Forestry Commission

Research Report

Wood properties and uses of Sitka spruce in Britain

SIRT
Strategic Integrated Research in Timber

Research Report

Wood properties and uses of Sitka spruce in Britain

John Moore

Forestry Commission: Edinburgh

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Foreword

The establishment of the Forestry Commission in 1919, with the stated aim of establishing a 'strategic reserve of timber', provided the stimulus needed to embark upon the reforestation of large parts of the UK, but particularly Wales, northern England and Scotland. The peak effort in establishment was reached in the 1960s, 1970s and 1980s. A variety of sites were planted over the years ranging from the fertile valleys of the pre-World War 2 days to the exposed upland sites of the later years. The availability of sites and locations were not of the forester's choosing. Market forces often dictated by the agricultural policies of the day determined which areas were available to be planted. The principal species of choice in these unashamedly commercial crops was Sitka spruce, a native of the Pacific Northwest of North America. As a new introduction to the UK it proved relatively easy to establish, showed rapid growth characteristics compared to both native and other species, and had attractions for the processing sector in terms of its properties and appearance.

Early experience on lowland sites with traditional silvicultural systems produced mature crops of top quality timber. However, the restrictions of the upland areas, where silviculture is limited by climatic factors such as wind exposure, proved to be more challenging, with the final crops from these sites providing much more variability in the raw material for primary processing.

While much work was done over the years by a large number of research organisations on the timber properties of Sitka spruce, it has taken until now for all of this work plus the recent efforts resulting from the Strategic Integrated Research in Timber (SIRT) project to be drawn together in one authoritative document. The establishment of the SIRT project under the leadership of John Moore provides an excellent model for collaborative research work. Not only does it bring together Edinburgh Napier University, the University of Glasgow and Forest Research, it critically involves the industry in guiding the agenda for the work. This surely provides an ideal model for future collaboration.

Given the potential for commercially grown trees and the use of timber in construction and timber products to provide some compelling answers to the current challenges of climate change, this publication is very timely. The process that is photosynthesis and the products derived from the growing and processing of commercial tree crops have the potential to contribute to the low carbon economy so demanded by politicians worldwide.

I started this foreword by citing the original reason for the establishment of the Forestry Commission, namely the creation of a strategic reserve of timber. In those days the need for the reserve related to outbreaks of war and the vulnerability we felt as an island nation. The primary reason for creating a reserve may have changed but the requirement is none the less compelling and Sitka spruce has an important role to play in this objective.

I am delighted that so many people have contributed to the production of this document and have no hesitation in commending it to you.

J. Kissock.

John Kissock, OBE
Chair, Forest Industries Advisory Board

Preface

Research into the wood properties and performance of products made from Sitka spruce has been undertaken in Great Britain for almost 90 years by a number of organisations, most notably the Forestry Commission, Forest Products Research Laboratory (FPRL), Building Research Establishment (BRE), Timber Research and Development Association (TRADA), Imperial College London, University of Oxford, University of Wales Bangor, and University of Aberdeen. Smaller research groups were also based at Abertay University and Buckinghamshire Chilterns University College. Most recently, research groups at Edinburgh Napier University and the University of Glasgow, in collaboration with Forest Research, have investigated the wood properties of Sitka spruce as part of the Strategic Integrated Research in Timber (SIRT) project.

One issue that arises from this diversity of research groups is the corresponding diversity of outputs, both published and unpublished, which presents two challenges. Firstly, simply finding and collating all the research that has been carried out is no trivial task. Secondly, only when the material is brought together and synthesised do the links between tree growth and management, cell wall structure, wood chemistry, timber processing and end-product performance become truly apparent. This is not the first publication to have attempted to bring together knowledge about the properties and uses of Sitka spruce. In the 1960s and early 1970s, the former FPRL produced a series of publications on the properties and uses of different conifer species grown in Great Britain, including Sitka spruce. These were collated together and updated in Forestry Commission Bulletin 77, which was published in 1988. Since then there have been many significant changes in the forest products sector including a very large increase in the volume of wood harvested from British forests, significant investment in sawmilling infrastructure, rapid growth in the timber-frame house market, development of common European standards for assessing the properties and performance of wood products, and the creation of a biomass energy sector in response to concerns about the impact of using fossil fuels for energy production. During the same period our knowledge of wood properties of Sitka spruce has improved, along with the technology to measure these properties in both laboratory and industrial environments. These changes and advances are incorporated in this publication.

This publication is written for forest scientists, engineers, wood processors, and end users of wood products who are seeking a better understanding of Sitka spruce's material properties and potential end uses. Clearly, this is a diverse potential readership and there is the risk that the publication is too technical for some and too applied for others. I hope that this is not the case and have tried to overcome this by dividing the publication into three parts. The first part is a general introduction that covers the origins of Sitka spruce, its introduction into Great Britain and its growth and management in this country. Part two contains information on the wood properties of Sitka spruce, including wood anatomy, general wood structure, and physical and mechanical properties. Part three contains an overview of the end products that are currently produced from Sitka spruce or that could potentially (and realistically) be produced from Sitka spruce in the future.

Contents

1. Origins of Sitka spruce

Sitka spruce in North America

Sitka spruce (*Picea sitchensis* (Bong.) Carr.) originates from the Pacific Northwest of the USA and Canada. Its natural range extends approximately 2900 km in the north–south direction and a maximum of 400 km in the east–west direction (Figure 1.1). The southernmost Sitka spruce tree is located in Mendocino County, California (latitude 39°20 N), while the northern extent of its range is Prince William Sound (61°00 N). The range of Sitka spruce is dependent on abundant moisture content during the growing season and its maximum development occurs when summer precipitation is high and there is no pronounced summer drought (Roche and Haddock, 1987). The common name for this species comes from Sitka Island (now called Baranof Island), Alaska, where botanical specimens were collected by the German naturalist Mertens in 1827 (Peterson *et al*., 1997). However, the species first became known to science in 1787 through Scottish botanist Archibald Menzies, who recorded it on the shores of Puget Sound. It was first introduced into Great Britain in 1831 by the Horticultural Society of London from seed collected by David Douglas, who named it *Pinus menziesii* (Mitchell, 1978). The present scientific name *Picea sitchensis* was assigned by two French botanists, Bongard and Carriere. Bongard described the species as *Pinus sitchensis* in 1832 based on the specimens collected by Mertens, with the species name *sitchensis* referring to Sitka Island, and in 1855 Carriere ascribed it to the genus *Picea* (spruce) rather than *Pinus* (pine) (Peterson *et al*., 1997).

The indigenous peoples of America used the roots of Sitka spruce for making baskets and weaving into hats. Resin obtained from the bark was also used for medicinal purposes, as a caulking material for canoes and as a glue, but little use was made of the wood (Brazier, 1987; Pojar and MacKinnon, 1994). The discovery of gold on the Fraser River near Vancouver, Canada, in 1858 and the resulting influx of miners created a need for timber for buildings and bridges, which in turn led to the development of a sawmilling industry; however, very little of the timber produced at this time was from Sitka spruce, with Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) the preferred species. In the USA the annual production of Sitka spruce timber was estimated at 400 000 m^3 in 1899, but it was still of relatively minor importance compared with other species (Harris, 1984).

Figure 1.1 Distribution of Sitka spruce along the Pacific Northwest coast of North America

In the early 1900s, Sitka spruce began to be used in the construction of aircraft due to its high specific strength and stiffness (i.e. its strength and stiffness relative to its density). The propellers and much of the airframe of the Wright Flyer, the aircraft built by the Wright brothers that achieved the first sustained and controlled heavier-than-air powered flight in 1903, were made from Sitka spruce. Two of the most successful allied aircraft of World War 1, the Sopwith Camel and Farnborough SE5a, made extensive use of Sitka spruce wood in their wings and fuselage, and this resulted in a rapid increase in demand for this species (Brazier, 1987). Within the space of a few months in 1917 this species, which had been of secondary importance to the timber industry in North America, became a most sought after timber (Cary, 1922). However, just over 10% of the sawn timber from these old growth Sitka spruce forests met the specifications for use in aircraft construction, and therefore uses had to be found for the remaining material (Brazier, 1987). The production of military aircraft almost ceased at the end of World War 1, and with it the demand for Sitka spruce wood. However, Sitka spruce wood was again used in aircraft construction during World War 2, most notably in the Mosquito bomber. Even today, Sitka spruce wood is still used in the production of pleasure aircraft, particularly gliders. High quality wood from the Pacific Northwest is also used in the manufacture of musical instruments, including guitars and piano soundboards. The remaining wood is used for doors and windows, construction timber, scaffold boards and boxes. Sitka spruce is still a minor component of timber production in the Pacific Northwest, except in Alaska where it represents approximately 25% of the total timber harvest (Eastin and Braden, 2000).

Introduction into Great Britain

In describing Sitka spruce David Douglas wrote that 'it may nevertheless become of equal or greater importance [than Douglas fir] as it possesses one great advantage over that one by growing to a very large size...in apparently poor, thin, damp soils... This unquestionably has great claims on our consideration as it would thrive in such places in Britain where even *Pinus sylvestris* L. [Scots pine] finds no shelter. It would become a large and useful tree' (Murray, 1931). While Sitka spruce was first introduced into Great Britain in 1831, significant afforestation did not commence until after the end of World War 1 when it was recognised that domestic timber production needed to increase to ensure national security (Birch, 1936). This led to the establishment of the Forestry Commission in 1919, which had the aim of supplying 20% of the UK's annual timber requirements. To achieve this objective the size of the forest estate was increased largely through afforestation with fast-growing exotic conifer species. Despite the fact that Norway spruce (*Picea abies* (L.) Karst.) was a proven species in Britain, Sitka spruce was preferred due to its more rapid growth and the ability to grow on a wider range of sites (Robinson, 1931), which enabled afforestation of upland sites with poor soils (Stirling-Maxwell, 1931). The period of major afforestation occurred from 1950 until the late 1980s, and the area of Sitka spruce forests increased from 67 000 ha in 1947 to 692 000 ha in 2007 (Forestry Commission, 2007; Mason, 2007). It now represents approximately 50% of the total area of conifer forests in Great Britain, with 76% of the area of Sitka spruce forests located in Scotland (Table 1.1).

Table 1.1 Area of Sitka spruce forests in Great Britain (after Forestry Commission, 2007).

Country	Area of Sitka spruce (000s ha)	Total conifer forests (000s ha)	Total forests (000s ha)
England	80	340 (24%)	988 (8%)
Scotland	528	916 (58%)	1 123 (47%)
Wales	84	149 (56%)	266 (32%)
Total	**692**	**1 407 (49%)**	**2 377 (29%)**

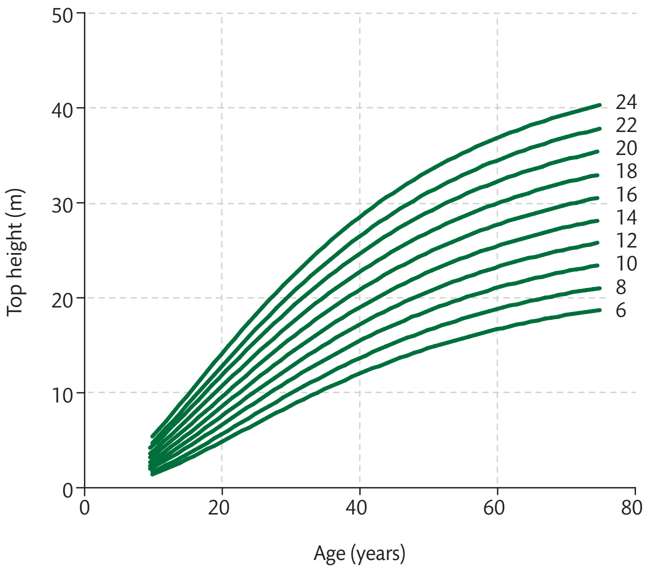
Note: numbers in parentheses are the percentages of the total areas that are Sitka spruce.

Many of the stands of Sitka spruce planted before the Forestry Commission was established were from seed of Washington or Oregon origin (Lines, 1987). The Forestry Commission imported large amounts of seed from the Queen Charlotte Islands (QCI), Canada, and this was the main source of seed from 1922 to 1981. These islands were chosen as a source of seed because they are on a similar latitude to parts of Britain, have a similar climate and the trees from QCI produce good quality timber (Hopkinson, 1931). Trials comparing the performance of different seed origins were planted by the Forestry Commission between 1929 and 1975 and showed that southerly origins (below latitude 47°N) grew the fastest, but were more susceptible to frost damage and had a lower wood density than origins from 53°N or above (Lines, 1987; Samuel *et al*., 2007). Washington origin seed has been planted in areas where frost is less common, for example in parts of Wales and south-west England. Since the mid 1970s most of the requirements for unimproved seed were met through collections from British stands. A selective breeding programme for Sitka spruce in Great Britain began in 1963 with the objective 'to develop breeding populations well adapted to a range of site types, with improved stem form and growth potential and wood qualities satisfactory for the sawn timber market' (Fletcher and Faulkner, 1972). Nowadays, almost all Sitka spruce planted in Britain is improved stock, either grown from seed or vegetatively propagated (Rook, 1992).

Growth and yield

The productivity of forest sites in Great Britain is usually expressed in terms of yield class, which is defined as the potential maximum mean annual volume (to a 7 cm top diameter) increment per hectare, irrespective of age of culmination or tree species (Hamilton and Christie, 1971). Yield class is determined from measurements of mean top height at a given age using a lookup chart (Figure 1.2). The mean yield class for Sitka spruce in Great Britain is 14 m^3 ha^{-1} $year^{-1}$, although many sites are significantly more productive, having a predicted yield class of 16–20 m^3 ha^{-1} $year^{-1}$ (Bateman and Lovett, 1998; Sing *et al*., 2006). The merchantable volume and mean tree size that can be achieved on a site of a certain yield class for various combinations of initial spacing, thinning options and rotation length can be estimated using the yield models developed by Edwards and Christie (1981).

Figure 1.2 Top height curves for unthinned Sitka spruce growing under different yield classes (after Hamilton and Christie, 1971).

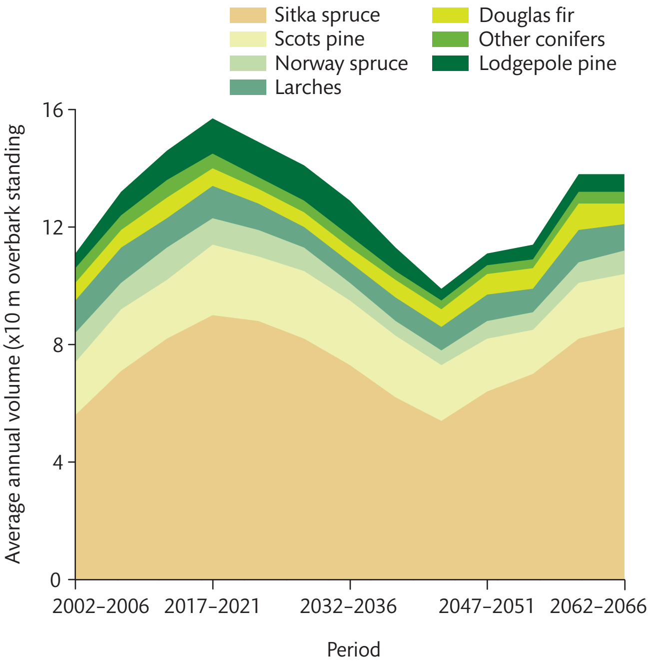


While Sitka spruce trees in old growth forests of the Pacific Northwest may be in excess of 500 years old, 70 m tall and 2 m in diameter (Pojar and MacKinnon, 1994), rotation lengths of 35–45 years are more typical for commercial Sitka spruce stands in Great Britain, although longer rotations may occur on some private estates. For rotation lengths of between 35 and 45 years, Sitka spruce growing at yield class 14 would typically reach a top height (mean height of the 100 largest trees per hectare by diameter) of between 16 and 23 m. At higher yield classes, for example YC 20, mean top heights of 23–28 m could be expected over the same rotation. While tree diameter will depend considerably on the choice of initial spacing and the thinning regime, the diameter at breast height (1.3 m above ground) of Sitka spruce harvested in Great Britain would typically be between 25 and 40 cm.

Current and future wood production

The volume of wood produced from Britain's conifer forests has almost quadrupled in the past 30 years and in 2009 the total volume of softwood harvested was 8.1 million cubic metres (8.3 million green tonnes), with Sitka spruce comprising approximately 60% of this total (Forestry Commission, 2010). Due to the significant afforestation that occurred during the period between 1950 and the end of the 1980s, softwood availability is forecast to increase, reaching a peak of approximately 14 million cubic metres between 2017 and 2021 (Halsall *et al.*, 2006). This represents planned timber production or potential timber availability. Longer term projections (Figure 1.3) indicate that potential timber availability will decrease to approximately 10 million cubic metres by 2040 (Smith *et al.*, 2001) mainly due to the uneven age class structure of British forests. (Note: that Figure 1.3 shows a higher peak softwood availability than is presented in Halsall *et al.* (2006); however, this more recent production forecast does not include longer term projections.)

Figure 1.3 Long-term trend in softwood availability for Great Britain by tree species (after Smith et al., 2001).



Sitka spruce in other countries

In addition to Great Britain, Sitka spruce has been introduced to several other countries, where it is of varying importance to the commercial forestry industry. Ireland, which has a similar temperate maritime climate to that of Great Britain, also has a similar history of substantial afforestation with Sitka spruce in the latter part of the 20th century. Today, the total area of Sitka spruce plantations in Ireland is approximately 500 000 ha and it is the main commercial tree species grown in that country (Joyce and O'Carroll, 2002). The wood properties and utilisation of Sitka spruce are also similar in Ireland and Great Britain. Sitka spruce is also grown in Iceland, north-western France, south-western Norway, Denmark and southern Sweden, and several stands were established in New Zealand (Peterson *et al.*, 1997). In Denmark, in particular, Sitka spruce is a commercially important species accounting for approximately 16% of the softwood timber harvest (Bräuner *et al.*, 2000).

2. Wood properties of Sitka spruce

Wood properties can be subdivided into two groups: microscopic and macroscopic (Megraw, 1986). Microscopic properties are linked to the anatomical structure of wood as well as its chemical composition, while macroscopic properties are primarily growth-related features and include knots, compression wood and spiral grain. These macroscopic features are often used as the basis for visual grading of wood products, particularly sawn timber.

General wood structure

Chemical composition

In common with all tree species, the wood of Sitka spruce is comprised of cellulose, hemicelluloses and lignin. At an elemental level, wood is approximately 50% carbon, 6% hydrogen and 44% oxygen. In addition, there are small amounts of extraneous chemicals which include extractives and inorganic compounds such as calcium, magnesium and potassium. Mean cellulose and lignin (Klason determination) contents in dry Sitka spruce wood by mass are approximately 44.3 and 28.4±1.9%, respectively (Nuopponen *et al.*, 2006). In Norway spruce, hemicelluloses (including pectins) typically comprise 22.3% of the wood dry mass (Bertaud and Holmbom, 2004), which is consistent with values obtained for Sitka spruce (Mike Jarvis, unpublished data).

Cellulose is a high molecular weight linear polymer of the 6-carbon sugar (hexose), β-glucose. Because the chemical link between adjacent sugar units is between carbon atoms 1 and 4, it is described as a β 1-4 glucan. The number of glucose monomers in the cellulose molecule (i.e. the degree of polymerisation) is in the order of 10 000 (Wilson and White, 1986; Walker, 2006) so that a cellulose molecule is approximately 5 μm long. These polymer chains pack together alongside one another in a highly ordered manner, thus forming a crystalline structure. This crystalline cellulose occurs in long thin filaments called microfibrils, which in turn are organised into the larger structural elements that make up the tracheid cell wall (See 'Wood anatomy' section on page 6).

In contrast to cellulose, which is a long unbranched polymer composed entirely of glucose units, the hemicelluloses are mixed polymers that have a low molecular weight. (Note: while Harris (2005) states that use of the term 'hemicelluloses' to refer to the class of non-cellulosic polysaccharides that are alkali soluble is not helpful, it will be retained here as it is widely used in wood science.) They typically contain 80–200 monomers of the pentose sugars, arabinose and xylose, and the hexose sugars, glucose, mannose and galactose (Wilson and White, 1986). Mannose is the most important hemicellulose monomer and is generally present in softwoods as O-acetyl-galacto-glucomannan, which is a 1-4 polymer of glucose and mannose (Dutton and Hunt, 1958b; Lundqvist *et al.*, 2002). The other principal hemicellulose in softwoods is arabino-4-O-methylglucuronoxylan, which is a 1-4 polymer of xylose units bearing methylated glucuronic acid groups laterally (Dutton and Hunt, 1958a; Wilson and White, 1986). The exact role of hemicelluloses in the plant cell wall is uncertain, but in the most general terms they provide a link between the cellulose and lignin, which in turn affects the mechanical behaviour of wood and its dimensional stability.

Lignin is an aromatic substance that is almost totally insoluble in most solvents. Sitka spruce lignin is similar in composition to Norway spruce lignin in that it is based almost entirely on guaiacylpropane units (~98%) that cross-link with each other to form a high molecular weight polymer (Wadenback *et al.*, 2004). Lignin is often referred to as the cementing agent that binds individual cells together and the process of lignification follows behind the laying down of structural carbohydrates (i.e. cellulose and hemicelluloses) that provide the overall architecture of the plant cell wall. Approximately 75% of the total lignin content in softwoods is found in the secondary wall of tracheids and 25% in the middle lamellae and cell corners; the lignin content of the middle lamellae is about 70–75% (Walker, 2006). The lignin of the middle lamella and cell corners, which must be depolymerised or mechanically fractured during pulping, is more cross-linked than that of the secondary wall (Onnerud and Gellerstedt, 2003).

Extractives is the collective term given to the different classes of chemical compounds that can be extracted from wood or bark by means of polar and non-polar solvents. They include tannins and other polyphenolics, colouring matter, essential oils, fats, gums, resins, waxes, starch and other substances (Wilson and White, 1986). These generally have no structural significance, but affect other properties such as colour, odour, taste, density, hygroscopicity and decay resistance. The total extractives content in Sitka spruce is approximately 1.9% by mass, which is relatively low compared with other conifer species, and is only slightly higher in heartwood than sapwood (Caron-Decloquement, 2008). A total of 33 different compounds were identified in Sitka spruce stem wood, with the greatest proportion of these (by mass) classified as resin acids and esters (Caron-Decloquement, 2008).

Wood anatomy

The wood of Sitka spruce, like that of other softwood species (gymnosperms), consists mostly of tracheids, which have thick, lignified cell walls. It also contains longitudinal resin ducts and horizontal rays (Figure 2.1). The rays consist of radially orientated parenchyma cells and their function is to transport water and photosynthesis products between the xylem and phloem and to serve as storage tissue (Wilson and White, 1986; Walker, 2006). In sapwood, the ray parenchyma cells are physiologically alive unlike tracheid cells. The cell wall of tracheids is comprised of a middle lamella (ML), primary wall (P) and compound secondary wall (S), which are laid down sequentially as the cell is formed (Figure 2.2). The middle lamella is not part of the cell wall proper and contains the intercellular material that cements neighbouring cells together; however, it is often considered together with the primary cell wall, and in this case is referred to as the compound middle lamella (CML). Three distinct layers can be identified in the secondary cell wall that differ in their microfibril orientation; these are referred to as the S_1, S_2 and S_3 layers. The S_2 layer can constitute 90% of the total cell wall thickness. The microfibril angle (the angle relative to the cell axis) in the S_1 and S_3 layers is high, while it is much lower in the S_2 layer; microfibril angles in the S_2 layer of Sitka spruce cell walls are typically between 10 and 40°, although values as low as 5° have been observed (McLean, 2008). The dimensions of Sitka spruce tracheids depend on their location in the tree (See 'Earlywood and latewood' section on page 7 and 'Sapwood and heartwood' section on page 8), but the range of values typically found is given in Table 2.1.

Figure 2.1 The transverse and tangential–longitudinal faces of Sitka spruce. The wood comprises longitudinal tracheids and uniseriate rays. Magnification × 60.

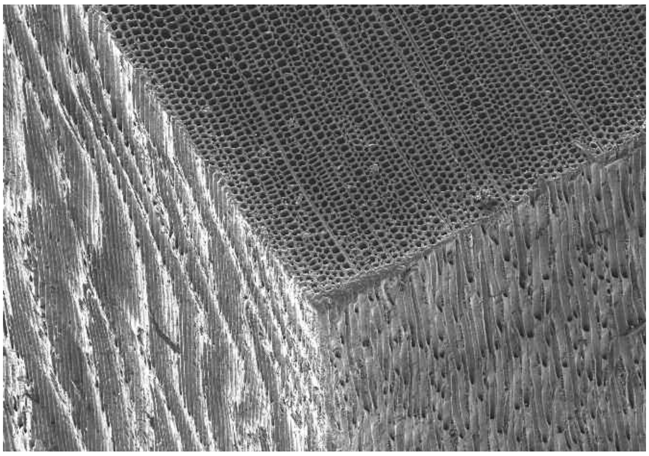


Figure 2.2 Schematic representation of the structure of cell wall of a Sitka spruce tracheid (after Eaton and Hale, 1993).

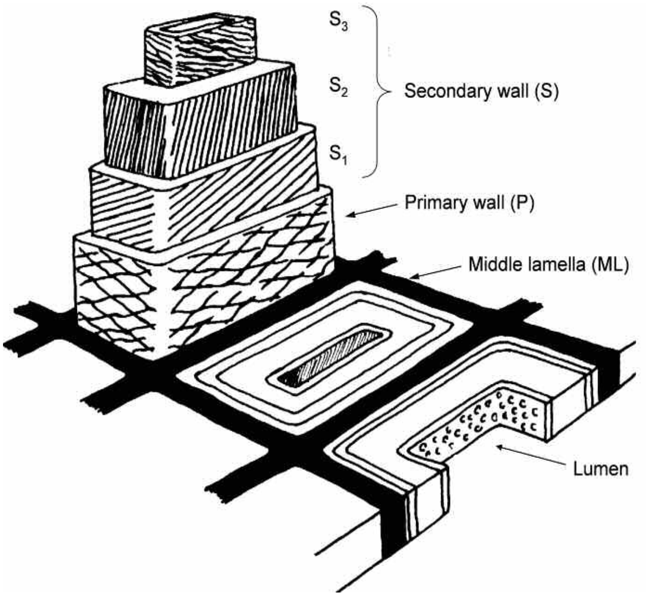
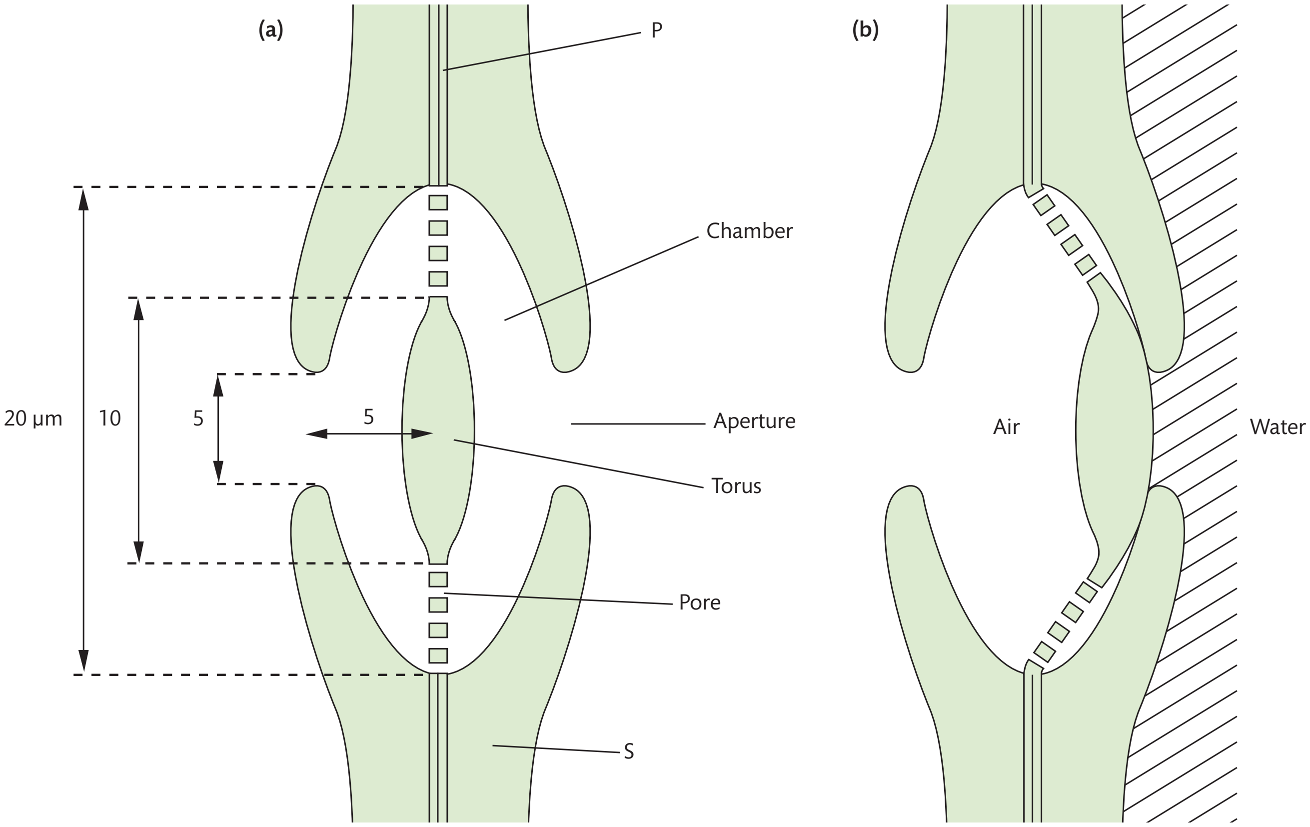


Table 2.1 Typical dimensions of Sitka spruce tracheids.

Tracheid dimension	Values	Reference
Length (mm)	1–3	Chalk (1930); Dinwoodie (1963); Brazier (1967)
Radial width (µm)	20–45	Brazier (1967); CTE (unpublished data)
Tangential width (µm)	20–40	CTE (unpublished data)
Wall thickness (µm)	2–7	CTE (unpublished data)
Lumen diameter (µm)	10–35	CTE (unpublished data)

Water moves longitudinally in a tree through the tracheid lumens and is able to move from one tracheid lumen to the next through bordered pits; a bordered pit is one in which the secondary cell wall over-arches the cell membrane, so as to enclose the pit cavity except for the relatively small pit aperture (Figure 2.3a). Bordered pits are generally restricted to the radial walls of tracheids and are typically 10–20 µm in diameter. In green wood water may pass from one pit aperture to another through the pit chamber and the pit membrane pores. If gas is admitted into a tracheid as a result of an injury or cavitation of the water column, aspiration occurs. During the process of aspiration, the torus moves across the pit chamber to seal off one of the pit apertures and to prevent the expansion of a gas bubble through the pit (Figure 2.3b). Aspiration also occurs with decreases in wood moisture content and therefore affects the permeability of dried timber (See 'Permeability' section on page 16).

Figure 2.3 (a) Diagrammatic representation of an earlywood bordered pit in section transverse to the pit membrane. Typical dimensions and primary (P) and secondary (S) cell wall layers are indicated, **(b)** aspiration of a bordered pit during drying. The torus is pulled across the pit chamber by surface tension forces. (From Petty, 1970, p 30).



Earlywood and latewood

Sitka spruce has a clearly defined annual ring structure and within each ring the wood formed early in the growing season is called earlywood (or spring wood), while the wood formed later in the growing season is called latewood (or summer wood) (Figure 2.4). Earlywood is characterised by tracheids with relatively large lumens and thin walls, while latewood cells have smaller lumens and thicker walls. The transition from earlywood to latewood is normally based on anatomical characteristics (i.e. Mork's definition) or wood density, and is not as abrupt in Sitka spruce as it is in species such as Douglas fir and some of the pines. In Sitka spruce, cell wall thickness increases from approximately 2 µm in earlywood to approximately 6 µm in latewood within the same annual ring, while lumen diameter can decrease from 30 µm down to 15 µm. Tracheid diameter also varies within an annual ring, particularly in the radial direction; differences of 15–20 µm can occur between earlywood and latewood, with latewood tracheids being smaller in diameter (Figure 2.5). Tracheid length decreases steadily in the earlywood part of the growth ring, before increasing rapidly again in the latewood zone, reaching a maximum at the end of the annual ring; tracheids at the end of the annual ring are 12 to 20% longer than at the beginning (Dinwoodie, 1963). The number of bordered pits is approximately 10 times greater in earlywood tracheids than in latewood tracheids; however, most of the earlywood pits become aspirated when the wood dries, while a considerable proportion of the latewood pits remain unaspirated (Phillips, 1933).

Figure 2.4 Transverse section of an annual ring boundary, showing thicker-walled latewood tracheids on the left and thin-walled earlywood tracheids on the right.

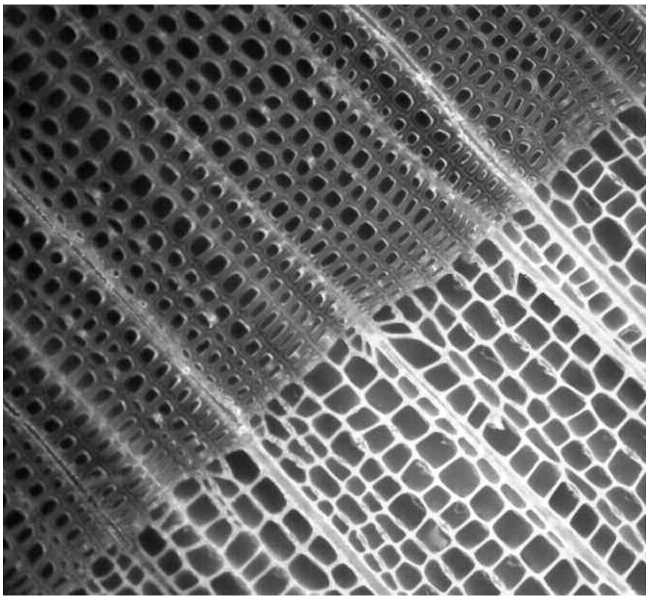
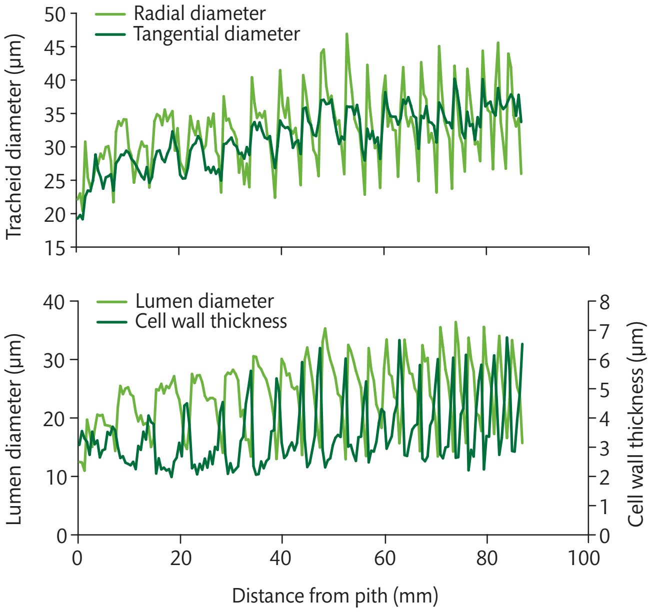


Figure 2.5 Radial variation in selected tracheid dimensions of Sitka spruce.



Sapwood and heartwood

Heartwood represents the inner layers of wood in the growing tree, which no longer contain living cells and where the reserve materials (e.g. starch) have been removed or transformed into heartwood extractives. Sapwood is located between the cambium and heartwood. It contains both living and dead cells and functions primarily in the storage of food; in the outer layers near the cambium, sapwood handles the transport of water or sap (Taylor *et al*., 2002). In Sitka spruce heartwood formation begins when the cambial age at any height in the tree is approximately seven years and progresses at an average rate of about 0.5–0.7 rings per year (Kate Beauchamp, pers. comm.). For a 35-year-old tree, the inner 16 rings at breast height would contain heartwood, and the area of heartwood would be about 50% of the cross-sectional area of the stem (Gibson, 1995).

In contrast to the other main softwood species grown in the UK (i.e. larch, Douglas fir and Scots pine), there is little difference in appearance between the heartwood and sapwood of Sitka spruce, particularly when the wood is dry. This is primarily due to the similar level of extractives in both wood types, *viz*. 1.3 and 1.5% for sapwood and heartwood, respectively (Caron-Decloquement, 2008). However, there are large differences in moisture content between sapwood and heartwood in Sitka spruce. Chalk and Bigg (1956) measured the profiles of moisture content in Sitka spruce trees aged between 23 and 38 years and found that moisture content (weight of water expressed as a percentage of the weight of dry wood) in the sapwood generally exceeded 120%, while at a distance of 50 mm in from the cambium (assumed to be in the heartwood zone) it decreased to between 40 and 80%. The lower moisture content of heartwood means that most of the bordered pits are aspirated, which makes it less permeable than sapwood (See 'Permeability' section on page 16).

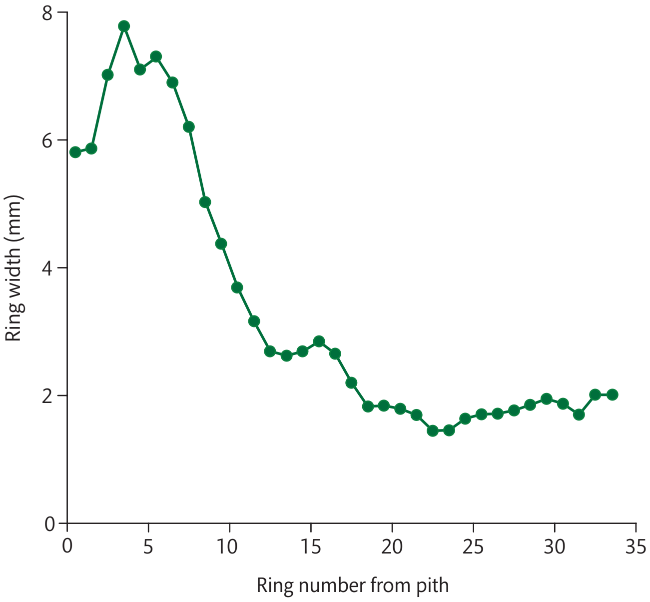
Growth-related features

At a macroscopic level there are a number of characteristics that affect the suitability of Sitka spruce for different products. These have been termed 'growth-related features' here because to varying degrees they are linked to the growing conditions and life history of the tree. Therefore, they can be manipulated to a certain extent through forest management (See 'Effects of site, silviculture and genetics on selected wood properties' section on page 21).

Ring width

Ring width provides the most obvious record of tree growth over time and is itself a visual characteristic of wood. In British-grown Sitka spruce planted at typical initial spacing (i.e. 2 × 2 m) ring widths of 5–8 mm are generally found in the innermost rings, decreasing to less than 2 mm after ring 20 (Figure 2.6). Ring widths of more than 10 mm are occasionally found near the pith, particularly in stands planted at a wide initial spacing. Much has been made of the relationship between growth rate (as inferred from ring width) and wood properties (e.g. Scott and MacGregor, 1953), and ring width is commonly used as an indicator of

Figure 2.6 Radial profile of ring width in 37-year-old Sitka spruce from Kershope forest. Data are from McLean (2008).



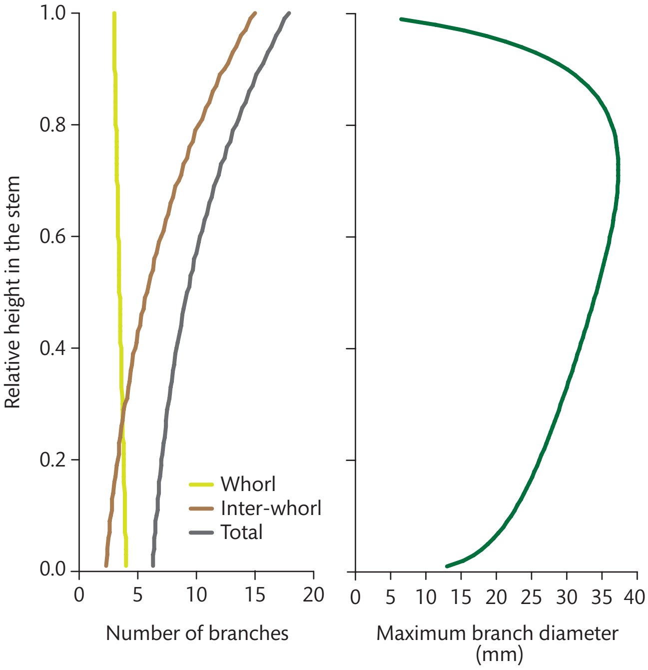
sawn timber quality, with narrow-ringed timber preferred (See 'Structural timber' section on page 28). However, ring width is also a function of radial position, with wide rings generally corresponding to the juvenile wood that is located near the pith (See 'Juvenile wood' section on page 11). This has often been a confounding factor when looking for relationships between ring width and various physical and mechanical wood properties.

Knots

The frequency, size and condition of knots are arguably the most important growth-related feature affecting the suitability of wood for a number of end-products, particularly sawn timber. Knot characteristics are in turn directly related to branching habit. Sitka spruce is a uni-nodal species that normally produces one distinct whorl of branches in a growing season, along with a number of inter-whorl branches; however, these inter-whorl branches are normally much smaller in diameter than whorl branches. The number of branches produced in a growing season increases with height up the tree and it is not uncommon for there to be more than ten branches in an annual growth unit (Cannell, 1974; Achim *et al.*, 2006). The frequency of knot clusters that are associated with branch whorls will depend on the distance between these whorls, which in turn is related to yield class. On low yield class sites the average distance between whorls can be 0.3 m, whereas on more productive sites it can be up to 0.7 m. Models for branch size, frequency and insertion angle have been developed for Sitka spruce by Achim *et al*. (2006) and Weiskittel *et al*. (in review). These allow the effects of tree growth and forest management to be investigated (See 'Effects of site, silviculture and genetics on selected wood properties' section on page 21). Vertical profiles of the number of branches per annual growth unit and the maximum branch diameter from the models developed by Weiskittel *et al*. (in review) are shown in Figure 2.7.

As a relatively shade-tolerant species, Sitka spruce generally retains a deeper crown of living branches than more light-demanding species such as Douglas fir, pines and larches, which exhibit a greater tendency to self-prune (Niinemets and Valladares, 2006). Sitka spruce can also produce large numbers of epicormic sprouts in response to changes in stand structure and light levels caused by wind damage, thinning or pruning (Deal *et al*., 2003; Quine 2004). While epicormic sprouts tend to be small in diameter, their frequency can have a negative impact on the visual characteristics of timber (Deal *et al*., 2003).

Figure 2.7 Vertical profiles showing the number of branches per annual growth unit and maximum branch diameter.

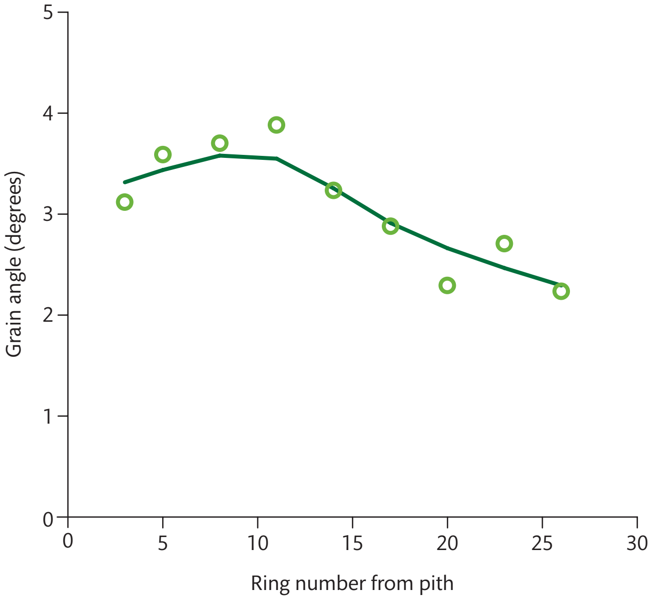


Spiral grain

Spiral grain refers to the spiral alignment of the longitudinal tracheids relative to the stem axis. The process by which spiral grain forms in the tree and the reasons for its existence have occupied the attention of botanists, foresters, wood scientists and wood users for over a century. It is generally accepted that spiral grain is formed during the process of cell division and maturation within the vascular cambium, but there is still debate over the exact mechanism involved (Schulgasser and Witztum, 2007). The function of spiral grain is also a subject of debate and a number of theories have been proposed (e.g. Harris, 1989; Kubler, 1991). Regardless of how or why it is formed, any pronounced spiral grain will reduce timber strength and stiffness and increase distortion, particularly twist.

The pattern of spiral grain variation in Sitka spruce is similar to that observed in many other conifer species. A left-handed (S) spiral is generally observed near the pith, and the spiral angle initially increases with increasing ring number from the pith before gradually decreasing after about ring 10 (Brazier, 1967; Figure 2.8). Hansen and Roulund (1998) found that the angle decreased with height up the stem; however, studies in Great Britain found no effect of height (Forest Research, unpublished data). There is considerable between-tree variation in grain angle at a given age and also in the age at which the maximum angle occurs; both are under a high degree of genetic control (Cahalan, 1987). Angles greater than 6° are uncommon.

Figure 2.8 Radial variation in spiral grain angle in young Sitka spruce (after Brazier, 1967).

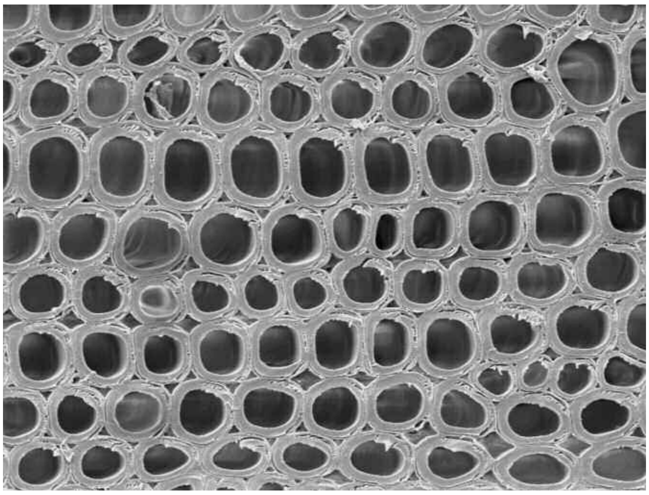


Compression wood

This type of wood is formed on the underside of branches and in the stems of leaning trees. Its purpose is to restore a leaning stem to a vertical orientation or to induce an upward inclination and/or minimise the downward inclination of a branch (Timell, 1986). The amount of compression wood in the stem of Sitka spruce trees varies considerably. Based on measurements made on 64 trees from four sites, Gardiner and Macdonald (2005) found that the compression wood content (on a volumetric basis) of an individual tree ranged from less than 1% up to 15.5%. Mean values for the four sites ranged from 2.2% up to 7.6%.

Compression wood has different anatomical, chemical and physical characteristics than so-called 'normal wood', most of which make it less desirable from a wood processing perspective (See 'Physical properties' section on page 11 and 'Mechanical properties' section on page 18). Anatomically, the tracheids found in compression wood have a more rounded shape in transverse section, have thicker cell walls and intercellular spaces are common. The S_2 layer of the cell wall often contains a series of helical splits (Figure 2.9) and the S_3 layer is generally missing in severe compression wood (Wilson and White, 1986). The mean microfibril angle in the S_2 layer of compression wood tracheids is higher than in normal wood, and one theory is that this means that on maturing the cell will tend to lengthen and produce a compressive stress (Schulgasser and Witztum, 2007). Interestingly, in compression wood the microfibril angle is higher in the latewood than in the earlywood, which is the opposite to what occurs in normal wood (Table 2.2).

Figure 2.9 Compression wood tracheids in Sitka spruce showing the intercellular spaces (top) and the helical splits in the S2 cell of severe compression wood (bottom). Images courtesy of Alan Crossley, Centre for Ecology and Hydrology.



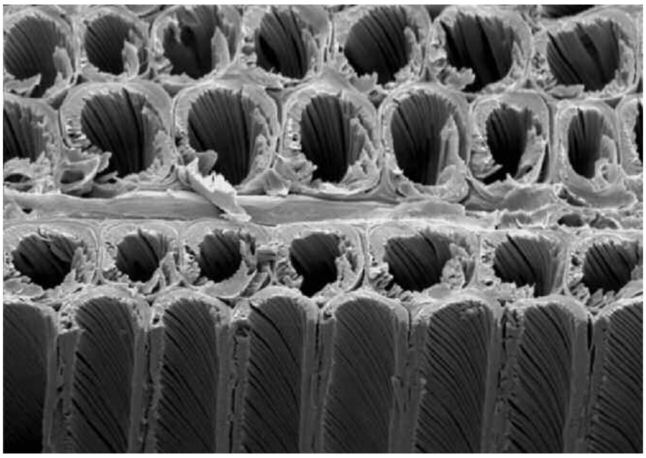


Table 2.2 Comparison of earlywood and latewood microfibril angle between compression wood and normal wood in Sitka spruce (from Gardiner and Macdonald, 2005).

Sample origin	Mean microfibril angle (degrees)			
	Normal wood		Compression wood	
	Earlywood	Latewood	Earlywood	Latewood
1	9.4	6.6	20.6	23.3
2	17.8	12.5	17.9	21.8

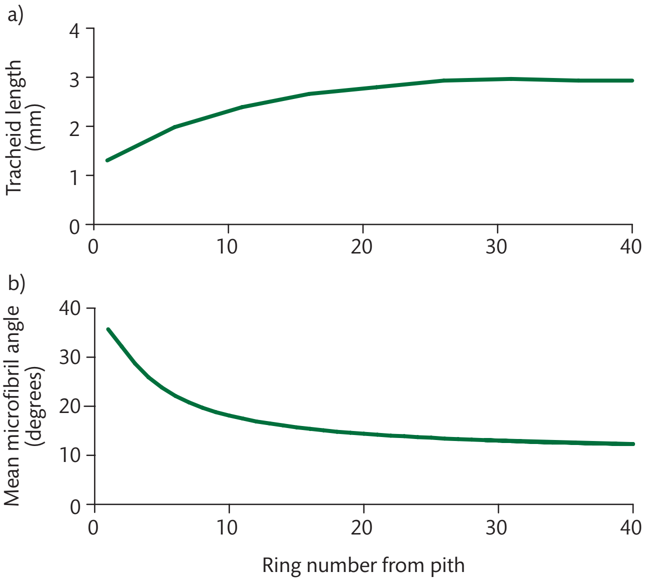
The chemical composition of compression wood also differs to that of normal wood. It can contain 30–40% more lignin and 20–25% less cellulose; however, for Sitka spruce lignin content was found to increase from 31 to 35%, while cellulose content decreased from 41 to 37% (Gardiner and Macdonald, 2005). Because of its higher lignin content and thicker cell walls compression wood absorbs more light and therefore appears darker in colour than normal wood; detection of compression wood on log ends and the surface of sawn timber is often based on its colour.

Juvenile wood

The wood located in the region close to the pith, which generally exhibits relatively large radial gradients in properties, is commonly referred to as juvenile wood owing to the young age of the vascular cambium at the time that it was formed, whereas wood located outside this zone is often referred to as mature wood (Zobel and Sprague, 1998). This is not to be confused with heartwood and sapwood (See 'Sapwood and heartwood' section on page 8); heartwood development occurs several years after the wood cells have been formed, whereas the anatomical structure of wood does not change after it is formed. A number of theories have been proposed for why trees exhibit a radial gradient in wood properties and these are reviewed in Lachenbruch *et al.* (2011). The terminology used to describe the wood found at different positions within a tree has been the source of much debate (e.g. Larson, 1969; Amarasekara and Denne, 2002; Burdon *et al.*, 2004). Larson (1969) argued that the term juvenile wood is a misnomer and that it would be more appropriate to refer to this type of wood from a positional perspective as 'core wood' or from a developmental perspective as 'crown-formed wood'. Despite this, the term juvenile wood will be used here because of its widespread acceptance in the forestry and wood science communities.

The age of transition between juvenile and mature wood depends on the property under consideration; tracheid length, cellulose microfibril angle and wood density are frequently used to determine this transition. In Sitka spruce tracheid length steadily increases from approximately 1 mm near the pith reaching an asymptotic value of approximately 3 mm after ring 15 to 20 (Dinwoodie, 1963; Brazier, 1967; Cameron *et al.*, 2005). Microfibril angle in Sitka spruce decreases from 30–45° near the pith to around 10° after ring 15 and thereafter remains relatively constant (Figure 2.10). The age that the transition from juvenile to mature wood occurs in Sitka spruce has been reported as ranging from 12 years (Brazier and Mobbs, 1993; Schiable and Gawn, 1989) up to 16 years (Evertsen, 1988). Based on the observed radial variation in tracheid length and microfibril angle, the age of transition would appear to be at the upper end of values reported in the literature, that is, closer to 15 years. The proportion of juvenile wood in a tree will depend on the rotation length on which it is grown as well as the choice of initial spacing and thinning regime, but is around 35% (on a tree volume basis) for a 45-year rotation increasing to around 50% for a 35-year rotation.

Figure 2.10 Variation in (a) tracheid length and (b) cellulose microfibril angle in Sitka spruce.



In addition to differences in tracheid length and microfibril angle, juvenile wood in Sitka spruce (and other softwoods) has growth rings consisting of a larger proportion of earlywood tracheids (which have larger diameter and thinner cell walls than latewood tracheids), a higher incidence of compression wood, lower cellulose content, a higher percentage of lignin and differences in the hemicellulose composition compared with mature wood (Zobel and Sprague, 1998). As a result there are differences in physical and mechanical properties, particularly density, strength, stiffness and longitudinal shrinkage (See 'Physical properties' section below and 'Mechanical properties' section on page 18). These properties generally mean that juvenile wood is seen as being less desirable for many products, particularly sawn timber, although it is actually preferred for the production of medium density fibreboard (Li Shi *et al.*, 2005).

Physical properties

The physical properties of Sitka spruce wood affect its suitability for different products and include characteristics such as appearance, density, moisture content, permeability, shrinkage, durability, thermal conductivity and calorific value.

Colour and appearance

The wood of Sitka spruce along with the other spruce species grown in Europe (mainly Norway spruce) is referred to as whitewood by the trade, because of its pale colour. The colour of Sitka spruce wood ranges from creamy white to a pale pink or pinkish brown colour in the central core, and it is generally not as light in colour as that of wood from other spruce species. When dry there is little difference in colour between heartwood and sapwood (Mullins and McKnight, 1981; Harding, 1988). The wood has a distinct grain pattern, but the contrast between earlywood and latewood is not as marked as in other species such as Douglas fir, the larches and hard pines. Resin (pitch) pockets occasionally occur on the surface of sawn timber, but they are generally small in size.

Moisture content

In addition to cellulose, hemicelluloses, lignin and extractives, wood contains water. This water can exist as absorbed (or free) water in the cell lumens and intercellular spaces, or as adsorbed (or bound) water within the cell walls. The moisture content of wood is calculated as the ratio of the mass of water to the mass of wood that has been oven-dried and is usually expressed as a percentage, i.e.

$$\text{Moisture content} = \frac{\text{Original mass} - \text{Oven dry mass}}{\text{Oven dry mass}} \times 100 \qquad [1]$$

Because of this definition, moisture content values exceeding 100% can and do occur. It should be noted that the biomass sector generally use original mass in the denominator for equation 1, which will result in lower values of moisture content. As already mentioned in the 'Sapwood and heartwood' section on page 8, the moisture content of green Sitka spruce sapwood is typically in excess of 120% (values close to 300% have been observed), while in heartwood it is typically between 40 and 80%. The average whole-tree moisture content typically ranges from 100 to 160% (Jeffers and Dowden, 1964).

Because wood is a hygroscopic material (i.e. it exchanges moisture with the atmosphere) its moisture content depends on the temperature and relative humidity of the environment that it is placed in. When a sample of freshly cut wood is placed in an environment where the relative humidity is less than 100% it will lose moisture (Siau, 1984). The absorbed water in the lumens and intercellular spaces evaporates first. The moisture content at which all the absorbed water has been removed but at which the cell walls are still fully saturated is referred to as the fibre saturation point (Stamm, 1964). For Sitka spruce, as well as other species, the fibre saturation point is generally assumed to be at 30% moisture content. Once moisture content of wood falls below fibre saturation point substantial changes in many of its physical and mechanical properties occur with further changes in moisture content.

Under conditions of constant temperature and relative humidity, wood will reach an equilibrium moisture content. At a given relative humidity the equilibrium moisture content will decrease with increasing temperature (Figure 2.11). The equilibrium moisture content will also depend on whether the wood has lost water (desorption) or has gained water (adsorption) as the adsorption–desorption cycle follows a hysteresis loop (Figure 2.11). The adsorption and desorption curves define the maximum and minimum equilibrium moisture contents that can be expected for a given relative humidity. A much more thorough investigation of the water vapour sorption behaviour of Sitka spruce is presented in Hill *et al*. (2010). Averaged values of equilibrium moisture for Sitka spruce at selected combinations of temperature and relative humidity are presented in Table 2.3 (after Ahmet *et al*., 2000).

Figure 2.11 Sorption isotherm for Sitka spruce showing desorption curves for different temperatures, but a single adsorption curve (after Hill et al., 2010).

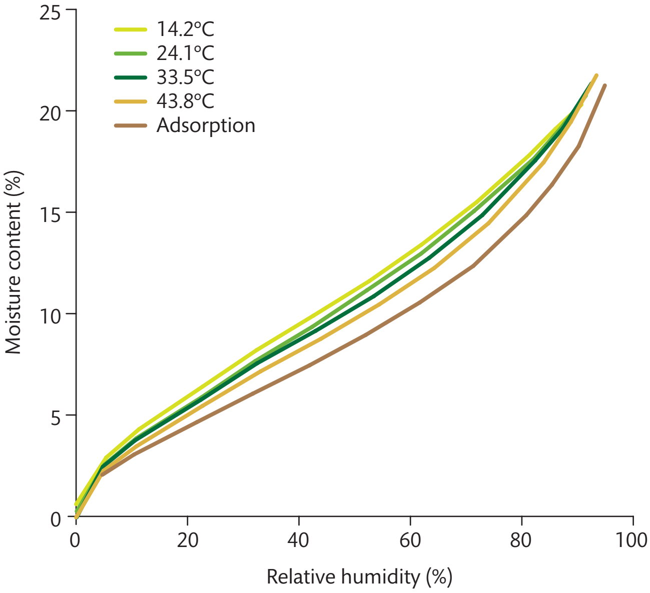


Table 2.3 Values of equilibrium moisture content for Sitka spruce averaged for adsorption and desorption (after Ahmet *et al*., 2000).

Temperature (°C)	Relative humidity (%)		
	35	55	75
10	9.7	12.9	15.0
20	8.4	11.8	14.7
30	7.6	11.1	14.4

Density

The density of wood is defined as the mass per unit volume. It is a property that is widely studied because it is relatively easy to measure and is correlated with a number of other physical and mechanical properties. Because the oven-dry density of cell wall material in all woody plants is approximately 1500 kg m^{-3}, the density of wood is determined by the amount of cell wall substance, the volume of voids and the moisture content. Therefore, a number of different definitions of wood density are possible based on the moisture content at which the mass and the volume of the sample are determined. The density at a specific moisture content is calculated using the following equation:

$$\text{Density at x\% moisture content} = \frac{\text{Mass of wood at x\% moinsture content}}{\text{Volume of wood at x\% moisture content}} \quad [2]$$

Often a reference moisture content of 12% is used, as this is considered to be the equilibrium moisture content that is achieved when timber is used in indoor conditions. At 12% moisture content the density of Sitka spruce sawn timber is 390±40 kg m^{-3} (CTE, unpublished data; FPRL, 1967; Harding, 1988). This is sometimes referred to as the air-dry density.

The density of freshly felled wood is of interest to those transporting timber and is used to convert between the volume and mass of logs. This is generally referred to as green density and is calculated as follows:

$$\text{Green density} = \frac{\text{Mass of wood when green}}{\text{Volume of wood when green}} \quad [3]$$

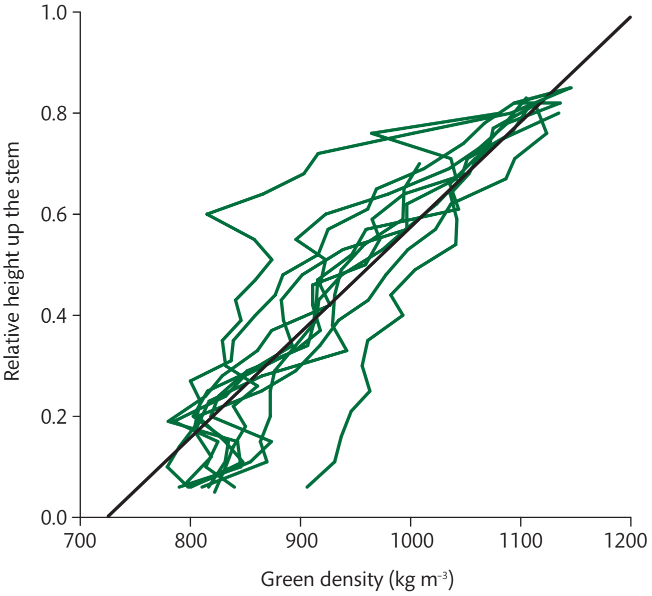
The green densities of Sitka spruce heartwood and sapwood are approximately 600 and 1000–1100 kg m^{-3}, respectively (CTE, unpublished data). Therefore, the average green density of a log will depend on the proportion of heartwood and sapwood it contains. For a 40–45-year-old tree, green density is approximately 800 kg m^{-3} at the base increasing to a value of 1100 kg m^{-3} near the top (Figure 2.12). The overall weighted average value for a tree is approximately 850 kg m^{-3} (CTE, unpublished data).

For wood processing industries, the main interest is usually how much dry material there is in a cubic metre of fresh wood. This is given by the basic density, which is calculated using the following equation:

$$\text{Basic density} = \frac{\text{Oven dry mass of wood}}{\text{Volume of wood when green}} \quad [4]$$

A closely related term is specific gravity, which is the ratio of the density of a substance to the density of pure water at 4°C. As the density of pure water is equal to 1000 kg m^{-3}, the specific gravity of wood is numerically equivalent to its basic density. There is also considerable interest in knowing the amount of carbon stored in wood. Because wood is approximately 50% carbon (See 'Chemical composition' section on page 5), the amount of carbon stored in a cubic metre of fresh wood is equal to half its basic density.

Figure 2.12 Variation in green density with relative height up stem. The green lines represent vertical profiles for ten individual trees, while the black line is a regression model fitted to the data.



Sitka spruce has an overall average value of basic density of 350 kg m^{-3} for the whole stem (although a value of nearly 400 kg m^{-3} was obtained by Jeffers and Dowden (1964)) and 330–340 kg m^{-3} for timber samples (Bryan and Pearson, 1955; Lavers, 1983; Moore *et al*., 2009c; CTE unpublished data). However, there is considerable variation in basic density within a tree, between trees within a stand and between sites. The first two sources of variation are discussed here, while between-site variation is discussed in the section entitled 'Effects of site, silviculture and genetics on selected wood properties' on page 21.

Variation within an annual ring

Basic density varies considerably within an annual ring of Sitka spruce. X-ray densitometry has enabled the density of Sitka spruce wood to be measured at very high resolution (~50 µm). This shows that within a growth ring, basic density can vary from a minimum of around 200 kg m^{-3} at the beginning of the earlywood to around 750 kg m^{-3} at the end of the latewood (Brazier, 1967, 1970) (Figure 2.13). There is also a tendency for the minimum density of earlywood to increase with increasing ring number from the pith; for example, values of 400 kg m^{-3} can be found at ring 45 from the pith. On average, the basic densities of earlywood and latewood in Sitka spruce are approximately 310 and 530 kg m^{-3}, respectively. The percentage of earlywood and latewood in a growth ring determines the overall density of the ring, and in Sitka spruce the latewood width is relatively constant so that ring width is closely related to earlywood width (Brazier, 1970) (Figure 2.14). Therefore, as the ring width in Sitka spruce increases, an increase in the width of earlywood without a corresponding increase in the amount of latewood results in a reduction in overall wood density (Brazier, 1970; Petty *et al*., 1990).

Figure 2.13 Variation in basic density within a growth ring. Data are for ring numbers 10–14 from the pith.

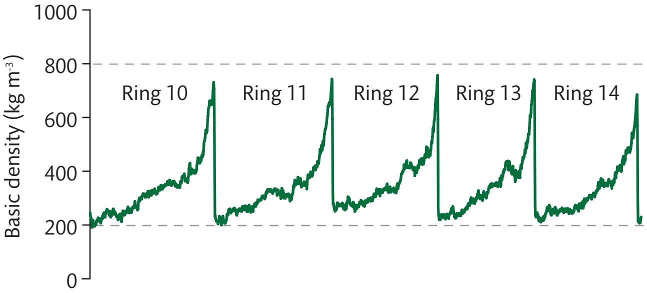
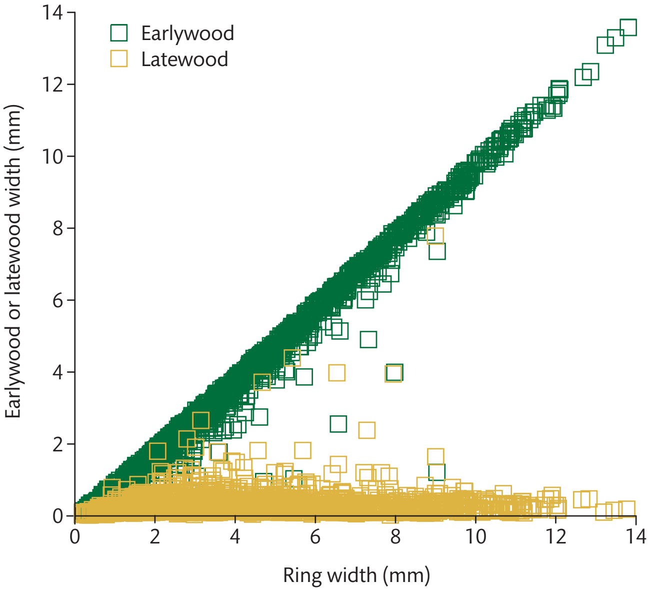


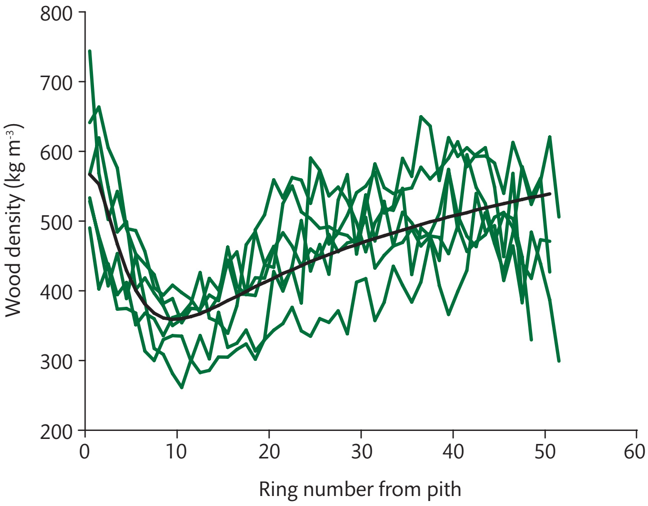
Figure 2.14 Contributions of earlywood and latewood width to total ring width in Sitka spruce.



Variation within a tree

Wood density varies considerably within a tree in both the radial and longitudinal directions. The radial variation in the wood density of Sitka spruce corresponds to the model II presented by Panshin and de Zeeuw (1980). In the juvenile core, wood density decreases from a maximum close to the pith down to a minimum value at between rings 10 and 20, before increasing again towards a quasi-asymptotic value in the mature wood (Bryan and Pearson, 1955; Brazier, 1967; Savill and Sandels, 1983; Petty *et al*., 1990; Mitchell and Denne, 1997; Simpson and Denne, 1997; McLean, 2008) (Figure 2.15). Elliot (1970) attributes the high density observed in the innermost rings to short, small diameter fibres resulting in an increased number of cell walls per unit volume of wood as well as the increased occurrence of compression wood in this region.

Figure 2.15 Radial profile of Sitka spruce wood density. The green lines show profiles for five individual trees sampled at Baronscourt in Northern Ireland, while the black line represents a model fitted to these data.



The longitudinal variation in Sitka spruce wood density is not as consistent as the radial variation. Some studies have reported a lack of systematic variation in wood density with height up the stem (e.g. Jones, 1957; Elliot, 1966), while others have reported a slight decrease (Harvald and Olesen, 1987; Mitchell and Denne 1997). Within a growth sheath (layer of wood formed in the same year or years), Simpson and Denne (1997) found that there was a decrease in wood density from the base of the tree up to approximately eight annual growth units from the top, followed by a large increase in density above this height.

Shrinkage

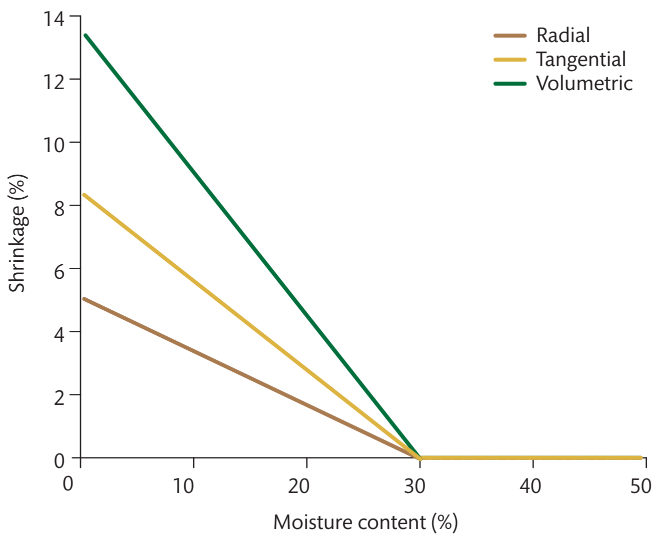
Above the fibre saturation point (~30% moisture content), wood is dimensionally stable. Below this point, wood shrinks as moisture is lost from the cell walls; conversely, it also swells as it gains moisture (Rijsdijk and Laming, 1994). This dimensional instability is an issue for the processing and use of timber, as timber will shrink during the drying process (both in the sawmill and in service), while fluctuations in the environment in which the timber is placed will result in changes in its dimensions. The amount that wood shrinks is not the same in all directions and it also differs with radial position within a tree stem. Therefore, the shape of sawn timber can distort as it dries, particularly when there is a gradient in shrinkage rate or where there is a high spiral grain angle, leading to twist. Wood shrinks significantly more in the radial and tangential directions than in the longitudinal direction. In Sitka spruce, the average amount of radial and tangential shrinkage from green to 12% moisture content is 3.0 and 5.0%, respectively (Harding, 1988; Table 2.4). These values represent the change in dimension as a percentage of the original green dimension. If it is assumed that the rate of shrinkage is linear between fibre saturation point and 0% moisture content, then the amount of shrinkage at any moisture content can be determined from Figure 2.16. Here, it is assumed that the volumetric shrinkage is the sum of the radial and tangential shrinkage because longitudinal shrinkage is much lower (Walker, 2006).

Table 2.4 Shrinkage and movement in the heartwood of Sitka spruce (after FPRL, 1967 and Harding, 1988).

Density (kg m^{-3})[1]	Shrinkage (%)[2]		Movement (%)[3]		Moisture content	
	Radial	Tangential	Radial	Tangential	60% RH	90% RH
400	3.0	5.0	0.9	1.3	12.5	19

[1] Mean density at 12% moisture content.
[2] Drying from green condition to 12% moisture content.
[3] Change in dimensions when relative humidity decreases from 90% to 60% at 25°C.

Figure 2.16 Approximate relationship between moisture content and shrinkage behaviour for Sitka spruce. The relationship is based on the assumption that fibre saturation point is at 30% moisture content and the values of shrinkage from green to 12% moisture content presented in Harding (1988).



Natural durability

Natural durability is defined in EN350-1 (CEN, 1994a) as ‘the inherent resistance of wood to attack by wood-destroying organisms’, with biological attack from fungi and insects considered the most important. The climate in Great Britain means that the main agents of biodegradation are various species of fungi, rather than insects. Natural durability of untreated wood to wood-destroying fungi is determined either from ground contact trials (sometimes referred to as ‘graveyard trials’) or from laboratory tests using the basidiomycete fungi (CEN, 1994a; Råberg *et al.*, 2005). Based on the results of these tests, wood from a particular species is assigned to one of five natural durability classes, 1–5, where 1 is very durable and 5 is not durable (Table 2.5). This assignment to classes is on the basis of the average life of the test stakes relative to the average service life of the most durable set of reference stakes for field tests, and on the basis of mass loss relative to that of the reference specimens for laboratory tests. In both types of test the reference specimens are Scots pine sapwood. Based on these tests, the heartwood of Sitka spruce is classified as slightly durable (durability class 4) (CEN, 1994b). The sapwood is classified as not durable (class 5).

Table 2.5 Classes of natural durability of wood to fungal attack (after EN350-1; CEN, 1994a).

Durability class	Description
1	very durable
2	durable
3	moderately durable
4	slightly durable
5	not durable

It is important to recognise that the amount of decay that occurs in timber in service will depend on the moisture content of the timber, the surrounding temperature and relative humidity, and the availability of oxygen. The different moisture content conditions that can occur for solid wood are represented through a series of five use classes, 1–5, where 1 corresponds to moisture content permanently below 20% and 5 corresponds to moisture content permanently above 20% (Table 2.6). The natural durability information obtained from field and laboratory tests relates to use class 4, which is timber in ground contact or in fresh water. The estimated service life will differ for wood in out-of-ground contact situations (i.e. use classes 1–3), and will depend on its ability to absorb moisture. Unfortunately, much less information is available on the durability and service life of Sitka spruce (as well as most other species) in above-ground conditions, partly because of the lack of a standard test method (Råberg *et al*., 2005). However, in one study performed in Norway (Evans *et al*., 2008), similar relative rankings for species were found from in-ground and above-ground tests.

Table 2.6 Definition of use classes which represent different service situations to which wood and wood-based products can be exposed (after EN335-1 and EN335-2; CEN, 2006a,b).

Use class	General service situation	Description of exposure to wetting in service*
1	interior, covered	Dry (max 20%)
2	interior or covered	Occasionally >20%
3	**3.1** exterior, above ground, protected.	Occasionally >20%
	3.2 exterior, above ground, unprotected	Frequently >20%
4	**4.1** exterior, in ground contact and/or fresh water	Predominantly or permanently >20%
	4.2 exterior, inc ground (severe) and/or fresh water	Permanently >20%
5	in salt water	Permanently >20%

*Moisture content values relate to solid timber.

Permeability

Permeability is defined as a measure of the ease by which a liquid or gas is able to move through wood (Siau, 1984). It is determined from Darcy's Law and is often expressed in Darcy units (1 Darcy is equivalent to 9.87 × 10^{-13} m^2). It is important to distinguish between permeability and porosity. Porosity refers to the relative proportion of void space in a material, but not necessarily to the ease with which fluid can move through it (Walker, 2006). Porosity is related to basic density, whereas permeability is related to wood structure and the direction of flow (radial, tangential and longitudinal) (Petty, 1970). The values of permeability also depend on the viscosity of the liquid or gas being considered; the permeability is lower for more viscous liquids than for less viscous liquids and gases.

As noted in the 'Wood anatomy' section on page 6, the longitudinal flow of water in the sapwood of living Sitka spruce trees is through the tracheid lumina, with flow from one tracheid lumen to the next via the bordered pits. Therefore, both the tracheid lumina and the bordered pits contribute to the total resistance to the flow and the two components are arranged in series in the flow path (Petty, 1970). The number, size and status of these bordered pits has a considerable effect on the permeability of Sitka spruce wood. In green sapwood, the majority (~95%) of these pits are unaspirated (Usta and Hale, 2006), while in dried wood the majority of pits are aspirated (Phillips, 1933). Petty (1970) found that in air-dried Sitka spruce, only 7% of the tracheids were conducting and it was assumed that conduction was occurring through the small number (two to five) of unaspirated pits in the conducting latewood tracheids. Overall, the high proportion of aspirated pits means that the longitudinal gaseous permeabilities of Sitka spruce sapwood and heartwood are relatively low compared with other species, particularly pines (Table 2.7). Furthermore, the radial and tangential gaseous permeabilities are many orders of magnitude less than the longitudinal permeability (Comstock, 1970; Eaton and Hale, 1993). This low overall permeability means that Sitka spruce is referred to as a refractory species, which affects its suitability for preservative treatment and chemical modification.

Table 2.7 Gas permeability of the heartwood and sapwood of spruce and pine in the three structural directions (after Comstock, 1970; Eaton and Hale, 1993).

Species	Moisture content (%)	Permeability (m^2)		
		Longitudinal	Tangential	Radial
Pine (sapwood)	9	2.98 × 10^{-11}	3.65 × 10^{-16}	2.07 × 10^{-15}
Pine (heartwood)	9	1.86 × 10^{-12}	7.80 × 10^{-17}	3.55 × 10^{-16}
Spruce (sapwood)	9	5.72 × 10^{-13}	7.80 × 10^{-18}	7.50 × 10^{-17}
Spruce (heartwood)	9	8.09 × 10^{-14}	3.65 × 10^{-18}	1.48 × 10^{-19}

Thermal properties

The main thermal properties of interest for wood are its conductivity, specific heat, diffusivity and thermal expansion. Limited experimental data are available specifically for Sitka spruce wood, and the information presented below is primarily taken from the *Wood handbook* (Forest Products Laboratory, 2010).

Thermal conductivity

Thermal conductivity (W m^{-1} K^{-1}) is a measure of the rate of heat flow through a unit thickness of a material subjected to a temperature difference between opposite sides. It is not only important for aspects of wood processing, such as drying, but also when calculating the thermal performance of timber structures. Thermal conductivity increases as density, moisture content, temperature, or extractive content of the wood increases. For moisture content levels below 25%, approximate thermal conductivity *k* across the grain can be calculated from the following equation (Forest Products Laboratory, 2010):

$$k = 0.01864 + (0.1941 + 0.004064M)G \qquad [5]$$

where *G* is specific gravity based on oven-dry weight and volume at a given moisture content *M* (%). The average specific gravity of British-grown Sitka spruce at 12% moisture content, based on this definition, is approximately 0.35. From equation 5 the average thermal conductivity of Sitka spruce at 12% moisture content is approximately 0.10 $W\ m^{-1}\ K^{-1}$. Wood with lower density (specific gravity) will have lower thermal conductivity and is therefore a better insulator. Over the typical range of values of specific gravity that occur in Sitka spruce (0.30–0.40), thermal conductivity ranges from 0.09 up to 0.12. Thermal conductivity is similar in the radial and tangential directions, but longitudinal conductivity is approximately twice as great.

Specific heat capacity

Heat capacity is defined as the amount of energy needed to increase one unit of mass (kg) one unit in temperature (K). The heat capacity of wood depends on its temperature and moisture content but is largely independent of density or species. Therefore the approximate heat capacity of oven-dry Sitka spruce wood c_{p0} ($kJ\ kg^{-1}{\cdot}K^{-1}$) as a function of temperature *T* (K) is given by:

$$c_{p0} = 0.1031 + 0.003867T \qquad [6]$$

The heat capacity of wood that contains water is greater than that of dry wood. Below fibre saturation, heat capacity can be calculated from the following equation, which is the sum of the heat capacity of the dry wood and that of water along with an additional adjustment factor that accounts for the additional energy in the wood–water bond (Forest Products Laboratory, 2010):

$$c_p = (c_{p0} + 0.0419M)/(1 + 0.01M) + (0.06191 + 2.36\text{x}10^{-4}T + 1.33\text{x}10^{-4}M) \qquad [7]$$

where *M* is moisture content (%).

Thermal diffusivity

Thermal diffusivity ($m^2\ s^{-1}$) is a measure of how quickly a material can absorb heat from its surroundings and is the ratio of thermal conductivity to the product of density and heat capacity, i.e.

$$a = \frac{k}{c_p G} \qquad [8]$$

A typical value of thermal diffusivity for Sitka spruce wood with specific gravity of 0.35 at 12% moisture content and with a temperature of 15°C is 0.177 x $10^{-6}\ m^2\ s^{-1}$. This is low compared with other materials, which is why wood does not normally feel particularly hot or cold to the touch.

Thermal expansion coefficient

The coefficient of thermal expansion is a measure of the change in dimensions caused by a change in temperature. The thermal expansion coefficients of completely dry wood are positive in all directions, that is, wood expands on heating and contracts on cooling. Dry wood has a low coefficient of thermal expansion, such that temperature-induced changes in dimensions are small compared with those caused by changes in the equilibrium moisture content.

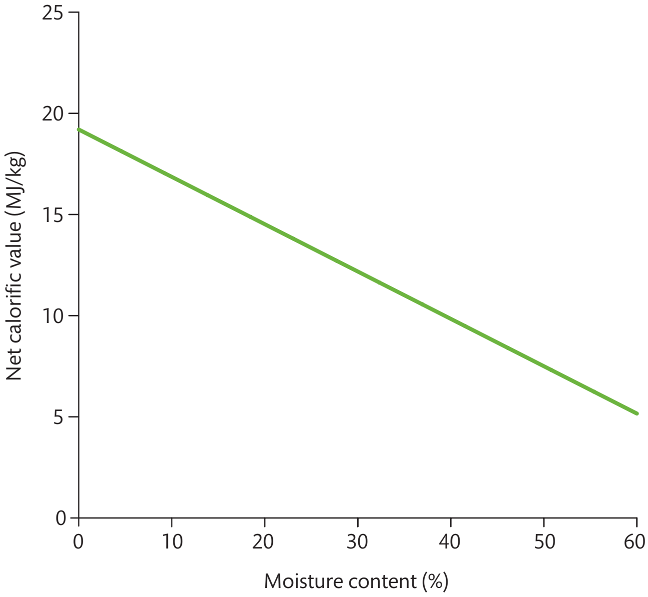
Calorific value

The calorific value (or heating value) of wood is the amount of heat released during the combustion of a specified amount of it and is an important property for assessing the biomass energy resource (See 'Biomass for energy' section on page 37). The usable energy content of wood is given by the net calorific value (NCV), which takes into account the energy that is required to vaporise the water that is present in the wood; this energy is not realised as heat. As the chemical composition of different wood species is approximately similar (See 'Chemical composition' section on page 5), so too is the NCV when expressed on a unit weight basis (i.e. $MJ\ kg^{-1}$). The net calorific value of Sitka spruce wood at different moisture contents can be calculated using the following equation:

$$\text{NCV}\ [MJ\ kg^{-1}] = 19.2 - 0.216M \qquad [9]$$

where *M* is moisture content (%). It is important to note that the values of moisture content used in equation 9 are calculated on a wet weight basis and not on a dry weight basis, which is the usual convention (See 'Moisture content' section on page 12). For example, a wood sample with a 'wet weight' of 8.5 kg and a dry weight of 3.5 kg would have a moisture content by the usual definition (equation 1) of 142% (i.e. (8.5–3.5)/3.5 x 100%), but a moisture content of 58% using the definition adopted by the biomass sector (i.e. (8.5–3.5)/ 8.5 x 100%). The effect of increasing moisture content on the calorific value of wood is shown in Figure 2.17.

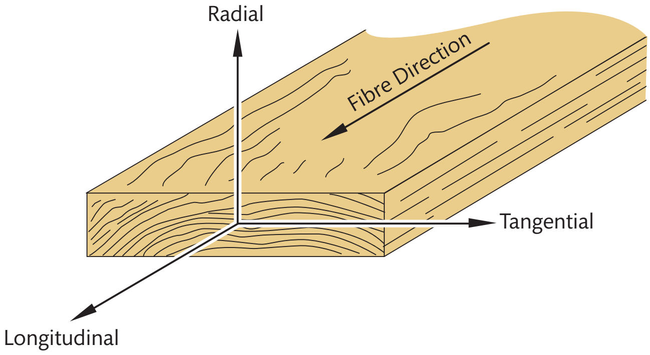
Figure 2.17 Relationship between net calorific value and moisture content as determined from equation 9.



Mechanical properties

The mechanical properties of wood determine its ability to resist applied forces, and it is largely these properties that affect the performance of wood in construction applications, as well as in other load-bearing applications such as pallets. These properties are influenced by many of the anatomical and growth-related features discussed in the sections entitled ‘General wood structure’ on page 5 and ‘Growth-related features’ on page 8, and many mechanical properties are also correlated, to varying degrees, with wood density. Mechanical properties are also affected by moisture content and it is therefore necessary to specify the moisture content at which the measurements were made; the standard reference moisture content is 12%. Furthermore, as wood is an anisotropic material (i.e. its properties are directionally dependent), many of its mechanical properties are determined for several different directions, for example parallel to grain (in the longitudinal direction) and perpendicular to the grain (in the radial or tangential directions) (Figure 2.18). In the past, information on the mechanical properties of Sitka spruce wood was obtained from tests made on small defect-free (clear) specimens (e.g. Broughton, 1962; FPRL, 1967; Brazier *et al.*, 1976; Lavers, 1983) using the methods described in BS373 (BSI, 1957). Nowadays, the mechanical properties of timber used in construction applications are normally established by tests made on structural-size specimens using the methods described in EN408 (CEN, 2003b), with characteristic values determined in accordance with EN384 (CEN, 1995).

Figure 2.18 The three principal axes of wood with respect to grain direction and growth ring orientation.



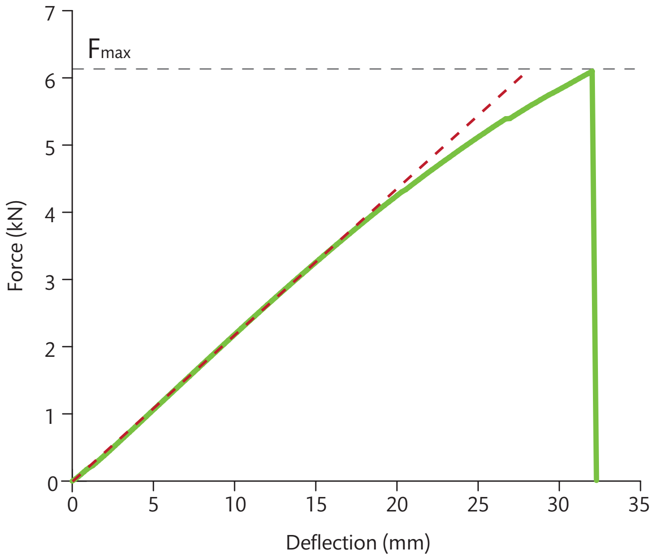
The main mechanical properties of Sitka spruce wood considered in this section are: (1) bending strength and modulus of elasticity, (2) compression strength, (3) shear strength and stiffness, (4) surface hardness, and (5) Impact bending and cleavage.

Bending strength and modulus of elasticity

Bending strength and modulus of elasticity are arguably the most important mechanical properties of wood as, along with density, they are used to directly assign structural timber to a strength class according to EN338 (CEN, 2003a) (See ‘Strength grading of structural timber’ Section on page 29). Both properties are determined from bending tests in which the applied stress (proportional to force) and the resulting strain (proportional to deflection) in the specimen are recorded. Bending strength reflects the maximum load-carrying capacity of a piece of timber in bending and, for a particular test set-up, is proportional to the maximum force (F_{max}) withstood by the specimen (Figure 2.19). The term ‘modulus of rupture’ is frequently used in North America in place of bending strength, but this is less common in Great Britain and other parts of Europe. The modulus of elasticity describes the amount of bending deformation for a particular load: it is the constant of proportionality between stress and strain over that region of the stress–strain curve where the two are linearly related (Figure 2.19). In this part of the curve (the linear-elastic region), the stresses are low enough that the resulting deformations are completely recoverable after the load is removed. The area under the stress–strain curve represents the work or energy required to deform the wood, and is a combined measure of the strength and toughness of wood under bending stresses.

Mean values of bending strength and modulus of elasticity for small defect-free specimens of Sitka spruce at 12% moisture content are approximately 60 N mm^{-2} and 8000 N mm^{-2},

Figure 2.19 Typical load-deflection relationship obtained from a bending test on Sitka spruce. The maximum force that the specimen could bear is indicated by F_{max}, while the slope in the linear-elastic region is indicated by the dashed red line.



respectively (Table 2.8). The mean value of modulus of elasticity obtained by McLean (2008) was slightly lower as his dataset contained a higher proportion of specimens taken from within the juvenile core of the trees. Values of modulus of elasticity obtained from tests on full-sized specimens are similar to those obtained from tests on the defect-free specimens, but mean values of bending strength are considerably lower. While values of mean bending strength are often presented, the characteristic bending strength is generally required by those designing timber structures. This value is based on the lower 5th percentile (i.e. the value for which the probability of getting a lower value is 5%) and is generally between 16 and 24 N mm^{-2} for Sitka spruce. At the individual specimen level, there is a moderate relationship between bending strength and modulus of elasticity (R^2 0.45–0.60), and this relationship is the basis for machine strength grading using bending-type machines and acoustic velocity/resonance (See 'Strength grading of structural timber' Section on page 29).

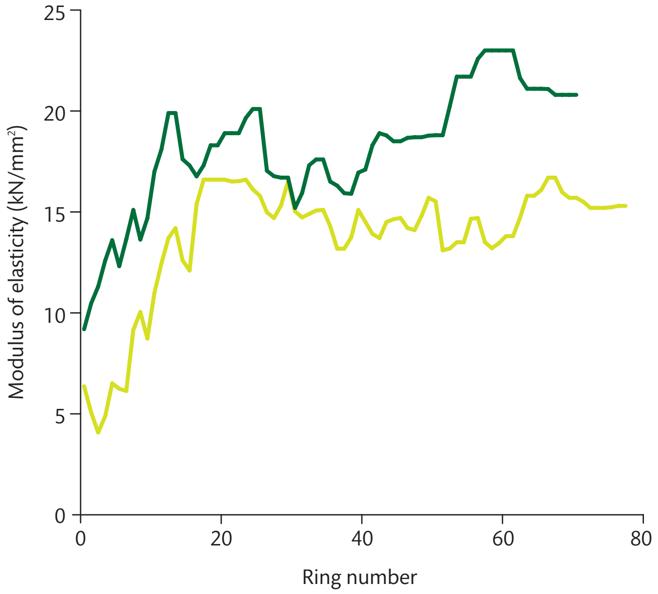
Both modulus of elasticity and bending strength vary considerably in the radial direction within a tree (McLean, 2008), and this pattern of variation is strongly linked to the radial profiles of microfibril angle. In Sitka spruce there is a strong negative relationship between microfibril angle and modulus of elasticity (Cowdrey and Preston, 1966; Treacy *et al*., 2000; McLean *et al*., 2010). Therefore, in the juvenile core, where microfibril angle is high, modulus of elasticity is low but increases with increasing ring number from the pith until it reaches a more or less constant value (Figure 2.20).

Table 2.8 Mechanical properties of wood from UK-grown Sitka spruce. Values presented are for wood at 12% moisture content.

Mechanical Property	Reference	Specimen type[1]	Value
Bending strength (N mm^{-2})	Brazier *et al.* (1976)	SC	61
	Lavers (1983)	SC	67
	McLean (2008)	SC	59
	Moore *et al.* (2009a)	FS	36
	Moore *et al.* (2009b)	FS	31
Modulus of elasticity (N mm^{-2})	Brazier *et al.* (1976)	SC	8400
	Lavers (1983)	SC	8100
	McLean (2008)	SC	6800
	Moore *et al.* (2009a)	FS	7900
	Moore *et al.* (2009b)	FS	7830
Work to maximum load (kJ m^{-3})	Lavers (1983)	SC	79
Work to total fracture (kJ m^{-3})	Lavers (1983)	SC	125
Impact bending (mm)	Lavers (1983)	SC	510
Compression strength parallel to grain (N mm^{-2})	Brazier *et al.* (1976)	SC	31.3
	Lavers (1983)	SC	36.1
Compression strength perpendicular to grain (N mm^{-2})	CTE (unpublished data)	FS	2.8
Side hardness (N)	Lavers (1983)	SC	2400
Shear strength parallel to grain (N mm^{-2})	Lavers (1983)	SC	8.7
	Khokhar *et al.* (2010)[2]	FS	7.2
Modulus of rigidity (N mm^{-2})	Khokhar *et al.* (2010)[2]	FS	520
Resistance to splitting in radial plane (N mm^{-1})	Lavers (1983)	SC	7.7
Resistance to splitting in tangential plane (N mm^{-1})	Lavers (1983)	SC	10.0

[1] SC = small clear specimen, FS = full-sized specimen containing defects.
[2] Shear properties measured using a torsion testing machine.

Figure 2.20 Example of the radial variation in modulus of elasticity for two specimens of Sitka spruce wood. Modulus of elasticity was estimated from data on density and microfibril angle obtained from SilviScan-3.



Compression strength

The compression strength of a piece of wood can be measured in the longitudinal direction (parallel to the grain) or in the radial and tangential directions (perpendicular to the grain). The maximum compressive strength parallel to the grain is a measure of the strength of wood when used as a stud or column. Average values of this property for Sitka spruce wood at 12% moisture content are approximately 36 N mm^{-2} (Table 2.8). Compression strength of Sitka spruce wood increases with increasing distance from the pith and is related to wood density (Bryan and Pearson, 1955). The strength of the relationship between density and compression strength increases with increasing distance from the pith, which is possibly due to greater variation in microfibril angle in those samples taken from close to the pith.

Compressive strength perpendicular to the grain has a number of different definitions as no clearly defined maximum load is recorded during testing. Generally, compressive strength perpendicular to the grain is calculated from either the applied load at the proportional limit (i.e. the upper limit of the linear elastic region) or the load required to generate a fixed amount of deformation. The European standard for determining the mechanical properties of structural timber (EN408 – CEN, 2003b) uses the second approach and the average value obtained for Sitka spruce is 2.8 N mm^{-2}. This is less than 10% of the value parallel to the grain.

Shear strength and stiffness

The modulus of rigidity of wood, also called shear modulus, indicates its resistance to deformation caused by shear stresses, while the shear strength indicates the maximum shear stress it can withstand. These properties are determined from tests in which the shear forces are applied in the longitudinal direction, that is, parallel to the grain (Bodig and Jayne, 1993). Information on shear properties is normally obtained by testing small defect-free wood blocks ('shear blocks'), but also can be obtained from full-scale bending tests and torsion tests conducted on larger specimens (Khokhar *et al.*, 2010). The shear strength for Sitka spruce wood is approximately 8 N mm^{-2}, with slightly higher values obtained from tests on small defect-free specimens than from torsion tests on full-size specimens containing defects (Table 2.8). The average modulus of rigidity is approximately 520 N mm^{-2} and is not related to the modulus of elasticity in bending (Khokhar *et al.*, 2010).

Surface hardness

Hardness is a measure of the resistance of wood to indentation. It is an important property for assessing the suitability of a species for uses such as flooring, furniture, and other uses where a good wearing surface is required (Bodig and Jayne, 1993). Hardness is generally defined as the resistance to indentation, and is determined through a Janka hardness test in which the force required to embed an 11.28-mm diameter steel ball to half its depth is measured. Tests are normally carried out on small defect-free specimens (Green, *et al.*, 2006). Values presented are the average of radial and tangential indentations, and have no direct design application; however, they do allow comparisons between different species. Sitka spruce wood has an average hardness of 2400 N at 12% moisture content (Table 2.8), which is 25–50% lower than the values obtained for Douglas fir, Scots pine and the three larch species grown in the UK (Lavers, 1983).

Impact bending and cleavage

Impact bending represents the ability of wood to absorb shocks that cause stresses beyond the proportional limit. In the impact bending test, a hammer of given weight is dropped upon a beam from successively greater heights until rupture occurs or the beam deflection exceeds a certain threshold. The height of the maximum drop, or the drop that causes failure, can be used as the basis for comparing species. For Sitka spruce, the maximum drop height is 510 mm (Table 2.8), which is less than the 600–700 mm obtained for Douglas fir, Scots pine and the three larch species grown in the UK (Lavers, 1983).

There are three principal modes of fracture for a material that are described by a combination of the direction of loading and crack propagation. Because of the orthotropic nature of wood the plane of the crack in relation to the symmetry planes must be specified in addition to the mode of crack propagation (Bodig and Jayne, 1993). As a result there are six combinations of material symmetry and crack direction for each failure mode. For solid wood, Mode 1 (the opening or cleavage mode) is the most important. Cleavage strength is generally measured in the tangential–longitudinal and radial–longitudinal planes and provides a measure of the resistance of wood to splitting, which is an important property for products such as firewood, fence rails and beams where splitting loads can occur (i.e. those in which notches have been cut). High resistance to splitting (low cleavability) is desirable in situations where wood must hold nails or screws (Record, 1914). Cleavage strength of wood is seldom measured now (Bodig and Jayne, 1993), but information on this property for Sitka spruce was presented by Lavers (1983). At 12% moisture content, Sitka spruce wood has a cleavage strength of 7.7 N mm^{-1} (the length dimension indicates the width of the specimen) in the radial plane and 10.0 N mm^{-1} in the tangential plane (Table 2.8).

Effects of site, silviculture and genetics on selected wood properties

The wood properties of a tree are a combination of its genetic make-up and the environment that it is grown in. There is therefore considerable scope to improve the wood properties of Sitka spruce through both tree breeding and forest management (Hubert and Lee, 2005). Because individual wood properties differ in the extent to which they are under environmental or genetic control (Rozenberg and Cahalan, 1997), the approach taken to improve these individual properties also differs. For example, tree breeding is typically used to improve those properties under strong genetic control, while site selection and silviculture are used to improve those properties that are under strong environmental control; however, the greatest improvement in wood properties is achieved when genetics, site selection and silviculture are combined appropriately. Much of the knowledge about the effects of these factors on Sitka spruce wood properties has been summarised in a number of comprehensive review papers (e.g. Brazier, 1977; Rozenberg and Cahalan, 1997; Lee, 1999; Macdonald and Hubert, 2002; Hubert and Lee, 2005). In addition to the more general information presented in these reviews, recent studies have yielded specific quantitative information on the effects of different factors on the wood properties of Sitka spruce (e.g. Achim *et al*., 2006; Moore *et al*., 2009a, b, c; Macdonald *et al*., 2010). This knowledge is being used to develop models (e.g. Gardiner *et al*., 2005) that are able to predict the wood properties of Sitka spruce and how these are affected by tree growth and forest management.

Forest location

Much of the previous work in this area has focused on the relationship between site factors and tree growth (e.g. Blyth and MacLeod, 1981; Worrell and Malcolm, 1990a, b). Soil type and soil nutrient levels are strongly associated with tree growth (Blyth and MacLeod, 1981), while Worrell and Malcolm (1990a, b) found that yield class declined with increasing elevation and was associated with indices of temperature and windiness. Trees growing at higher elevation sites and with increased wind exposure also tend to have poorer form (Forest Research, unpublished data). This is probably due to higher levels of leader loss and meristem desiccation in more wind exposed locations (Grace, 1989; Baldwin, 1993). Poor stem form not only reduces the yield of sawlog material that can be obtained from a stand but is also associated with a higher incidence of compression wood and a higher grain angle (Spicer *et al*., 2000).

While it is known that the environment is likely to have a considerable effect on the wood density of Sitka spruce, few studies have actually quantified the inter-site variation in wood density. Bryan and Pearson (1955) found that wood density declined by approximately 10 kg m^{-3} for every one degree increase in latitude, with the lowest values of wood density found in the north of Scotland. Their conclusion was based on data from six sites. A more comprehensive study was undertaken by Jeffers and Dowden (1964). Based on a recent analysis of their data, it was found that latitude alone accounted for approximately 22% of the variation in wood density, with a decrease in density of 6 kg m^{-3} for every one degree increase in latitude (Figure 2.21). Interestingly, there is a stronger relationship between wood density and longitude ($R^2 = 0.34$), with sites in the east having higher density than those in the west.

As the wood samples collected from across Great Britain as part of the Sitka spruce benchmarking study (Moore *et al.*, 2009b) are processed and the data analysed, a more complete picture should emerge of the effects of environmental factors on wood density. Preliminary results indicate that average density decreases by approximately 6 kg m^{-3} for every 100 m increase in elevation (Vihermaa, 2010). Elevation also has an effect on the modulus of elasticity of wood, with trees growing at higher elevations having lower modulus of elasticity than those growing at lower elevations

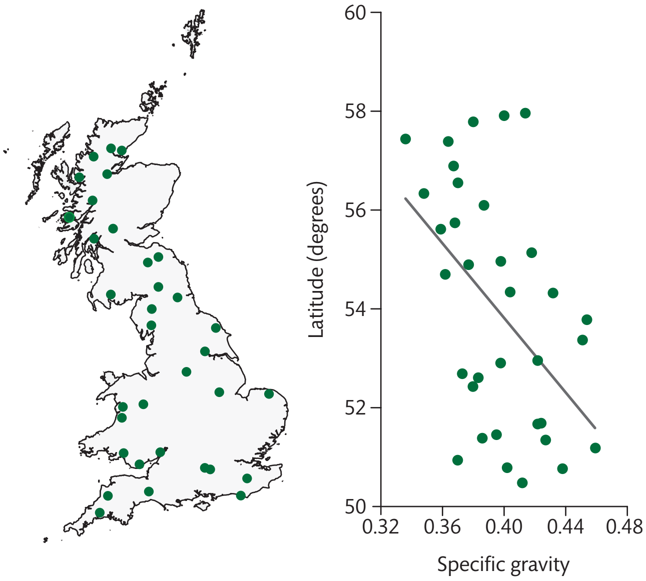


Figure 2.21 Location of sites where density measurements were made by Jeffers and Dowden (1964) (left) and the relationship between specific gravity and latitude (right).

(Moore *et al*., 2009b). Results from this study also indicate that there is a small decrease in modulus of elasticity with increasing latitude.

Choice of genetic material

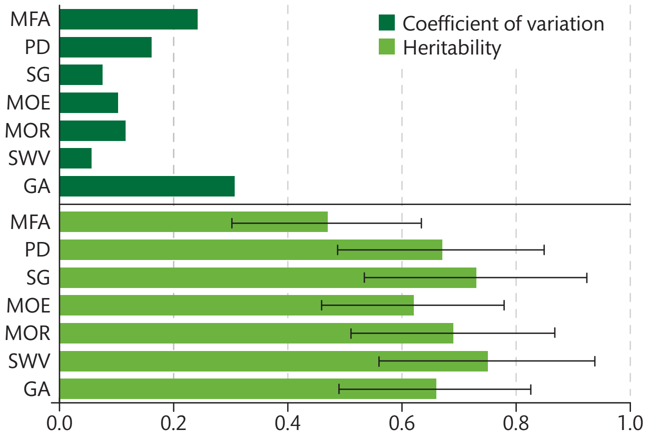
The original Sitka spruce trees grown in Great Britain were from unimproved seed collected from different parts of the Pacific Northwest of North America. The early focus of tree genetics research was evaluating the performance in British conditions of trees grown from different seed origins (Lines, 1987). This showed that, while growth rates were higher in the more southerly seed origins, the risk of forest damage was higher. Therefore, most of the Sitka spruce grown in Great Britain originates from the Queen Charlotte Islands (QCI), Canada, although Washington origin material is planted on sites where the risk of frost damage is lower. Comparison of material produced from Washington and QCI origin stands revealed few differences in the quantity and quality of sawn timber produced (Lee *et al*., 1999), while Treacy *et al*. (2000) found some small differences in microfibril angle, density and strength properties of wood from QCI, Washington, Oregon and California origin stands.

A selective breeding programme for Sitka spruce was established in Great Britain in 1963 with its main objective 'to develop breeding populations well adapted to a range of site-types, with improved stem form and growth potential and wood qualities satisfactory for the sawn timber market' (Fletcher and Faulkner, 1972). Approximately 1800 'plus trees', which had a combination of superior height, diameter, stem straightness, branching quality and low external grain angle, were selected during the first 20 years of the breeding programme. Progeny testing has been subsequently used to determine the relative genetic value of these selections and the heritability of the various traits, as well as the genetic correlations between traits (Lee, 1999). Gains in volume production of 20% relative to the QCI material have been achieved (Lee and Matthews, 2004). However, a strong negative correlation exists between growth rate and wood density in Sitka spruce (Lee, 1999), which means that the most vigorous progenies have, on average, lower wood density. Trees from the fast-growing progenies also have significantly larger branches, less latewood, more compression wood and a greater proportion of juvenile wood for a given diameter in comparison with unimproved QCI stock and slower-growing progenies (Livingston *et al*., 2004; Cameron *et al*., 2005).

While wood density is correlated with a number of mechanical properties, these properties are also affected by knot size. Maun (1992) found that by selecting trees with lighter branching, the reduction in knot size meant that the same proportion of timber suitable for construction purposes could be produced even if wood density decreased by up to 10%. A recent study comparing bending strength and modulus of elasticity of Sitka spruce structural timber from different improved families and an unimproved QCI seedlot did not find any significant differences (Moore *et al*., 2009c). This indicates that gains in merchantable volume that have been achieved due to tree breeding appear to have been achieved with no reduction in the mechanical properties of the timber.

To date, tree breeding has focused on selecting trees with improved growth rate, stem form and branching characteristics while ensuring that these gains are achieved without a substantial decrease in wood density. However, many of the properties that affect the performance of wood in service are under moderate to strong genetic control and, therefore, it should be possible to breed trees with improved wood properties. For this to be successful, there must be variation in the trait of interest and this trait must be at least moderately heritable. The variation and heritability of a number of wood properties (and indirect measures of them) were assessed in a progeny trial by Kennedy (2009). For the wood properties studied (density, microfibril angle, grain angle, modulus of elasticity and bending strength), approximately 20% of the total phenotypic variation observed was due to genetic variation; the remaining 80% was due to environmental variation. The coefficient of variation for the component of genetic variation that can be passed on to successive generations was between 10 and 30% for the properties examined, while the heritability ranged from 0.5 up to 0.75 (Figure 2.22). In addition, the two indirect methods for assessing wood properties in standing trees, that is, pilodyn (wood density assessment) and portable acoustic tools (modulus of elasticity assessment), offer a rapid way to screen trees in a breeding programme. Overall, Kennedy (2009) found that despite the unfavourable correlation between growth rate and some key wood quality traits associated with timber strength, selection of certain families would enable modest gains to be made in both growth rate and wood quality.

Figure 2.22 Coefficient of variation and heritability for selected Sitka spruce wood properties. MFA = microfibril angle, PD = pilodyn penetration, SG = specific gravity, MOE = modulus of elasticity in bending, MOR = bending strength, SWV = stress wave velocity and GA = grain angle (after Kennedy, 2009).



Initial spacing

Over the past 80 years there have been considerable changes to the silvicultural management of Sitka spruce stands in the UK. In the first substantial period of afforestation that occurred between 1920 and 1940, stands were established at an initial spacing of between 1.0 and 1.5 m. During the period between 1960 and 1980, initial planting spacing had increased to 2.4 m (and in some cases up to 2.7 m) in order to reduce establishment costs and because of the risk of wind damage following thinning (Wardle, 1967). Wider initial spacing generally results in increased branch size, a deeper living crown, greater stem taper and fewer trees to select from for the final crop (Brazier, 1977; Macdonald and Hubert, 2002). Because there is a negative relationship between growth rate and wood density in Sitka spruce (Brazier, 1970), increased growth resulting from wider initial spacing would be expected to lead to a reduction in wood density. More rapid initial growth also increases the size of the juvenile wood zone, which in turn can have detrimental effects on mechanical wood properties.

The effect of initial spacing on the mechanical properties of Sitka spruce grown in Great Britain was studied by Brazier *et al*. (1985) and Brazier and Mobbs (1993) who found that the modulus of elasticity of timber (the mean minimum reaction force as measured by a machine strength grader) decreased with increasing initial spacing. Based on this result, Brazier and Mobbs (1993) recommended that the maximum initial planting spacing for British-grown Sitka spruce should not exceed 2 x 2 m (2500 trees per hectare) if commercially acceptable yields of structural quality timber were to be obtained. This recommendation on initial planting spacing for Sitka spruce still holds today.

Re-spacing and thinning

In addition to the choice of initial planting spacing, the growing space available to each tree within a stand can be controlled through thinning. The aim of thinning is normally to concentrate the growth on a smaller number of trees, so that the target tree size is reached in a shorter period of time, and to improve log quality by removing those trees with poor form. The effect of thinning on wood properties will depend on when in the rotation it is carried out and its intensity (i.e. the number of trees that are removed). Because of the risk of wind damage coupled with the low value obtained for the thinned trees, thinning of older stands of Sitka spruce is becoming less common, particularly on exposed upland sites (Rollinson, 1988; Cameron, 2002), although this may change with the increasing demand for biomass energy. This reduces the radial growth rate, resulting in a large number of small diameter trees, which in turn results in a smaller proportion of the total standing volume achieving the minimum size requirements for sawlogs (See 'Sawn timber' section on page 28). Few, if any, studies have examined the effects of thinning later in the life of a stand on the wood properties of Sitka spruce. Therefore, the effects of later thinning on the wood properties of Sitka spruce are largely unknown. However, it is thought that while the reduced rate of radial growth following canopy closure may result in an increase in wood density, it also means that there is a smaller amount of mature wood produced. Therefore, a tree growing in a stand which has been regularly thinned will have a smaller proportion of juvenile wood than a tree of the same age from an unthinned stand (Brazier and Mobbs, 1993).

Thinning carried out prior to canopy closure is generally referred to as re-spacing in Britain and has been proposed as a means of increasing mean tree size and improving stand stability on more wind exposed sites. Increasing re-spacing intensity leads to a reduction in total volume yield, and an increase in both mean tree size and branch size in Sitka spruce (Kilpatrick *et al*., 1981; Rollinson, 1988; Deans and Milne, 1999). The effects of re-spacing on wood properties of Sitka spruce are similar to those observed for initial spacing. Wider re-spacing results in trees with wood of lower density, larger knots and poorer mechanical properties (Savill and Sandels, 1983; Moore *et al*., 2009a). Results from the Baronscourt experiment in Northern Ireland showed that the proportion of structural quality timber decreased with increasing re-spacing intensity (Moore *et al*., 2009a).

Fertiliser application

Sitka spruce grows across a wide range of soil types within Great Britain, which vary widely in their fertility. On sites with low natural fertility, remedial fertiliser treatments can be used to increase growth rates at different stages in the rotation. For example, on the most infertile deep peat sites in Dumfries and Galloway a total of up to 1725 kg ha^{-1} of P and K and 350 kg ha^{-1} of N have in the past been applied in the first 12 years after tree establishment (Davies, 1982). Such applications of fertiliser have resulted in considerable increases in volume production (McIntosh, 1978, 1981). The effect of fertiliser treatments of wood properties depends on the age of the stand when the treatments were applied and the growth conditions prior to treatment (Brazier, 1977). Brazier (1977) considered that the application of fertiliser at time of planting does not have a significance effect on the overall wood properties of a tree as the fertiliser response only lasts for approximately five years and, therefore, the volume of wood affected is low. The effect of fertiliser application during the first 10–15 years of growth can have significant effects on wood properties, mainly through increasing the size of the juvenile core. At later stages in the rotation, the application of fertiliser can lead to a reduction in wood density, particularly when there is a dramatic increase in growth rate. However, for Sitka spruce that was fertilised with nitrogen, potassium and phosphorus when the trees were 20–25 years, Macdonald (1990) found that there was no effect on basic density and tracheid length other than that attributable to increased vigour.

Rotation length

Because of the increase in Sitka spruce growth rates that have been achieved through tree breeding and silviculture, trees are able to reach a merchantable size at younger ages and therefore rotation lengths are generally declining. From an economic perspective, shorter rotations are normally more attractive as they enable a financial return on the investment in tree stocks and silviculture to be realised sooner. In Great Britain, the risk of wind damage on exposed sites provides an additional reason for shortening rotations, as the vulnerability of a stand increases with increasing tree height. Nowadays, Sitka spruce is typically grown on 35–45 year rotations, but rotation lengths of 25 years have been proposed (Moore and Wilson, 1970).

The choice of rotation length affects the physical and mechanical properties of wood produced from planted forests through its influence on the relative proportions of juvenile and mature wood within tree stems. As rotation length decreases the proportion of juvenile wood in a tree increases (Figure 2.23), and this wood has lower density, bending strength and modulus of elasticity than wood that is located further from the pith. Data from small defect-free specimens taken from 83-year-old Sitka spruce from Kielder Forest showed that there was a 33% increase in bending strength from the centre of the tree (position 1) to the outside (position 6) and a 49% increase in modulus of elasticity (Table 2.9). Therefore, the overall strength and modulus of elasticity of timber cut from trees will decrease as rotation age decreases as there will be proportionally less mature wood which has higher strength and modulus of elasticity.

Figure 2.23 Effect of rotation length on the proportion of juvenile wood by cross-sectional area in the butt log of a Sitka spruce tree. The extent of juvenile wood is assumed to be limited to the first 12 growth rings from the pith.

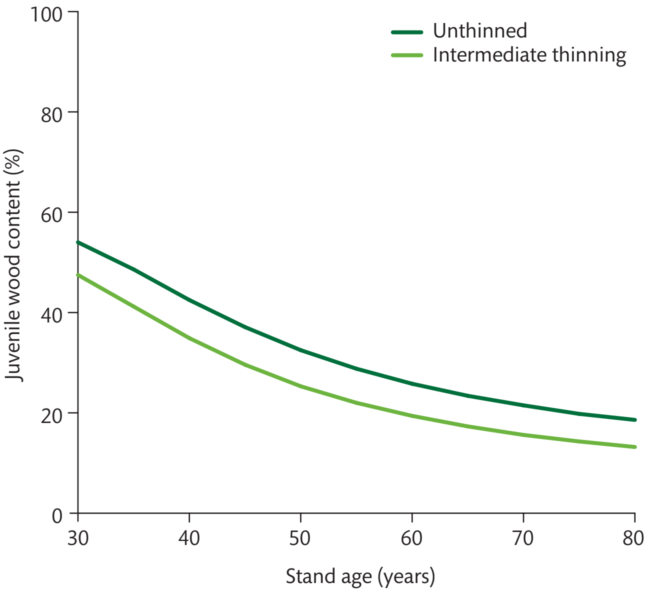


Table 2.9 Mean values of bending strength (MOR), basic density and modulus of elasticity (MOE) of small clear specimens cut from different radial positions within 83-year-old Sitka spruce trees.

Property	Radial Position					
	1	2	3	4	5	6
Ring number	<5	5–15	16–30	31–45	46–60	>60
MOR (N mm^{-2})	57.4	57.2	64.9	63.7	71.0	76.3
MOE (kN mm^{-2})	6.43	7.50	8.56	8.34	8.97	9.53
Density (kg m^{-3})	404	352	375	362	395	421

Pruning

Pruning is arguably the most obvious silvicultural practice that can directly improve wood properties by limiting the size and extent of knots in timber. The removal of live branches from the lower part of the stem restricts the occurrence of knots to a central core in the stem and also ensures that loose knots are not formed as a result of natural branch mortality. There may also be a small increase in wood density if pruning results in a reduction in tree vigour (Brazier, 1977). A series of experiments were established in the 1930s to study the impact of pruning on conifer species, including Sitka spruce, growing in Great Britain (Henman, 1963). These experiments highlighted the importance of early pruning to limit the size of the knotty core, only selecting a limited number of the most vigorous trees to prune and favouring these trees by selective thinning.

The decision to prune is based on economic reasons, which are to increase the value of the stand by targeting those products that either require knot-free wood or which pay a premium for such wood. While pruning is a key component of the silviculture of radiata pine (*Pinus radiata* D. Don) in New Zealand (Cown, 1999), it is seldom applied to Sitka spruce growing in Great Britain as it is generally considered that premiums paid for pruned logs are insufficient to cover the future compounded cost of the pruning operation.

3. Suitability for different products

Introduction

As the area of Sitka spruce plantations in Great Britain has increased substantially over the past 70 years, so too have the scale and diversity of the wood processing industries that utilise this resource (Smith, 1927; Watt, 1957; Banks and Cooper, 1997). The wood properties of Sitka spruce mean that it is suitable for a wide range of products including structural timber, pallets, fencing, structural poles, panel products and paper. Currently, harvest levels of Sitka spruce timber in Great Britain are approximately 5 million cubic metres per annum, of which nearly two-thirds is sent to sawmills with a further 15% sent to wood panel producers.

In this section, an overview of the properties and performance of different end-products that can be produced from Sitka spruce is given. Because of its relative size and value, this section will focus primarily on the sawn timber market, although the suitability of Sitka spruce for other current and future products is discussed.

Roundwood

Historically, the main use for Sitka spruce roundwood was pit props for the mining industry. Much of the early research into the mechanical properties of British timber species was focussed on pit props (e.g. Armstrong, 1947), where compression strength parallel to the grain was the main property of interest. With the decline in deep-pit coal mining in Great Britain in the 1970s and 1980s, there is now little if any demand for timber pit props and, therefore, the main uses for Sitka spruce roundwood in the future are likely to be fencing, structural poles (this includes supports for electricity transmission lines), log homes, and, potentially, for piled foundations.

Structural poles

The term pole generally refers to machine debarked timber of round cross-section which retains the natural taper of the original tree. Poles can also be machine rounded (sometimes referred to as 'shaved'), whereby the nodal swellings are removed. Historically, the main use for structural poles in Britain was as supports for overhead transmission lines. The requirements for this end use are given in BS1990-1 (BSI, 1984). (Note: this standard will be superseded by the European standard EN14229 (CEN, 2008), which is currently in draft form). Preferred pole lengths range from 6 m up to 24 m, and the minimum and maximum diameters for a given length and type of pole (i.e. light, medium or stout) are given in BS1990-1. Apart from size, the main requirements for wood poles for overhead line support are straightness, bending strength and durability. An average service life of 40 years is expected from wood poles, and because transmission line poles are in ground contact (i.e. use class 4), preservative treatment is required.

Traditionally, transmission poles were produced from Scots pine imported from Scandinavia. Because of the increase in supply of Sitka spruce trees of a suitable size, a considerable amount of research was undertaken in the 1980s to determine the suitability of Sitka spruce poles for this use (Anon, 1983; Fowlie and Sheard, 1983). Tests on sections of poles from different species showed that the bending strength of Sitka spruce poles was on average 18% lower than that of Scots pine, which means that either the design loads must be reduced or the pole diameter increased. Fulfilling the service life requirements presents a greater challenge for the use of Sitka spruce, as preservative treatment is more difficult. High pressure sap-displacement using chromated copper arsenate (CCA) was investigated as a treatment option to provide the necessary durability (Bruce *et al*., 1991; Evans *et al*., 1991). Results showed that this treatment was inadequate for Sitka spruce due to checks which penetrated the preservative treated annulus allowing decay organisms access to the untreated non-durable wood in the centre of the pole. In addition, the supply of CCA preservative was banned in the European Union in 2006 and, therefore, future use of Sitka spruce for transmission poles is dependent on the development of a non-CCA preservative treatment process that can provide the necessary service life.

Round timbers can also be used as structural elements in buildings, particularly rural buildings that are based on post and beam or portal frame structural forms (Thepaut and Hislop, 2004). They can also be used in other structural forms such as space-frames, towers, domes, bridges, and pre-stressed pole structures (e.g. light pre-stressed arches and bent poles). Untreated Sitka spruce poles are best suited to those applications where the risk of fungal decay is low, that is, in above-ground contact where the timber moisture content is below 20%. Where timber is partially or fully exposed to the weather, preservative treatment will be necessary.

Piles

A potential future use for Sitka spruce poles is timber piling. Untreated Norway spruce timber piles are widely used in the Netherlands, where the geology consists of a 10–15 m layer of soft clay and peat overlying sand, and a high water table. There is the potential to use untreated Sitka spruce timber piles in those areas of Great Britain that have similar geology, such as estuarine areas (Reynolds and Bates, 2009). For this use, straight stems with small knots are required. Preliminary trials have demonstrated that Sitka spruce can withstand the forces necessary to drive the pile into the ground (Reynolds and Bates, 2009). Timber piles driven below the waterline can have a very long service life, and will often perform better than concrete in conditions of high acidity or alkalinity; however, data on the long-term performance of untreated Sitka spruce piles in service are currently not available, which is limiting their use in Great Britain.

Sawn timber

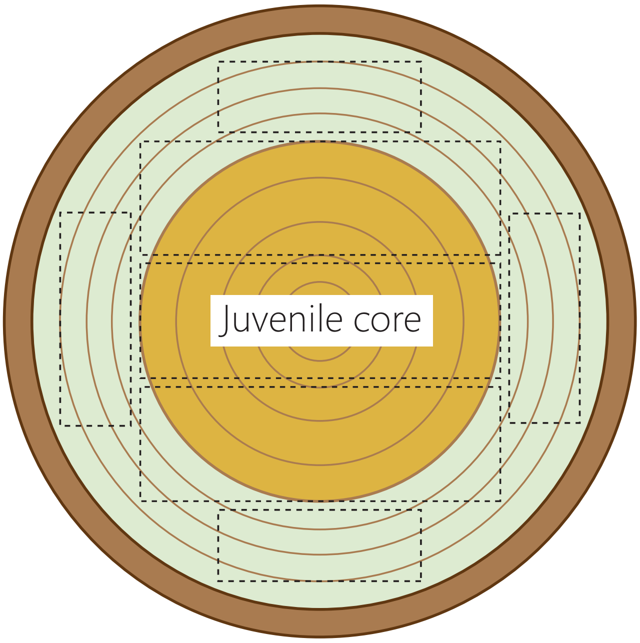
In Britain, Sitka spruce sawlogs are graded on the basis of diameter, length, straightness and branch size. The Forestry Commission classifies sawlogs into two grades: green and red (Forestry Commission, 1993). To be classified as green, sawlogs must have a minimum top (small-end) diameter of 160 mm, maximum sweep of 10 mm per metre of length, and 80% of the branches in any one whorl must have a diameter less than 50 mm (Table 3.1). Private companies have their own log grade definitions and sawmills often accept logs to a 'millable' specification, which can be verified using modern log scanners. Sawlogs are processed into three main products: structural timber, pallet and packaging timber, and fencing components.

Table 3.1 Specifications for green and red sawlogs (after Forestry Commission, 1993).

Characteristic	Requirement for each log grade	
	Green	Red
Top diameter	160 mm	140 mm
Sweep (maximum deviation in one plane per m length)	10 mm per m	15 mm per m
Branch size	80% of branches in a whorl less than 50 mm in diameter	No numerical limit, but logs must not be excessively rough

Appearance grade timber for joinery or furniture manufacture is rarely cut from British-grown Sitka spruce trees, although a small number of research trials have investigated the possibility of using Sitka spruce timber in joinery applications (e.g. window frames). Structural timber is normally cut from the centre of the highest grade sawlogs, while timber for fencing, pallets and packaging is cut from the outside of these logs or from lower quality sawlogs (Figure 3.1). Of these products, structural timber has the most demanding requirements in terms of wood properties, but also has the highest value. Typically, the volume of sawn timber produced from a log is between 50 and 60% of the volume of the original log. The remaining volume of the log is converted into wood chips and sawdust during the sawing process, and collectively these are referred to as co-products. These co-products are used to produce other products such as panel boards, paper and paperboard, and biomass energy.

Figure 3.1 Typical cutting pattern used for Sitka spruce logs in Great Britain. Larger dimension structural timber is cut from the centre of the log, which contains the juvenile wood, while smaller dimension sideboards are cut from the outside of the log.



Structural timber

Structural timber is primarily used in construction applications where strength and stiffness are important properties. Wood density is also important as it affects the performance of timber connections, while knot size and frequency, and absence of distortion are important particularly where the timber is used in light timber-frame construction. Sitka spruce structural timber is typically produced with thicknesses of 47 or 75 mm and widths ranging from 75 mm up to 250 mm (Table 3.2); the full range of target sizes is listed in EN336 (CEN, 2003c). It has recently become common practice for structural timber to be planed on all four sides and in some cases to have the sharp edges (arrises) rounded off. This typically reduces the cross-sectional dimensions by 2–5 mm in each direction. Timber with rounded edges is generally referred to as 'eased edge'. Sitka spruce structural timber is normally available in standard lengths of 2.4, 3.0, 3.6, 4.2 and 4.8 m, while lengths of 5.4 and 6.0 m or even longer are sometimes available. In addition, 'odd' lengths of 2.7, 3.3, 3.9, 4.5 and 5.1 m are available from a few suppliers.

Table 3.2 Common section sizes for Sitka spruce structural timber produced in Great Britain.

Thickness (mm)	Width (mm)							
	75 (72)	100 (97)	125 (120)	150 (145)	175 (170)	200 (195)	225 (220)	250 (245)
47 (44)	✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓
75 (72)	✓	✓✓	✓	✓✓	✓✓	✓✓	✓✓	✓

Note: Values in parenthesis are the dimensions of timber that has been machined on all four sides.
✓ - less common sizes produced by fewer mills or produced less often
✓✓ - common sizes routinely produced by most sawmills

Strength grading of structural timber

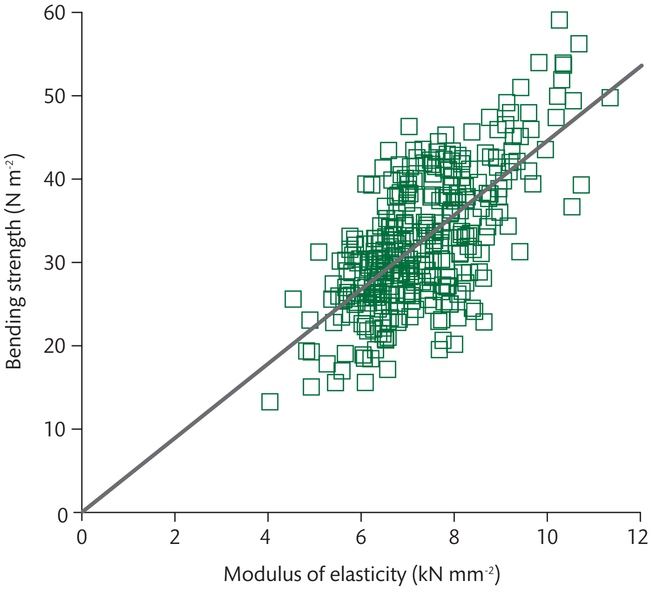
Pieces of timber with similar mechanical properties are grouped together in strength classes, which are characterised by a set of properties for engineering design. This permits an engineer to specify a chosen strength class and use the characteristic strength values of that class in design calculations. A common set of strength classes are used throughout Europe and the characteristic values for density, strength and stiffness for these strength classes are given in EN338 (CEN, 2003a). The classes are named for the characteristic value of bending strength, and for softwoods range from C14 up to C50. Characteristic values of bending strength, stiffness and density for strength classes C14 to C24 are presented in Table 3.3.

The process of sorting timber into grades to which characteristic values of strength, stiffness and density can be allocated is referred to as strength grading. This can either be done by means of visual inspection (visual strength grading) or by a machine sensing one or more properties of the timber (machine strength grading), and the general requirements for strength grading of timber in Europe are contained in EN14081-1 (CEN, 2005a). Machine strength grading is generally the norm in British sawmills producing structural timber, due to the higher throughput and improved yields that can be achieved (Benham *et al.*, 2003). With machine strength grading, the grading machine measures one or more properties of the timber that are related to the bending strength (these are referred to as 'indicating properties'). Modulus of elasticity and density are frequently chosen as the indicating property owing to their degree of correlation with bending strength (Figure 3.2). Machine strength grading also requires a visual override inspection to remove those pieces of timber containing strength-reducing defects or other undesirable properties (e.g. excessive distortion or wane) that are not automatically sensed by the grading machine.

Table 3.3 Characteristic values of selected mechanical properties for strength classes C14-C24 (from EN338). Values for bending strength and density refer to the lower 5th percentile, while values for modulus of elasticity refer to the mean.

Property	Characteristic property values for each strength class					
	C14	C16	C18	C20	C22	C24
Bending strength (N mm^{-2})	14	16	18	20	22	24
Modulus of elasticity (kN mm^{-2})	7	8	9	9.5	10	11
Density (kg m^{-3})	290	310	320	330	340	350

Figure 3.2 Relationship between bending strength and modulus of elasticity for Sitka spruce structural timber.



The first grading machines to be used in Great Britain bent pieces of timber about their minor axis and measured the reaction force generated for a fixed deflection or the amount of deflection produced from a fixed force. In both cases the quantity measured is directly proportional to the modulus of elasticity of the timber. A number of new machines have been developed in recent years based on different technologies including: prediction of strength from measurements of wood density and knot characteristics made using X-rays; and the determination of dynamic modulus of elasticity from measurements of stress wave velocity. From the relationship between the indicating property and bending strength, a minimum value or values of the indicating property is determined for the grade or grade combination of interest. The process by which these settings are developed is described in more detail in EN14081-2 (CEN, 2005b) and the settings used by different machines for different species and grade combinations are listed in EN14081-4 (CEN, 2009a). British Sitka spruce timber is almost always graded using a C16/reject setting and yields in excess of 90% are normally achieved. While a combined C24/C16/reject setting is available for a number of grading machines, it is rarely used as the overall reject rate is too high resulting in a reduction in financial return to the sawmiller. This is a consequence of needing to maintain the characteristic values for the C16 graded timber following assignment of the higher strength and stiffness material to the C24 grade.

Visual grading is now a relatively uncommon practice in sawmills producing structural timber from Sitka spruce, although it is sometimes used for pieces of timber that are outside the size range covered by grading machines. In Great Britain, the method for visual strength grading of timber is described in BS4978 (BSI, 1996). Following this method, timber can be placed into one of two grades, General Structural (GS) or Special Structural (SS), based on permissible limits of visual characteristics. These characteristics include knots, slope of grain, rate of growth (ring width), fissures, wane, distortion, resin pockets and insect damage. The proportion of the cross-section occupied by knots and the location of these knots affect the strength of a piece of timber and therefore these are one of the main criteria in visual grading. Timber meeting the requirements for these visual grades is then assigned to a strength class using the tables presented in EN1912 (CEN, 1998); these tables are based on the results of mechanical tests on samples of visually graded timber from different species and country of origin. For Sitka spruce grown in Great Britain, timber in the GS grade is assigned to the C14 strength class, while timber in the SS grade is assigned to the C18 strength class.

Pallet and packaging timber

Timber used for the top and bottom decks of pallets is produced with thicknesses ranging from 16 mm up to 22 mm and widths ranging from 75 mm up to 150 mm, while the blocks separating the decks of four-way entry pallets are typically 75 x 75 mm up to 100 x 100 mm in size (CEN, 1999a), and the bearers separating the desk of two-way entry pallets are typically 75 mm up to 100 mm high. Timber used for pallets does not normally require the same level of mechanical performance as structural timber, but the pallets must still be capable of withstanding the loads placed upon them. The thicker deck boards are used when heavier loads are required, but the timber itself must have sufficient bending strength. Ease of nailing, resistance to splitting upon nailing and nail holding ability are also important characteristics for timber used in pallet manufacture, although these are affected by both the method of nailing and the type of nail used as well as by wood properties. The main requirements for timber used in pallet manufacture are described in more detail in ISO/TR 11444 (ISO, 1995) and a system for sorting timber into quality classes based on visual assessment is presented in EN12246 (CEN, 1999b). For good pallet performance, features that reduce timber strength, such as excessively large knots and slope of grain, should be avoided. Pallet and packaging timber is not normally preservative treated, but is frequently heat-treated in order to comply with the international phytosanitary requirement IPSM 15 (FAO, 2009); heat treatment is required if the pallets or packaging material are going to be used to move goods outside the European Union.

Sitka spruce timber is suitable for the manufacture of pallets as it is easy to nail, has good resistance to splitting and has satisfactory nail holding ability (Harding, 1988). It also has relatively small, sound knots. While it has lower bending strength and wood density than other British timber species used for pallet production, it is well suited to the production of lightweight pallets.

Fencing

Sitka spruce is used to produce a range of components for agricultural and domestic fencing, including posts, rails and boards. Timber posts can be either of round or rectangular cross-section and for the latter typical cross-sectional dimensions range between 75 x 75 mm and 100 x 100 mm. Typical cross-sections for rails range from 38 x 75 mm up to 47 x 100 mm, and for boards they range from 22 x 75 mm up to 22 x 150 mm. There are a number of quality requirements for fencing timber components given in BS1722-7 (BSI, 2006), but the main requirement is durability. Under normal service conditions the life expectancy of timber components in fencing is 15 years. As Sitka spruce is a non-durable species, preservative treatment is required to achieve the required service life in use classes 3 and 4 (See ‘Preservation’ Section on page 31).

External cladding

The use of timber cladding is becoming increasingly popular in Great Britain. Most timber used as external cladding on buildings is imported Siberian larch (*Larix sibirica* (Munchh.) Ledeb.), but British-grown larch is increasingly being used. Larch is generally preferred for cladding due to the natural durability of its heartwood, but less durable species such as Norway spruce are commonly used as external cladding in Scandinavian countries where the climate is broadly similar to that of Great Britain. Therefore, there is the possibility that Sitka spruce timber could be used for external cladding. A considerable amount of research has already been carried out to investigate the potential for using Sitka spruce for cladding, and on-going field trials are being used to demonstrate and monitor the performance of Sitka spruce cladding (Jones and Suttie, 2006).

Drying

Traditionally, most Sitka spruce timber was air-dried but the drying rate was relatively slow and this required that large stocks of timber be held in the sawmill to allow the material sufficient time to dry. Nowadays, almost all strength graded timber is kiln-dried as this allows more rapid drying as well as more control over the drying process. Kilns are also used to heat treat timber for use in pallets and packaging in order to comply with the international phytosanitary requirement IPSM 15 (See 'Pallet and packaging timber' section on page 30) as well as to pre-dry timber down to 30% moisture content prior to preservative treatment.

The rate of drying in a kiln is controlled by the relative humidity and temperature of the air, and the airflow across the timber surfaces. This drying rate is selected to ensure that water is evaporated from the timber surface slightly faster than it can be replenished. If the drying rate is too rapid, the resulting drying stresses may cause checking of the timber. The rate at which water evaporated from the surface of the timber is replenished depends on the permeability of the timber – as already noted in the section entitled 'Permeability' on page 16, Sitka spruce has relatively low permeability compared with other softwoods due to the high level of pit aspiration that occurs as the timber dries.

Conventional kiln schedules are based upon the slowest-to-dry timber, but must also ensure that the range of final moisture content values is within a specified tolerance (often 2–3%). A typical drying schedule for Sitka spruce timber is given in Table 3.4. Following the final drying step in the schedule, equalising and conditioning phases are carried out to reduce the variability in moisture content between boards as well as reducing the moisture content gradients within the boards themselves. The target moisture content for kiln-dried Sitka spruce timber is typically 18%, which requires between 90 and 130 hours of drying for 47-mm-thick timber and 200 hours for 75-mm-thick timber. Drying times can be reduced to approximately 60 hours through using high temperature drying (i.e. drying with a dry-bulb temperature above 100°C), although it can be difficult to achieve a uniform moisture content, the mechanical strength of the timber can be slightly reduced and distortion can be greater unless the timber is restrained to prevent movement (Cooper, 2006).

Table 3.4 Typical kiln schedule for Sitka spruce timber (after Maun and Coday, 1997).

Moisture content of wettest timber in stack	Dry-bulb temperature (°C)	Wet-bulb temperature (°C)	Approximate relative humidity (%)
Green	60	53	70
50	60	50.5	60
40	60	47.5	50
30	65	48.5	40
20	75	52	30

Preservation

The need for wood preservation and the type of preservative used depends on a number of factors including: the environment in which the timber is placed, the service life required and the ability of the species to be preservative treated (see EN335-2 (CEN, 2006b)). Sitka spruce wood is classified as non-durable to slightly durable (See 'Natural durability' section on page 15) and therefore preservative treatment is necessary if it is going to be used in ground contact. Preservative treatment is also advised in those above-ground uses where wetting is likely to occur. However, Sitka spruce, generally, is classified in EN350-2 (CEN, 1994b) as being difficult to treat with preservatives. Complete penetration of preservative is difficult to achieve with conventional pressure treatment; instead a shell of treated wood is created that surrounds a core of untreated wood. This is sufficient to protect the timber in above-ground situations, provided that the integrity of this treated shell is maintained, but is not usually sufficient to protect timber in ground contact. It is possible to increase the penetration of preservative by incising the timber using toothed rollers. Trials have shown that with the appropriate choice of preservative, sufficient protection can be achieved for the timber to be used in ground contact (Suttie, 2005).

Sitka spruce structural timber can be treated with boron to provide protection against mould fungi and decay fungi that may occur due to occasional wetting of the timber. The most common form of boron treatment is disodium octaborate tetrahydrate (DOT), which in combination with partial drying is able to penetrate refractory species such as Sitka spruce. Because boron is not fixed in the wood, it can be readily leached out if the timber comes in contact with liquid water. Therefore, when Sitka spruce timber is used in environments where it will come into contact with water and where there is a higher decay risk, it needs to be treated with a preservative that has sufficient toxicity to decay fungi and low leach resistance.

Chromated copper arsenate (CCA) was, until recently, the most commonly used wood preservative for timber used in ground contact situations, while creosote has been used for treating poles used for supporting overhead transmission lines. A number of studies have investigated the uptake and penetration of CCA and creosote in Sitka spruce wood (e.g. Purslow and Redding, 1978; Bruce *et al*., 1991; Evans *et al*, 1991). Concerns over the toxicity of creosote and CCA have either stopped or severely restricted their use in most parts of Europe and North America. The use of CCA has been effectively stopped in Europe because the use of arsenic and chromium is no longer supported under the Biocidal Products Directive. There are a number of alternatives to CCA and the two main preservatives used are alkaline copper quat (ACQ) and copper azole. A number of commercially available ACQ formulations exist and they all share a similar composition. The primary fungicide and insecticide protection is provided by copper, while the quaternary ammonium compounds ('quats') provide additional protection against copper-tolerant fungi (Walker, 2006). The alkaline formulating agents in ACQ have the ability to swell wood cell walls and can potentially improve the penetration of preservatives into refractory species such as Sitka spruce. As with ACQ formulations, the main fungicide and insecticide action in copper azole preservative treatments is provided by the copper.

Wood modification

Wood modification involves enhancing one or more properties of the material through the action of a chemical, biological or physical agent (Hill, 2006). The main types of modification methods are chemical modification, thermal modification, surface modification and impregnation modification. Chemical modification involves the reaction of a reagent with the hydroxyl groups of the cell wall polymers (i.e. cellulose and hemicellulose). It differs from preservative treatment of wood as the reagents used are non-biocidal in nature and are chemically bonded to the wood. Acetylation is the most well-known chemical modification reaction and is currently the only one that has been commercialised. Research has shown that acetylated wood has improved dimensional stability, improved resistance to decay and in some cases improved mechanical properties. Currently, the only species that is acetylated commercially is radiata pine due to its high level of permeability. In practice this means that refractory species such as Sitka spruce are not likely to be easily or uniformly acetylated (Hill, 2009).

In thermal modification, wood is typically heated to between 180 and 260°C. This results in the loss of the bound water and volatile extractives as well as degradation of the cell wall polymers, particularly the hemicelluloses. The physical and mechanical properties of the wood are altered; wood that has been thermally modified is normally darker in colour, and has improved dimensional stability and resistance to decay. However, depending on the process, there will be some loss in mechanical properties, particularly strength, which means that thermally modified wood is normally not appropriate for use in structural applications. There are a number of commercially available thermal modification processes available (e.g. ThermoWood® and Plato®WOOD) and in practice these are the only wood modification options available for Sitka spruce. Thermally modified Sitka spruce timber could be used in applications such as external cladding where improved decay resistance and dimensional stability are required.

Wood-based panels

Sitka spruce wood is used in the manufacture of three main types of wood-based panels in Great Britain: particleboard, oriented strand board (OSB) and medium density fibreboard (MDF). These panel products are used in a wide range of applications including construction, interior joinery and furniture making. All these products are manufactured from wood particles of various sizes held together by synthetic adhesives, and the relatively small size of particles used in these products means that they can be made from raw material that has much more variable quality than is required for products such as plywood. Because the panels are formed by pressing, the density of the panel is usually significantly higher than the density of wood from which the particles were obtained. While the mechanical properties of panel products are influenced to some extent by the properties of the wood used to make them, the lay-up of the fibres or particles, properties of the adhesives and the nature of the pressing process have a much greater influence on panel performance. Overall, MDF has the highest bending strength of these three panel products, followed by OSB and then particleboard (Thompson *et al*., 2002). A significant proportion of the raw material used to manufacture MDF and particleboard is obtained from sawmills in the form of co-product.

Particleboard

Particleboard is made from various sized particles of wood that are mostly obtained as residues (sawdust and shavings) from other wood processing operations, although an increasing amount of recycled wood is now used. Roundwood is also chipped to produce particles, but the proportion of this type of material is often limited to that necessary to meet product requirements, due to its relatively high cost of production (Walker, 2006). Particles are bonded together with melamine urea formaldehyde resins and are pressed to form panels of different thicknesses and grades. The mechanical property requirements for the different grades are given in EN312 (CEN, 2003d). The most common particleboard grades produced in Great Britain are shown in Table 3.5. Heavy duty particleboards (grades P6 and P7) are not produced in Britain. Particleboard is also produced with decorative facing such as melamine or wood veneer.

Table 3.5 Grades of particleboard manufactured in Great Britain.

Grade	Description
P1	General purpose boards for use in dry conditions
P2	Boards for interior fitments for use in dry conditions
P3	Non load-bearing boards for use in humid conditions
P4	Load-bearing boards for use in dry conditions
P5	Load-bearing boards for use in humid conditions

Oriented strand board

Oriented strand board was originally developed as an alternative to plywood in order to overcome the declining availability of large diameter logs used to produced plywood (although plywood was never made from Sitka spruce in Great Britain). The main advantage of OSB compared to plywood is that it can be made from small diameter logs and is therefore suited to the relatively small diameter logs that are typically produced from British forests. OSB consists of small thin flakes or strands, which are oriented in order to provide directional properties. In Britain, these strands are obtained from Sitka spruce, Scots pine and lodgepole pine (*Pinus contorta* Dougl. ex Loud.) logs. Typically, the strands are compressed into three or four layers; the surface layer strands are generally laid parallel with the long edges of the panel ('oriented') while the core strands are ideally at right angles to the surface layer strands. Strands are bonded together with melamine urea formaldehyde resins and are pressed to form panels of different thicknesses and grades. The two grades produced in Great Britain are OSB2 and OSB3, which are load-bearing boards for use in dry and humid conditions, respectively. The mechanical property requirements for the different board grades are given in EN300 (CEN, 2006c). Heavy duty OSB (OSB 4) is not produced in Britian. OSB is used in a wide variety of applications including site hoardings, sheathing material in closed-panel timber-framed houses and as for the web material in I-joists.

Medium density fibreboard

Medium density fibreboard is manufactured from individual fibres and fibre bundles that have a much higher slenderness ratio than those used to produce particleboard. At a global level, MDF initially filled the market segment between solid wood and particleboard, and was widely used in the furniture and joinery industries due to the ability to create a profiled edge and the better ability to hold fastenings than particleboard. The raw material for MDF is usually a combination of sawmill residues and chips obtained from roundwood. The fibres are prepared using a low energy thermo-mechanical pulping process and are then combined with an adhesive and pressed to form boards with a range of densities and thicknesses. In Great Britain, most of the wood used in the manufacture of MDF is Sitka spruce. Sitka spruce is suitable for a wide range of MDF products and its natural colour means that light coloured boards can be produced. Its low density wood containing relatively thin-walled fibres does not require large amounts of pressing force to create good bond strength. Therefore, it is possible to produce lightweight panels that have the desired strength properties. In Great Britain a range of standard and lightweight boards are produced for use in both dry and humid environments. The mechanical property requirements for the different board grades are given in EN622-5 (CEN, 2009b).

Engineered wood products

Engineered wood products consist of smaller pieces, veneers, strands, particles, or fibres of wood that are bonded together with adhesives, to form composite materials. Engineered wood products can also be created by combining wood with other materials, either as an intimate mixture (e.g. wood–plastic composites – See 'Composite materials' section on page 36) or through connecting one material to the other (e.g. metal web joists, composite insulated beams). These products are manufactured to certain specifications and are designed to have superior properties to solid timber and/or to have dimensions that cannot be achieved with solid timber. In addition, they normally have less variation in their properties than solid wood.

Engineered wood products can be classified into different groups based on their method of manufacture and end use. There are at least five groups of engineered wood products: (1) structural composite lumber, (2) glued-laminated timber, (3) timber composite beams and panels, (4) composite materials and (5) wood-based panels. Wood-based panels were discussed on page 32 and will not be discussed further here. In general, most engineered wood products other than wood-based panels and I-joists are not produced in Great Britain, so this section presents an overview of some of the products that are available and that could potentially be manufactured from Sitka spruce in the future. Further information about the potential for using Sitka spruce in engineered wood products is given in BRE (2007) and Robinson (2007).

Structural composite lumber

Structural composite lumber (SCL) is manufactured by gluing smaller pieces of wood together to form products that have dimensions similar to the typical range for solid timber. These products are intended to replace solid timber in applications where higher levels of mechanical performance are required and are also used in the manufacture of other engineered wood products such as I-joists (Walker, 2006; Forest Products Laboratory, 2010). Probably the most well-known SCL product is laminated veneer lumber (LVL), which is manufactured by laminating a number of thin veneers (~2–3 mm thick) together, with all plies oriented parallel to the long axis of the board. Interestingly, the first LVL was produced from North American Sitka spruce in the 1940s in order to make high strength components for aircraft manufacture (Forest Products Laboratory, 2010). LVL requires high quality veneers in order to achieve the desired engineering properties as well as a supply of well-formed logs that are large enough to peel into veneer. The inability to produce a sufficient quantity of high quality veneer from Sitka spruce grown in Great Britain (Cahalan, 1987) means that there is no commercial manufacture of LVL from Sitka spruce in this country.

The other main types of SCL are parallel strand lumber (PSL), laminated strand lumber (LSL) and oriented strand lumber (OSL). Parallel strand lumber is made from strands of veneer that are typically 20 mm wide and 300 mm long (i.e. much smaller than the veneer sheets used to make LVL). Laminated strand lumber and oriented strand lumber are an extension of the technology used to produce OSB panels (See 'Oriented strand board' section on page 33). These products need a greater degree of alignment of the strands and greater pressing forces than OSB, but can be made from a lower quality and cheaper raw material. However, LSL and OSL generally have slightly poorer mechanical properties than LVL and PSL (Walker, 2006; Forest Products Laboratory, 2010). As with LVL, none of these other SCL products are currently manufactured from Sitka spruce grown in Great Britain. However, it is likely that they could be made from British-grown Sitka spruce, but trials would be needed to determine that any products produced have the necessary performance characteristics.

Glued-laminated and cross-laminated timber

Glued-laminated timber (glulam) consists of two or more layers (laminations or lamellas) of timber that are glued together with the grain direction of all lamellas parallel to the longitudinal axis of the member. The individual lamella thickness normally ranges from 19 mm up to 50 mm (the maximum thickness permitted); thinner lamellas are generally used when producing curved members. The lamellas can be joined end-to-end (normally finger-jointed) to produce members that are much longer than the lamellas themselves. Finger-jointing is often used in combination with defect-cutting to remove the worst strength-reducing defects (e.g. large knots) in the timber. The lamellas can also be glued or placed edge-to-edge to produce a member that is wider than the original lamellas. Sorting of the lamellas on the basis of modulus of elasticity is frequently carried out, with the stiffest material placed on the top and bottom surfaces of the member and the least stiff lamellas placed in the centre. A number of research projects have investigated the potential to produce glulam beams from Sitka spruce, particularly from sideboard material that would normally be used to manufacture pallets and boxes. While these studies showed that glulam can be produced from Sitka spruce, there is currently no commercial-scale production of glulam in Great Britain.

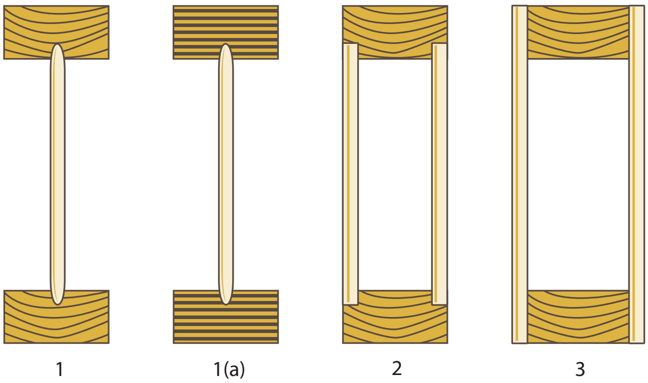
Lamellas can also be glued together to form multi-layer panels. Each layer in these panels consists of individual lamellas that are glued or placed edge-to-edge. Layers are then glued (or in some cases dowelled) together in alternating longitudinal and transverse directions in a similar manner to the layers in plywood (Figure 3.3). The resulting panels are referred to as cross-laminated timber (CLT) and sometimes also as massive wood. As with plywood, CLT panels have an odd number of layers (typically, panels are made from three, five or seven layers) with the higher quality timber used for the outside layers which are visible. Because large panels can be produced (up to 3 x 16 m), CLT can be used for a wide range of building elements including floors, walls and ceilings for single houses up to multi-storey buildings. Panels are currently made from a number of different timber species including Norway spruce, but are not at present manufactured in Great Britain using home-grown species. Sitka spruce timber is suitable for use in CLT panels, as these are already being made from C16 grade lamellas of other species, but extensive testing to determine the performance of panels made from this species has not been undertaken.

Figure 3.3 Five layer cross-laminated timber panel with insulation and cladding attached.

Timber composite beams and panels

This class of engineered wood product includes beams and panels that are either produced from various combinations of solid wood, panel products and structural composite lumber, or from wood-based materials in combination with other materials. I-joists are probably the most well-known composite beam and have replaced larger timber sections in many floor and roof applications. They are based on the principle that in a beam subjected to bending, the maximum tensile and compressive stresses occur at the top and bottom surfaces. Therefore, significant weight savings can be achieved without loss of performance by placing the strongest material at the top and bottom surfaces (flanges) of the beam separated by a central core (web) that has sufficient strength to withstand the forces (mainly shear) that occur in this part of the beam. I-joists normally consist of either plywood or OSB for the web material and either solid wood or structural composite lumber for the flanges (Figure 3.4), and in Great Britain they are manufactured using imported timber for the flanges and locally produced OSB for the web material. Metal web joists are based on the same general principle as I-joists, whereby the timber flanges resist bending, while the metal web resists the shear forces. The open nature of the metal web is designed to provide easy access for installing services during construction. Metal web joists are currently manufactured in Great Britain, but imported timber is used for the flanges. While they could be manufactured using Sitka spruce, higher strength class timber is normally preferred.

Figure 3.4 Types of engineered joists available, including I-beams and boxed beams.



Beams with timber flanges:
(1) I-beam (2) Recessed beam (3) Box beam

Beams with LVL flanges:
1(a) LVL I-beam

Box beams are similar to I-joists, except that the web material is connected to each side of the flanges (Figure 3.4). A solid timber box beam has been developed using Sitka spruce and this forms the main structural component of the Ty Unnos system for constructing affordable rural housing (Coombs *et al*., 2009). An extension of the box beam (and the double-web I-joist) is the composite insulated beam (CIB), in which an insulating material such as polystyrene or rigid polyurethane foam is placed between the web material. The aim is to improve both the structural and insulation performance of the beam. Different wood products can be used for the flanges and web, and beams have been made from Sitka spruce structural timber and OSB (Bahadori Jahromi, 2006). Extensive laboratory tests have been undertaken of these beams, but at present they are not manufactured commercially.

Structural panel systems can also be produced in which two thin facings are bonded to a thick core. These are generally referred to as sandwich panels or as structural insulated panels (SIPs) due to the insulation function performed by the core material. The facings contribute most of the structural performance of the panels, although the core stabilises the thin panels and provides the shear rigidity. SIPs are most commonly made of OSB panels sandwiched around a foam core made of expanded polystyrene, extruded polystyrene or rigid polyurethane foam. These panels are manufactured in Great Britain using locally produced OSB3.

Composite materials

The final class of engineered wood products that will be considered in this section are composites consisting of wood mixed with other materials. Wood-based panels, glued-laminated timber and structural composite lumber are all examples of composite materials consisting of wood combined with resin; however, this section will focus on wood–plastic composites (WPCs). WPCs are composites that contain wood and thermoplastics such as polyethylene, polypropylene or polyvinyl chloride (Klyosov, 2007). The wood used in WPCs is generally in the form of wood flour or very short fibres, rather than longer individual fibres, and is normally obtained as sawdust from primary and secondary processors. Products typically contain approximately 50%, although some contain as much as 70% while others contain very little wood (Clemons, 2002). Most WPCs are manufactured by profile extrusion, which allows the material to be moulded to meet almost any desired shape. Most WPCs are less stiff than solid wood, but have better decay resistance and dimensional stability when exposed to moisture. Therefore, they are particularly suitable for products such as decking, flooring, and landscape timbers that have limited structural requirements. Because WPCs are made from very fine wood particles, they can be made from almost any type of wood. Sawmill residues that are sufficiently dry and free from contamination from other material can be used as raw material.

Paper and paperboard

Wood fibres can be used as the raw material for a wide variety of paper and paperboard products. In the manufacture of these products, wood must first be pulped in order to reduce it to a mixture of fibres and fibre debris. This reduction can either be achieved by mechanical or chemical means, or by a combination of the two. Mechanical pulps are produced through the stone groundwood process or the refiner process, while chemical pulps are produced from digesting wood chips in strong alkaline or sulphite solutions to remove much of the lignin. Semi-chemical pulps are generally made from chips that have been treated with chemicals at high temperatures to remove some of the lignin and hemicelluloses, before being defibred in a disc refiner (Packman, 1966). The properties of paper and paperboard depend strongly on the pulping process used as well as on the fibre characteristics of the wood raw material, and the main characteristics of pulp and paper that affect its performance and suitability for different end uses are listed in Table 3.6.

Table 3.6 Description of key properties used to characterise pulp and paper.

Property	Description
Tensile index (Nm g^{-1})	The tensile force per unit width required to break a standard specimen.
Tear index (mN m^2 g^{-1})	A measure of resistance to tearing once a small tear has been initiated. It is generally the property most commonly used to compare softwood pulp strength and is positively related to fibre length and cell wall thickness.
Strength index	This is calculated as the product of the tensile index and tear index.
Burst index (kPa m^2 g^{-1})	This is determined from the hydraulic pressure required to rupture the paper and is linearly related to tensile strength.
Density (kg m^{-3})	This is determined from the sheet thickness and the grammage (i.e. g cm^{-2}). Tensile and burst strength are directly related to density, while tear strength is inversely related.
Brightness (%ISO)	The percentage of light reflected from a thick pad of papers relative to the reflectance of a known standard.
Light scattering (m^2 kg^{-1})	This property affects the opacity of paper, which is the ability to see objects on the other side of the paper. Paper with high opacity is suitable for double-sided printing.

Note: Index values are expressed on a per unit mass basis.

The pulp and paper industry in Great Britain has changed considerably since the 1970s. At the end of the 1970s there were seven mills producing wood pulp from virgin fibre, all of which were integrated with paper mills on the same site (Birchmore, 1979). Four of these mills were producing softwood mechanical pulp, while another was producing softwood chemical pulp using the sulphite process. Only one of these mills from this era still exists today, while another new mill that produces mechanical pulp from virgin fibre was built in the 1990s. All other paper and paperboard produced in Great Britain is made from imported pulp, or pulp made locally from recycled fibre.

Sitka spruce mechanical pulp for paper making is produced using the pressurised stone groundwood (PGW) process, in which short logs (~2 m in length) are abraded tangentially by a rotating grindstone in a pressurised container. The resulting pulp is suitable for lightweight coated and supercalendered grades of paper, which are typically used in magazines. Sitka spruce is well suited to the PGW pulping process due to its light colour and low extractives content, which results in a pulp with high brightness and high opacity (Packman, 1966). The pulp is normally made from the top logs of trees and thinnings, which contain a large proportion of juvenile wood. The thin-walled tracheids found in juvenile wood are readily collapsible and form a smooth paper surface which has good printing quality (Edlin, 1965). However, the short tracheids found in juvenile wood mean that Sitka spruce pulps made from the PGW process have comparatively low tear strength. Chemical pulp, which has longer fibres and higher tear strength, is often added to mechanical pulp produced by the PGW process to improve tear strength. The proportion of chemical pulp added depends on the grade of paper being produced.

Mechanical pulp for paperboard manufacture is made from wood chips using a disc refiner. This process has a number of similarities to that used for producing fibres for MDF production, but is carried out at lower temperatures. Refiner pulp has better strength properties than groundwood pulp, but these are still lower than those of chemical pulp. The wood chips used to produce refiner pulp come from different parts of the tree and therefore include a proportion of outerwood which has longer fibres; tear strength of pulp is positively related to fibre length. Sitka spruce mechanical pulp is used to make multilayered folding box board, which in turn is used for products such as book covers, greeting cards and packaging for food and cosmetics. As with PGW pulp, chemical pulp is added to refiner mechanical pulp to improve its strength properties, particularly tear strength.

While chemical pulp was produced from Sitka spruce in the past using the sulphite process (Packman and Orsler, 1964), there is no longer any chemical pulp produced in Great Britain. All chemical pulp used in paper and paperboard production is now imported, although studies have been undertaken to characterise the properties of Sitka spruce kraft pulp (Table 3.7). Overall, kraft pulp produced from British-grown Sitka spruce was reported to be of modest quality compared with Scandinavian softwood bleached kraft pulp, mainly due to the relatively short fibre length. However, it is possible that fibre length could be increased by increasing the proportion of slabwood chips that are used in the manufacture of the pulp as these chips originate from the outermost part of the stem which contains the longest tracheids (Figure 2.10).

Table 3.7 Comparison of selected properties of bleached Sitka spruce kraft pulp with those of fully-bleached softwood kraft pulp produced in Scandinavia.

Property	Sitka spruce kraft pulp	Fully bleached Scandinavian softwood kraft pulp
Fibre length (mm)	1.95	2.4–2.6
Brightness (% ISO)	88–91	88–91
Tear index* (mN m^2 g^{-1})	18–20	18–20
Strength index	1200–1300	1000–1300
Scott bond* (J m^{-2})	340–350	300–400
Density (kg m^{-3})	750	660–680
Light scattering (m^2 kg^{-1})	26	22.5–24.5

*At tensile index 70 Nm g^{-1}

Biomass for energy

At a global scale energy production is the single largest use of the world's wood resource. Historically, the use of wood for energy production has been greatest in developing countries, but recent concerns over the carbon emissions associated with the use of fossil fuels for energy generation has led many developed countries to focus more on the use of woody biomass for energy production. There are a number of ways in which woody biomass can be used to produce energy, including combustion, partial or controlled combustion (i.e. pyrolysis or gasification), and chemical conversion to liquid fuels such as methanol, ethanol or Fischer–Tropsch liquids (a complex mixture of hydrocarbons that can be used as a substitute for diesel). The focus of this section is the burning of wood for energy, and the production of liquid biofuels along with other chemicals will be discussed in the section entitled 'Chemicals' on page 38.

The biomass energy sector in Great Britain has developed rapidly over the past decade with wood from a variety of sources used to generate heat and electrical energy. Several dedicated biomass power stations have been commissioned and more are planned, while a number of existing power stations are now co-fired with wood. Woody biomass is also used for domestic electricity and heat production. The main sources of biomass for combustion in Great Britain are traditional forestry (either as low grade sawlogs or brash), sawmill co-products, arboricultural arisings and short-rotation coppice (McKay, 2003). As Sitka spruce is a major component of the standing forest resource and the roundwood harvest, it will certainly provide a substantial component of the woody biomass supply for energy. Currently, woody biomass for energy production is supplied as chips and as pellets that have been produced from fine particles. Both of these products generally contain a mixture of different species, which will depend on what is currently available. The choice of species does not affect the amount of energy produced as the calorific value of wood is largely independent of species (See 'Calorific value' section on page 17). However, wood moisture content does vary within a tree and with time of year, so that sapwood, which has a higher moisture content than heartwood, generally has be dried for a longer period of time before being burnt. The moisture content of the fuel will depend on the type of boiler that it is being burned in, but values of approximately 50% (on a wet weight basis) are often specified.

Bark

In Sitka spruce approximately 10% of a typical log consists of bark, which is a lower proportion compared with the other conifer species grown in Great Britain (Scott and MacGregor, 1953; Aaron, 1982). This bark is removed when logs are processed and, therefore, with the increasing volumes of wood being processed in Great Britain the volume of bark produced is also increasing. While the bark of a number of conifer species including Sitka spruce was used by the indigenous peoples of North America for a variety of purposes, the modern-day wood processing sector often viewed bark as a low value co-product, if not a waste product. Bark was often burned to provide heat and electricity, despite it being less suitable as a fuel than wood due to the amounts of smoke produced and its much higher ash content. Because of the increased volumes of bark being produced by the wood processing sector and the problems associated with burning it, other alternative uses for bark have been and are continuing to be developed.

Currently, the main commercial use for bark is in the horticultural sector where it can be used for potting mixtures, mulching and landscaping and soil improvement. In other countries, the bark of various conifer species has been used in combination with wood to produce particleboard (Yemele *et al*., 2008) and can also be used as an absorbent material in products designed to control oil spills. More recently the use of bark as a source of chemicals, including liquid biofuels, adhesives and pharmaceuticals, has been the subject of considerable international research effort (See 'Chemicals' section below). Sitka spruce bark has an extractives content of nearly 30%, compared with approximately 1.5% for both sapwood and heartwood (Caron-Decloquement, 2008). It has a high tannin content relative to other common conifer and broadleaved species grown in Great Britain (Aaron, 1982), but the costs of extracting the tannin currently makes its use uneconomic compared with other sources.

Chemicals

The production of chemicals, including liquid biofuels, adhesives and pharmaceuticals, from woody biomass has attracted considerable research attention in recent years. Particular focus has been given to the development of biorefineries, which are facilities where the processes and equipment used to convert biomass into fuels, power, materials and chemicals are integrated. The biorefineries concept is analogous to petroleum refineries, which produce multiple fuels and products from petroleum (Clark *et al*., 2006). One of the key products produced in a biorefinery is bioethanol, which is normally produced from fermentation of corn, sugarcane or other starch-rich crops. Because of the impact that current bioethanol production processes have had on food prices, more attention is being focused on producing it from cellulosic materials such as wheat straw and wood (Koh and Ghazoul, 2008). Currently, the cost of producing bioethanol from cellulosic materials means that the process by itself is uneconomic, but this may not be the case for a biorefinery producing multiple products. These products could include high value, but low volume chemicals along with liquid biofuel. The extractives found in wood and bark include terpenes, flavonoids, sterols and resin acids (See 'Chemical composition' section on page 5), while a range of products can be produced from the primary constituents of wood (i.e. cellulose, hemicelluloses and lignin). Due to the size of the Sitka spruce resource in Great Britain, there has already been a certain amount of research into chemicals that can be produced from biomass in this country (Clark *et al*., 2006). For example, Curling *et al*. (2007) investigated the yield and composition of hemicelluloses extracted from Sitka spruce. While the field of biorefineries is still in its infancy, it is expected that in the future they will be important sources of renewable energy and materials for developed countries such as Great Britain that have a large reliance on fossil fuels.

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Sitka spruce is the main conifer species grown in Great Britain and the commercial wood products industry is primarily based on this species. Wood from Sitka spruce is sawn into timber for use in construction, pallets/packaging and fencing, and is also used in the production of paper and panel products. Research into the wood properties and performance of products made from Sitka spruce has been undertaken in Great Britain for almost 90 years by a number of organisations and the results from this research are contained in a large number of published and unpublished sources.

This report collates and synthesises this research and is written for forest scientists, engineers, wood processors, and end users of wood products who are seeking a better understanding of the material properties and potential end uses of Sitka spruce. It is divided into three parts: (1) the origins of Sitka spruce, its introduction into Great Britain and its growth and management in this country; (2) Sitka spruce wood properties, including wood anatomy, general wood structure, and physical and mechanical properties; and (3) an overview of the end products that are currently produced from Sitka spruce or that could potentially be produced in the future.

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