].

quarters of global production) and yet have increased combined forest cover by ~1 Mha/yr [147]. This, however, is in stark contrast to the management of forest resources in the tropical, developing regions (namely, South America, Africa, and south-east Asia), which account for over ~80% of global forest losses through degradation and deforestation [150,151].

Fig. 29 examines the primary drivers for degradation and deforestation (defined in the figure caption). Degradation of primary forests (of the order of ~6 Mha/yr) is almost exclusively due to commercial timber extraction and fuelwood collection. Deforestation (of the order of ~13 Mha/yr [147,148]) is principally driven by uncontrolled conversion of forests into agricultural land for commercial and subsistence farming. Notably, international pressures to clear forests are anticipated to increase due to population growth trends (and associated food security issues and urbanisation) and socio-economic aspirations [151], leading to estimates of reduced forest cover by 200–490 Mha by 2050 in the developing regions [152].

There are, however, positive trends too. Global conservation efforts through reforestation (~5 Mha per year) and increasing rates of active afforestation (~6 Mha per year, principally in China) in planted forests, dampen the global net loss of forest area to ~5 Mha/yr [147,148]. In fact, planted forests play a valuable rule in balancing limited forest resources and persistent wood demand. While planted forests account for less than a tenth of our world's forests, they supply 35–40% of the global annual roundwood harvest (Fig. 27) [152–154]. Current trends suggest that by continuing our expansion of planted forests, they will supply up to 80% of global annual wood harvests by 2030, enabling much larger but still sustainable harvests [155]. Currently, native species make up three-quarters of planted forests [148]. Softwoods constitute about three-quarters of planted forests, with Pinus spp being the most populous (60% of all softwoods) [149]. Eucalyptus and Acacia are the most preferred hardwood genus (half of all hardwoods), although the former are primarily used in pulp production [149].

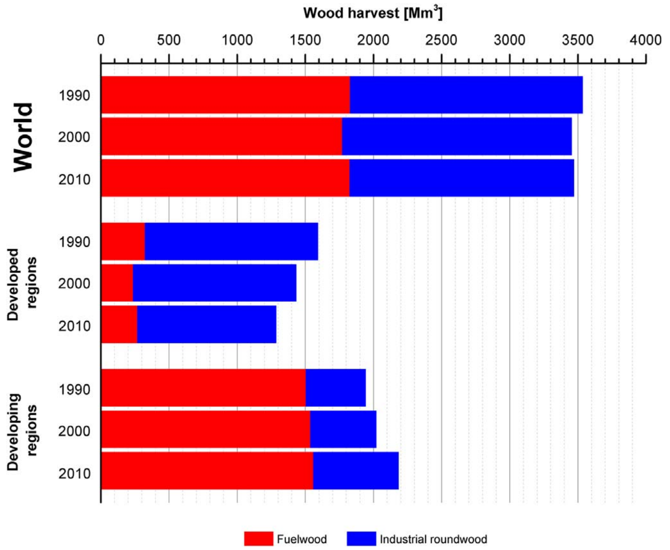


Fig. 30. Trends in processing of wood for fuelwood and industrial roundwood from 1990 to 2010. Global wood harvest and its use has been steady since 1990. While wood production in developed regions (Oceania, Europe and North America) has declined over the period, its use has been primarily for industrial roundwood. In contrast, while wood production in developing regions (South America, Africa and Asia) has increased, its use has been primarily for fuelwood.

9.2. Global flow of wood through society

Since the 1990s, global annual roundwood harvest has been ~3500 Mm^3 [147]. The third segment of our map in Fig. 27 traces the processing and end-use of the harvested wood. Roundwood has two principal uses: fuelwood for bioenergy, and industrial roundwood for conversion into pulp and timber products. Globally, both fuelwood and industrial roundwood account for half of total removals (Fig. 30). However, as illustrated in Fig. 30, removals in the developing nations are mainly for fuel, while removals in the developed regions are mainly for industrial roundwood [147]. It is noteworthy that in developing regions biomass is often burnt inefficiently and policies are needed to

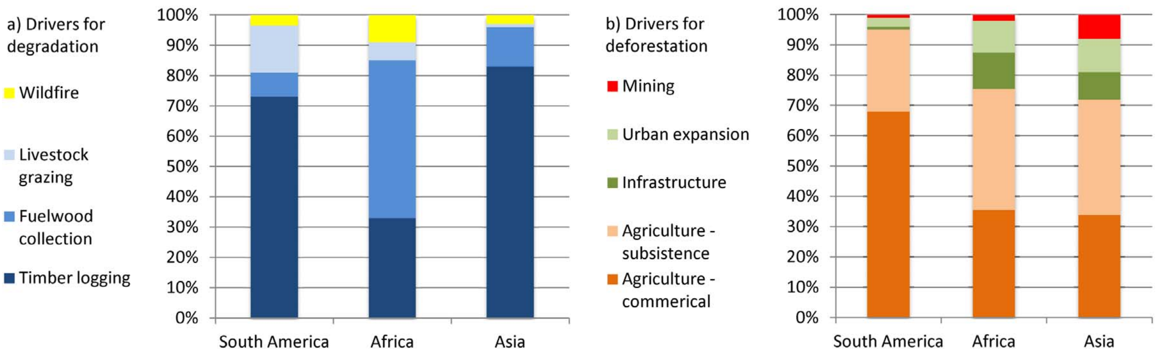


Fig. 29. Drivers for a) forest degradation and b) deforestation in developing regions. Forest degradation refers to damage to forest 'quality' (vis tree density, biodiversity), but the damage is not associated with a change in land use, and the forest is expected to naturally regrow. In contrast, deforestation refers to reduction in forest area due to conversion of forests (by complete removal of trees) into other land uses, and consequently the forest is not expected to naturally regrow. Data for 2000–2010. Adapted from Hosonuma et al. [150] and Kissinger et al. [151].

target this [127]. Nonetheless, as i) fuelwood is a primary source of energy in less developed regions (e.g. 27% of total energy supply in Africa [127]) where population growth is predicted to be highest, and ii) bioenergy policies in developed regions, particularly Europe, are fueling a dramatic increase in wood pellet production (e.g. for domestic heating), bioenergy will remain as a stable, major driver of end-use in the wood industry (Fig. 31). In addition, by-products from wood processing (including tree bark, woodchips, sawdust and even by-products from pulp-making), which account for up to 50% of the initial material (Section 5.3), are often used as an important, renewable energy source in the (nearly) closed-loop wood production cycle. For example, the US timber industry met over 65% of its energy needs through manufacturing process by-products, which in turn represented over 90% of total wood fuel usage by US manufacturing industries [156]. On-site usage of wood waste (e.g. for fuel) is particularly attractive due to the emissions associated with the transportation, often by road, of wood waste to another site (for energy recovery or panel production), as well as the empty return journey of the transport vehicle. This is specifically the case for woodchips, which due to their low bulk density have up to 65% higher transportation energy requirements than roundwood and even whole trees of the same volume [157].

Moving along the third segment of our map in Fig. 27, industrial roundwood, which has on average five times higher value than fuelwood [148], is processed into products whose end-use lies in paper and packaging (10% of total wood removals), and building and construction (38% of total wood removals) (Fig. 27) [147].

Fig. 31 examines the trends in various wood products since 1990. While the wood pulp (for paper) market has been stable since 1990, the paper and packaging market had grown tremendously over the same period due to improved recycling rates (from 35% in 1990 to 54% today) [147,158]. However, the paper and packaging market has been stagnant for the past five years: balanced by the decline in newsprint production (particularly in China) due to prevalence of electronic media, but a rise in usage of wrapping and packaging paper [158]. In contrast, the production and consumption of industrial roundwood for the construction market (i.e. wood-based panels and sawnwood) has shown strong growth in most regions over the past five years [147]. In particular, wood-based panels have been the only wood product category to show rapid, consistent growth since 1990, particularly in Asia and South America [147]. New products, such as wood plastic composites, have also shown exceptional growth over the past five years (e.g. six-fold for China) and are now well-established in the construction market (primarily for decking) [159].

Notably, over 99% of total fuelwood production is consumed in the domestic markets [147]. In contrast, 20–30% of industrial roundwood products end up in international trade markets [147]. Increasing trade levels are further strengthening the role of timber products in the wood industry [147,158]. China and the US are quite comfortably the top consumers and producers, but are also major traders in all industrial roundwood product categories. Due to insufficient domestic production, the EU and UK are net-importers of many wood products, including timber products (e.g. sawnwood and wood-based panels) but also paper products, and pellets [147,158,160]. As the EU and UK currently harvest only 50–60% of the annual growth in their forests [161], there is potential to substantially increase sustainable wood harvest and boost domestic production, to reduce import of wood products and/or increase export of construction timber products. Notably, the factors contributing to the sub-100% harvest of annual growth in the UK, and probably the EU, are: i) no harvestation of unmanaged forests (especially hardwoods), which make up ~10% of UK forests, ii) forests in inaccessible areas that cannot be economically harvested, and iii) delayed harvesting to balance a current hump in growth to fill a (prospective) future dip. At least, the first factor can be easily addressed by implementing a management plan for unmanaged forests.

Within the UK the contribution of timber transport to total emissions associated with timber production are 6% for sawnwood and 15% for fuelwood [162]. International trading, however, contributes to emissions associated with long-distance transportation by road, rail and/or ships. Locally-sourced timber products should, therefore, be the first option. While different modes of transport have different emissions (e.g. transporting 1 tonne across 1 km by ship or rail would lead to 32 and 8 times fewer emissions than by road, respectively [163]), their usage depends on practical and logistical considerations.

9.3. Policy review

Section 4.2 explains how forests act as greenhouse gas sinks/reservoirs. As part of global efforts to mitigate climate change, international environmental commitments (e.g. UNFCC (since 1992) and Kyoto Protocol (2005–2020)) explicitly direct the accounting of changes in forest area (through afforestation, reforestation, and deforestation) and land-use (e.g. conversion of forests to agricultural land) to greenhouse gas emission targets [152,164]. Consequently, while large-scale reforestation (or assisted natural regeneration of natural forests) and afforestation (of planted forests) are important in the short-run, improved forest management (e.g. through selective logging, setting maturation periods after tree planting, and policing forest protection) and institutional strengthening are vital for the long-run. In developed regions, various regional and national policy frameworks have been put in place (such as the European Forest Strategy) to protect forests and improve long-term competitiveness of the forest sector.

Long-term measures in sustainable forest management are particularly relevant to developing regions, where socialistic forestry and weak forest-sector governance have been unable to halt illegal deforestation [151], and in some cases have corruptly promoted under-valuation of forest land and under-pricing of forest products leading to government-complicit deforestation, both for conversion to agricultural land and illegal logging (Fig. 29) [127,165,166]. Given the large global trade in forest and agricultural products, a notable fraction of deforestation embodied in such products enters the international market for consumption. For example, 33% of the deforestation embodied in crops and 8% of the deforestation embodied in livestock products enters the trade market [167], and up to 40% of the global roundwood production is from illegal logging [168]. Acknowledging this, developed regions such as the EU are actively and increasingly implementing supply-side and demand-side measures to regulate the traded products, in order to encourage sustainable forest management practices in the developing regions. New technologies in forensic methods, remote sensing, and isotope and DNA analysis are useful to

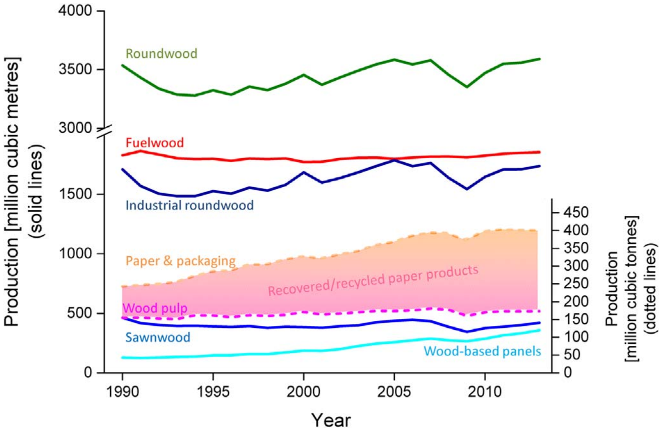


Fig. 31. Trends in global roundwood harvest and wood-products production from 1990 to today. Data from FAO [147].

independently verify the origin of timber and timber products [168]. To complement this, bilateral agreements and regulations have been established (e.g. through the EU Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan) to ensure standardised, third-party auditing (e.g. from the FSC/PEFC) of wood products, certifying that they have come from responsibly managed forests, and also enabling systematic tracking of the wood from the certified forest right through to the end product. Currently, only ~10% of global forests are certified (the majority of which are in North America and Western Europe), and an estimated 30% of global roundwood production originates from these certified forests [167]. It is evident that substantially more needs to be done, particularly in developing countries, to ensure that timber is sourced from responsibly managed forests, and national strategies are in place to effectively prevent deforestation and forest degradation. The World Bank's Forest Carbon Partnership Facility (FCRF) and the UN-REDD programme are examples of new multi-lateral initiatives which support, incentivise (through performance-based payments), monitor and verify voluntary national efforts of a REDD+ developing country to 'reduce emissions from deforestation and forest degradation, and promote conservation, the sustainable management of forests, and enhancement of forest carbon stocks(REDD)' [169]. There are 47 partner developing countries in the FCRF, and 64 member developing nations in the UN-REDD programme. While these programs have not yet reached the stage (in any REDD+ country) where reduction in emissions from deforestation and forest degradation through REDD+ activities have been measured, several countries have demonstrated progress in terms of institutional, technical, and social REDD+ readiness to action their proposed plans and strategies [169]. In fact, the Democratic Republic of Congo and Costa Rica became the first two REDD+ countries to have their 'Readiness Package' approved, on-track to receive their performance-based payments.

Forest ownership has also been linked to both forest health and productivity [166]. 80% of the world's forests are publicly owned, but differences in regions are striking; developed regions, such as the EU, have a higher proportion of private ownership, where up to 60% of forests are privately-owned [147,148,161]. Finland and UK are examples of countries where private forests not only produce more, but also show the majority of increase in forest cover [166]. Perhaps, even in publicly owned forests, increased involvement of communities and private companies in forest management may be effective [152,164].

Apart from international and national initiatives in forest management, promoting the usage of sustainable wood products, where appropriate, as alternatives to other non-renewable or high-embodied energy materials would contribute to environmental efforts [152,154]. Good examples of these are 'wood first policies' in building and construction at national level (e.g. in Japan, and several EU countries) and local level (e.g. in various states in Canada and Australia, but also in borough councils in London). These policies in general encourage environmental performance assessment of buildings, and specifically encourage the use of wood as a primary building material. As a caveat, while wood encouragement programs are attractive to answer 'why, how and when is using wood good', improving the efficiency of wood production and wood use (i.e. how much wood should be used) is also critical [152]. However, regional-level regulations may aid in this. For example, while promoting the use of wood in the EU building sector, the EU Construction Products Regulation legally requires that construction must be designed, built, demolished and recycled ensuring sustainable use of natural resources [167]. Specifically, life-cycle analysis (LCA) based Environmental Product Declarations (EPDs) should be used to assess the sustainable use of resources in all construction products. Consequently, efforts are under-way to compile comprehensive LCA data for wood and wood products (e.g. through UK's Wood First Plus Initiative).

9.4. Research questions

From a global perspective, there are three important research questions that need to be addressed:

- Wood use priority: Given the contrasting usage of wood for fuelwood and industrial roundwood in developing and developed regions, what specific case studies can be developed to demonstrate the more efficient use of wood products in structural construction?
- Timber trade: What are the emissions associated with the global trade and transport of timber and timber products? Subsequently, when is locally-sourced (or locally-grown) timber better than traded timber, and vice versa? Answering these questions is pivotal in the future framework and development of forest-sector based industries.
- Policy formulation: Given that planted forests will play an increasingly important role in the future, and keeping in mind global issues such as increasing land-use competition, what regional and international (rather than just national) forest plantation strategies could be adopted to co-operatively meet global needs for wood products? Such strategies would possibly include measures ranging from forest management (e.g. diversifying forest ownership, and certification of wood from such plantations), to optimising balance between forest sustainability and wood harvesting (e.g. by considering scientific progress in areas such as tree-breeding and seed-selection programs, as well as genetically modified trees for fast-growing plantations), to setting end-use regulations (e.g. restricting the amount of primary wood used for fuel).

10. Concluding remarks

At the smallest scale, we need to better understand how the elements that make up the structure of wood contribute to its various properties at a macro scale. At the largest scale, engineering mega buildings with timber may require material properties that do not yet exist in timber. Bringing these two scales together through research should increase the already significant potential for using plant material at a large scale in the built environment.

Timber excels where strength (or stiffness) to weight is more important than absolute strength (or stiffness). Specific architectural and engineering designs can maximise this relationship, but it also suggests that timber buildings may be fundamentally different from steel or concrete buildings in structural and spatial layout.

The open research questions highlighted point to areas to develop that would greatly enhance the viability of timber in big buildings worldwide. We look forward to results from those and similar questions that bring together the wood science, engineering, and policy that ensure the best environmental outcomes for constructing with natural materials.

Acknowledgments

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