Forestry Commission

Wood properties and uses of Scots pine in Britain

Forest Research

Research Report

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Contents

1. Distribution of Scots pine

The natural distribution of Scots pine covers a large area spanning Europe and Asia. It was once the dominant tree species in northern Great Britain covering around 20% of Scotland (6% of Great Britain). While only a small fraction of these natural forests remain, thanks to a century of reafforestation Scots pine now covers around 1% of Great Britain. It remains an important timber species in areas that are too dry for the faster growing Sitka spruce, and is therefore of considerable regional significance, particularly in southern and eastern areas of Great Britain.

Natural distribution

Scots pine (*Pinus sylvestris*) has a larger natural range than any other pine in the world[1], spanning northwards from Mediterranean Spain to Arctic Norway, and eastwards from Atlantic Scotland to almost the Pacific coast of Siberia (Figure 1.1). In the north of its range it grows as low as sea level, while in the south it is only found in the mountains.

Natural pinewoods in Great Britain

Scots pine may have survived the last Ice Age in glacial refugia in northwest Scotland, but is generally believed to have advanced into England from northeast France, when those two countries remained joined together following the glacial retreat. As the climate subsequently warmed, Scots pine was displaced across most of Great Britain by other species such as oak and alder, but it remained the dominant species in the cooler north of Scotland. About 5000 years ago, natural pinewoods were estimated to cover 1.5 million hectares of Scotland (Mason, 2000). Since then, largely due

1 Scots pine is often mistakenly believed to be the most widely distributed conifer, although that is actually the common juniper (*Juniperus communis*), whose natural range spans Europe, Asia and North America.

to human activity, the area of natural pinewoods has reduced to approximately 19 000 ha and are found only in the Scottish Highlands (Figure 1.2). These protected forests provide a habitat for a number of rare species including the crested tit, capercaillie and twinflower (Mason, Hampson and Edwards, 2004).

Scots pine accounts for 7% of the national forest area (Table 1.1). In Scotland, approximately 96 000 ha of Scots pine is within the native pinewood zone; 26 000 ha of this is natural or almost natural, and therefore conservation is most likely to be the main management objective (Patterson *et al*., 2014). Planted Scots pine forests, with the primary aim of timber production, are estimated to account for 90% of the area under Scots pine in Great Britain. Scots pine plantations were established from the 17th century onwards. Scots pine was then, as now, favoured for its rapid early growth, timber properties and adaptability to a range of site conditions. Scots pine can thrive in drier areas that are unsuitable for Sitka spruce, where there are large maintained plantations (Table 1.2, Figure 1.3). The largest of these are in north and northeast Scotland, and south and southeast England. Planted Scots pine is found throughout Wales but represents only a small proportion of the total forest area. Regional timber production is covered in Current and future wood production on page 4.

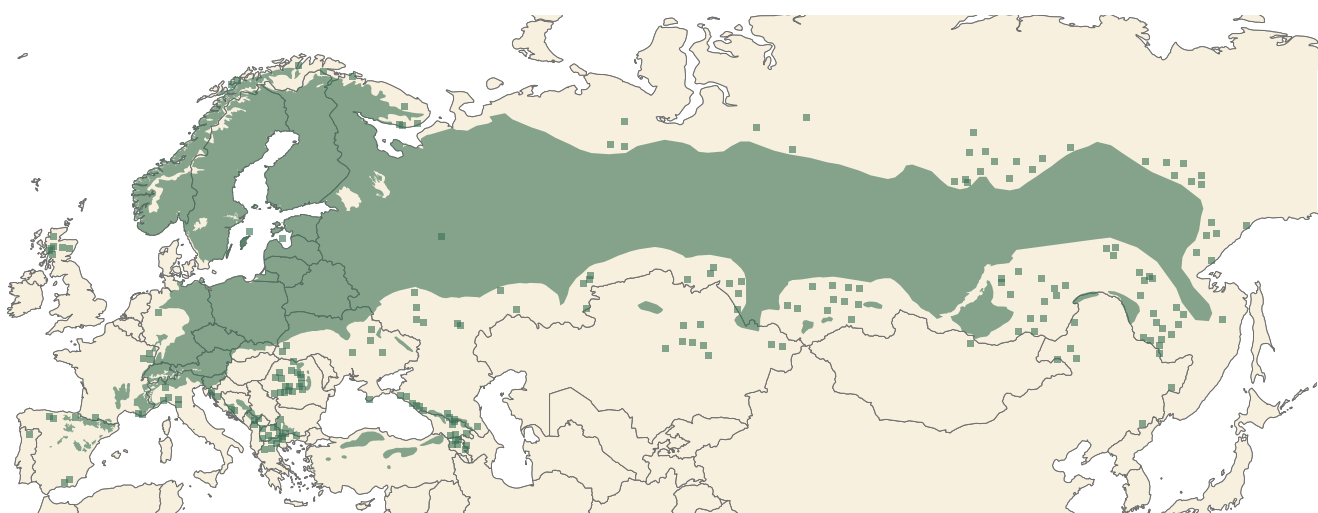**Figure 1.1** The natural range of *Pinus sylvestris*.

Figure 1.2 The location of the remaining natural (Caledonian) pinewoods of Scotland and the zone estimated to have been dominated by pine forests following glaciation.
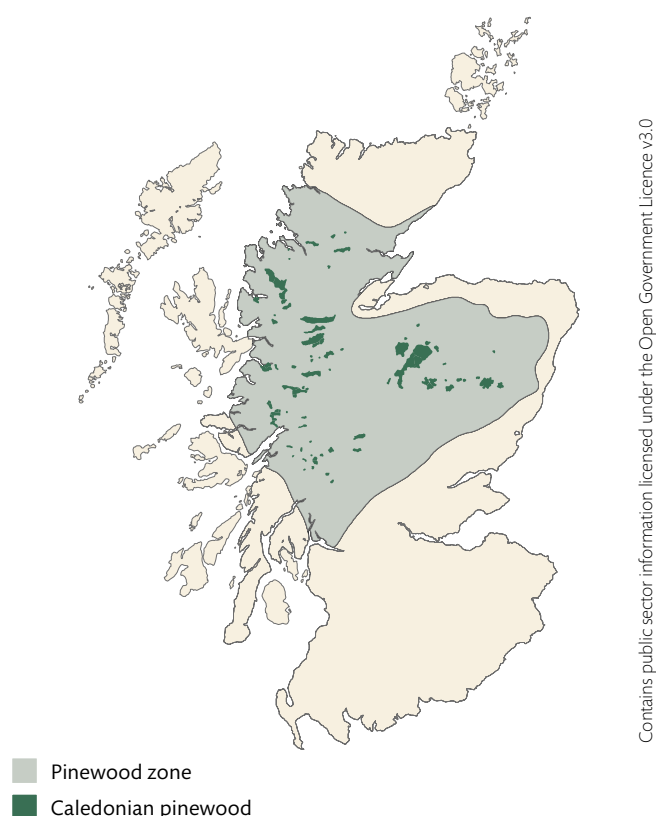
- Pinewood zone
- Caledonian pinewood

Table 1.1 Area of Scots pine forests in Great Britain in 2014 (numbers in parentheses are the percentages of the total areas that are Scots pine).
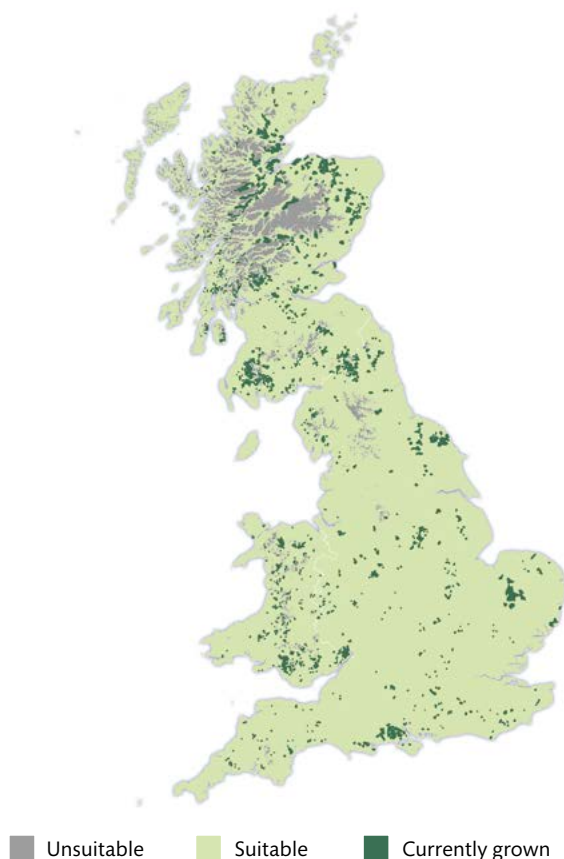
Country	Area of Scots pine (ha)	Total conifer forests (ha)	Total forests (ha)
England	61 000	307 000 (20%)	1 304 000 (5%)
Scotland*	154 000	872 000 (18%)	1 432 000 (11%)
Wales	3 000	129 000 (2%)	306 000 (1%)
Total	**218 000**	**1 308 000 (17%)**	**3 042 000 (7%)**

* Approximately 10% of the area in Scotland is estimated to be managed primarily for conservation.

Table 1.2 Site requirements for growing Scots pine for timber according to principles used in the Forest Research Ecological Site Classification.

Site property	Species requirements
Elevation	Although often found between 450–550 m in northeast Scotland, only sites below 300 m should realistically be considered for timber production.
Exposure	Wind-firm and tolerant of wind exposure, but not tolerant of salt-laden sea winds or atmospheric pollution. Relatively sheltered sites are preferable for timber production.
Temperature	Sites where the accumulated temperature is ≥ 575 day-degrees (> 5°C) per annum are suitable (cool to warm), while those where the accumulated temperature is ≥ 975 day-degrees are considered optimal (warm).
Frost tolerance	Extremely frost hardy, the natural range includes the Arctic Circle.
Soil nutrient regime	Low nutrient demand. For sawn wood-based products, Scots pine is considered to grow best under conditions of relatively low fertility. This is because vigorous growth on more fertile sites will be accompanied by coarser branches, and may also be accompanied by poorer stem form. There are, however, forest products such as orientated strand board (see wood-based panels) that rely on the amount of biomass produced, rather than on straight logs or small branches, so fertile sites could be considered for these.
Soil type	Tolerant of poor soils and harsh microclimates. Will grow on gley, brown earths and peat soils in its native range, but is best suited to light and acidic sandy soils, typically mineral podzols and ironpans of poor-to-moderate fertility. Avoid heavy mineral soils, wet coastal uplands (chalk, limestone, rendzinas) and any soft ground. For example, Scots pine is probably the best conifer for planting on dry heather sites.
pH	Typically 3.5–4.5 in its native range. Grows best on acidic to neutral soils. Avoid alkaline soils.
Moisture regimes	Low moisture demand. Does well in low rainfall areas and is drought-tolerant. Sites where the soil moisture regime is very dry to very moist are likely to be suitable, while those which are moist to moderately dry are considered optimal. Better stands are usually associated with free-draining soil conditions.
Drainage	Continually waterlogged ground is unsuitable and therefore good drainage is required.
Rootable depth	Scots pine has an adaptable rooting habit and will develop as shallow or deep taproots (at 1–4 m), depending on soil type and available rooting depth. Scots pine will establish on relatively shallow soils over rock and at higher elevations, although these conditions are unlikely to be ideal for growing timber.

Figure 1.3 Current climatic suitability for growing Scots pine for timber in Great Britain, according to the Forest Research Ecological Site Classification, in addition to sites where it is currently growing in areas ≥ 0.5 ha. Scots pine can and does still grow in some of the unsuitable areas, but is unlikely to be a productive crop.

Unsuitable   Suitable   Currently grown

Figure 1.4 Top height curves (top graph) and mean tree diameter curves (bottom graph) for unthinned Scots pine growing under different yield classes (data from Edwards and Christie, 1981).

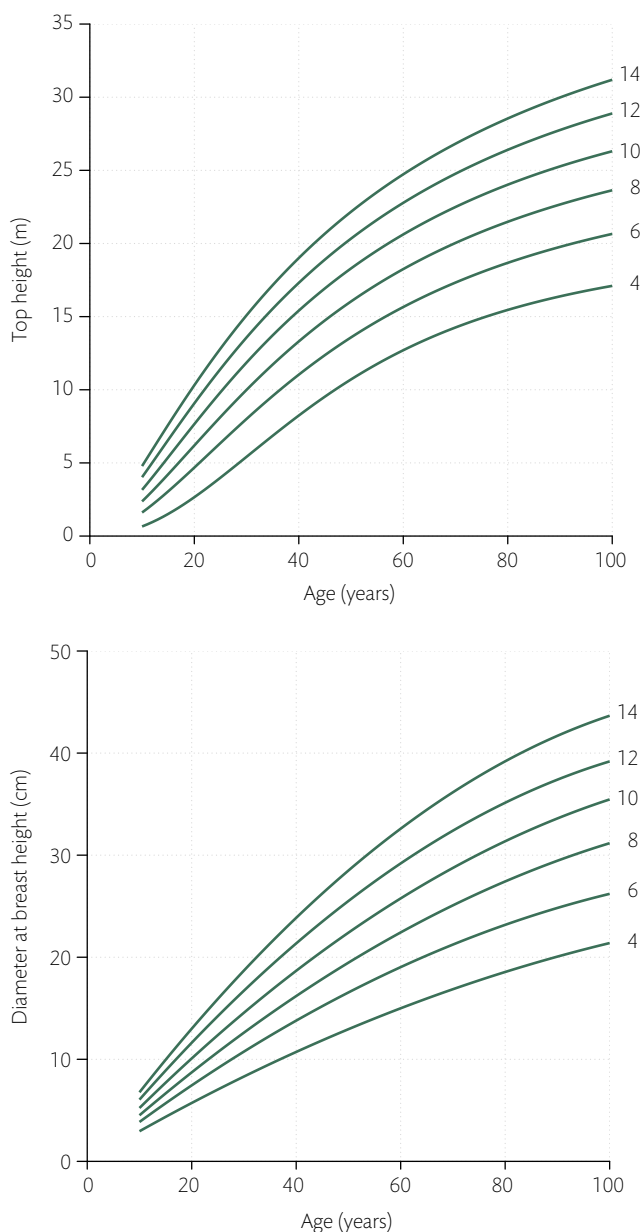Contains public sector information licensed under the Open Government Licence v3.0

Growth and yield

Yield Classes are used in Great Britain as a metric measurement of site productivity (Edwards and Christie, 1981), where a yield class of 10 signifies an average mean volume increment of 10 m³ per ha per year over the rotation. Scots pine is typically in the range of yield class 4–14 (Figure 1.4) and the mean national yield class of Scots pine is currently 10 (Forestry Commission, 2015). In comparison, Sitka spruce is in the range of yield class 6–24, and the national average is currently 16 (Forestry Commission, 2015). Mean annual volume increment curves for Sitka spruce and Scots pine of equivalent yield class are shown in Figure 1.5. It should be noted that yield class 12 is towards the lower end of the productivity scale for Sitka spruce, but at the higher end of the productivity scale for Scots pine.

The maximum mean annual increment (MAI) for Scots pine is slightly lower than Sitka spruce and is reached later[2], and

2 In these data, Scots pine has a higher mortality than Sitka spruce, and hence there are fewer live trees per ha, and consequentially a lower volume is obtained.

therefore Scots pine of an equivalent yield class to Sitka spruce would normally be grown on a longer rotation. For the lower yield class sites more typical of Scots pine, the maximum MAI of a thinned yield class 4 site occurs at approximately 100 years. However, a survey of rotation lengths in north Scotland (Macdonald *et al*., 2008) revealed that the average rotation length was 63 years, 57 years for the Public Forest Estate, and 74 years for other ownerships.

The stem profile of a typical Scots pine tree is different to a Sitka spruce tree of equivalent age and yield class (Figure 1.6), whereby the potential merchantable volume of a single Scots pine tree is slightly higher in this scenario. However, Sitka spruce will for the most part be a more productive crop in a given area of land due to its faster growth.

Figure 1.5 Mean annual volume increment curves for unthinned Scots pine and Sitka spruce at yield class 12. The maximum for Sitka spruce is at 55 years and for Scots pine is at 64 years (data from Edwards and Christie, 1981).
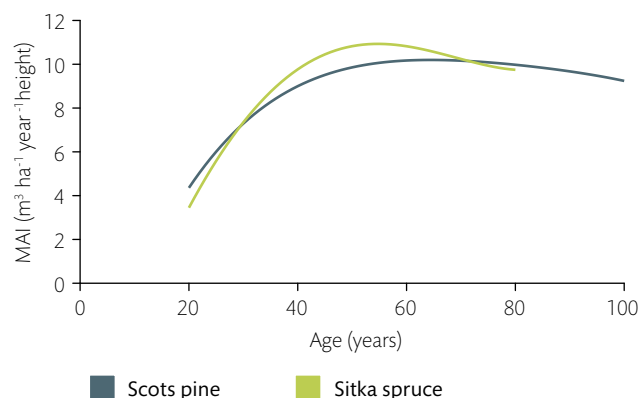
Figure 1.6 Stem profile or taper of 60-year-old Scots pine and Sitka spruce from comparable growing conditions: yield class 12, 1.8 m initial spacing and no thinning. Based on taper functions presented by Fonweban *et al.* (2011) and data from Edwards and Christie (1981).

Current and future wood production

Scots pine is forecast to produce around 10% (standing volume) of Great Britain's softwood supply for the next 50 years, most of which will be produced in private estates, with a peak in production predicted in 2036 (Figure 1.7) due to the extensive planting that took place in the 1950s and 1960s (Figure 1.8).

When this forecast is broken down by country and National Forest Inventory reporting region (Table 1.3), production in Wales is negligible. Current production in England is approximately 40% of the total, but is set to decrease to 30% at the end of the 50-year period. Scotland currently produces the majority of the resource and its share is set to

Figure 1.7 The 50-year forecast of wood production from Scots pine in Great Britain (Forestry Commission, 2014).
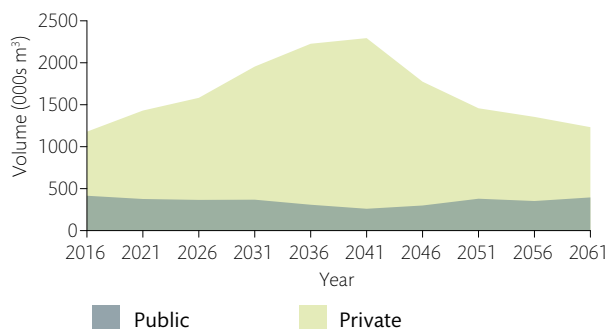
Figure 1.8 The planting decade of Scots pine forests in Great Britain (data from the National Forest Inventory).
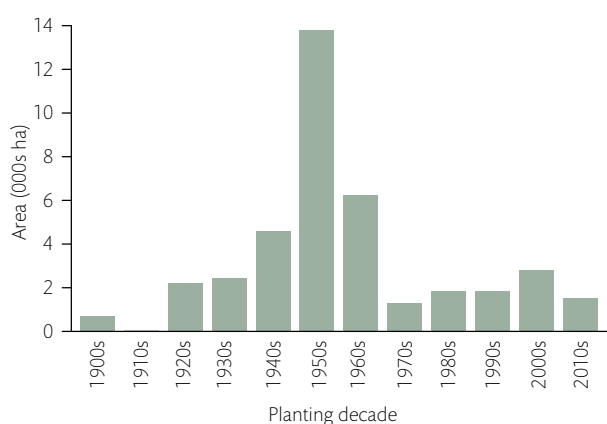
increase. Regionally, the northeast of Scotland is currently, and will continue to be for at least the next 50 years, the place where most Scots pine logs are produced.

Scots pine in other countries

Scots pine is widespread and is commercially important throughout Europe. Relative to other tree species, it tends to be used more for large scale timber production in the northern regions of Europe, with Spain being a notable exception (Pasalodos-Tato and Pukkala, 2007). The UK imports Scots pine timber predominantly from Scandinavia, Russia and the Baltics, but also from France. The relative importance of Scots pine to a number of countries can be seen in Table 1.4.

Table 1.3 Volume of Scots pine timber forecast in the next 50 years (Forestry Commission, 2014). Values are volumes in thousands of cubic meters overbark; the numbers in parenthesis indicate the proportion of forecasted softwood volume as percentages.

Region	Period										Regional 50-year total
	2013–16	2017–21	2022–26	2027–31	2032–36	2037–41	2042–46	2047–51	2052–56	2057–61	
England (total)	**671 (15)**	**672 (15)**	**747 (18)**	**987 (24)**	**904 (23)**	**834 (26)**	**556 (19)**	**562 (22)**	**391 (17)**	**484 (17)**	**6 809 (19)**
East England	74 (20)	82 (22)	85 (24)	114 (26)	189 (41)	153 (38)	72 (27)	56 (28)	66 (32)	57 (32)	947 (29)
East Midlands	75 (35)	63 (28)	92 (43)	102 (45)	67 (34)	77 (48)	66 (34)	50 (35)	49 (29)	48 (27)	689 (36)
North East England	82 (9)	103 (13)	91 (13)	178 (23)	132 (16)	111 (15)	70 (12)	71 (15)	58 (14)	97 (15)	993 (15)
North West England	29 (7)	38 (9)	38 (6)	66 (12)	40 (10)	53 (17)	58 (18)	35 (13)	24 (8)	32 (8)	415 (10)
South East England and London	226 (30)	192 (27)	210 (30)	238 (35)	235 (40)	210 (39)	167 (31)	146 (34)	96 (25)	106 (29)	1827 (32)
South West England	43 (4)	44 (4)	59 (8)	98 (14)	80 (13)	65 (12)	34 (7)	69 (14)	38 (9)	51 (10)	580 (9)
West Midlands	70 (13)	66 (14)	74 (17)	88 (25)	78 (16)	100 (34)	32 (14)	79 (29)	24 (12)	35 (17)	646 (19)
Yorkshire and the Humber	72 (17)	84 (19)	97 (23)	102 (23)	82 (25)	66 (22)	58 (23)	56 (22)	37 (19)	59 (17)	712 (21)
Scotland (total)	**901 (9)**	**1081 (10)**	**1176 (10)**	**1315 (10)**	**1614 (13)**	**1704 (15)**	**1496 (16)**	**1249 (15)**	**1265 (15)**	**1116 (14)**	**12 916 (13)**
East Scotland	118 (10)	152 (13)	163 (18)	158 (18)	119 (11)	244 (25)	216 (24)	148 (22)	172 (15)	131 (22)	1622 (17)
North East Scotland	463 (32)	534 (32)	582 (36)	679 (37)	870 (45)	825 (44)	777 (42)	588 (40)	650 (40)	608 (39)	6576 (39)
North Scotland	214 (19)	234 (20)	241 (24)	322 (24)	390 (22)	499 (25)	245 (19)	303 (29)	280 (24)	190 (18)	2918 (22)
South Scotland	82 (2)	121 (3)	158 (3)	117 (2)	213 (5)	93 (3)	150 (5)	133 (5)	115 (4)	134 (4)	1317 (4)
West Scotland	25 (1)	41 (1)	31 (1)	39 (1)	22 (1)	42 (1)	107 (5)	77 (3)	47 (3)	53 (3)	483 (2)
Wales (total)	**23 (1)**	**54 (3)**	**24 (1)**	**21 (1)**	**17 (1)**	**16 (1)**	**22 (2)**	**26 (2)**	**51 (4)**	**28 (2)**	**282 (2)**
Great Britain (total)	**1594 (10)**	**1807 (11)**	**1948 (11)**	**2323 (13)**	**2535 (14)**	**2554 (16)**	**2074 (16)**	**1837 (15)**	**1707 (14)**	**1628 (13)**	**20 007 (13)**

Table 1.4 Volume of Scots pine in selected European countries. Percentages in parenthesis represent the relative proportion of Scots pine to the respective national total.

Country	Volume of Scots pine (millions of m³)	Forest area of Scots pine (thousands of ha)	Reference
Belgium	12 (8%)*	62 (10%)	Lust, Geudens and Olsthoorn (2000)
Czech Republic	769 (14%)		Ústav Pro Hospodářskou Úpravu Lesů (2004)
Estonia	128 (28%)*		
Finland	1035 (50%)		Gjerdrum (2009)
France	413 (16%)		Institut Géographique National (2013)
Germany	733 (21%)		Federal Ministry of Food and Agriculture (2014)
Latvia	233 (43%)*		
Lithuania	156 (42%)*	778 (36%)	Aleinikovas and Nas (2006)
Netherlands	17 (28%)*	142 (39%)	Lust, Geudens and Olsthoorn (2000)
Norway	265 (33%)*		
Poland	1047 (59%)	5602 (60%)	Lasy Paostwowe (2015)
Russia	16 290 (20%)*		
Spain	146 (16%)		Área de Inventario y Estadísticas Forestales (2011)
Sweden	1330 (39%)		SLU (2015)
UK	51 (9%)[a]	218 (7%)[b]	[a] 2014 Forestry Commission statistics [b] 2015 Forestry Commission statistics

* Calculated from the FAO Global Forest Resources Assessment 2005 since more recent data was not available.

2. Wood properties and uses of Scots pine

Scots pine shares a common general wood anatomy and basic chemical composition with other softwood species. Its heartwood is more durable, and it has superior clearwood mechanical properties and wood density to Sitka spruce. Some of the clearwood mechanical properties of domestic Scots pine even match that of Scandinavian origin. The problems for British Scots pine are large knots, particularly dead knots, and the tendency to attract bluestain fungi when freshly felled. Silvicultural practices are not currently optimised for the control of knots, and so some options are discussed that could improve the quality of sawnwood.

Chemical composition

The function of the basic chemical components and wood anatomy was covered in detail for conifers by Moore (2011) and will not be repeated here. Scots pine wood does not differ substantially from other well characterised conifers in terms of its basic chemical composition (Table 2.1), but it has a notably higher extractive content than Sitka spruce. A qualitative characterisation of the heartwood extractives in Scots pine can be found in Ekeberg *et al.* (2006).

diameters), varies as a function of tree age (Mencuccini, Grace and Fioravanti, 1997) and environment (Fritts, 1976), and therefore the interpretation of such information should be conducted on a local basis. Table 2.2 presents typical Scots pine data collected in East Anglia and northern Scotland. These data are comparable to data for Finland (Havimo, Rikala and Sipi, 2009) and Latvia (Sable *et al.*, 2012; Irbe *et al.*, 2013).

Figure 2.1 The transverse and radial-longitudinal faces of Scots pine. Resin canals are clearly visible.
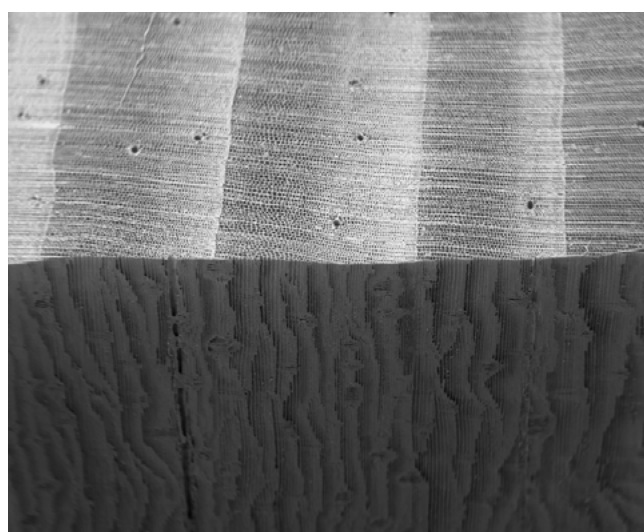
Image courtesy of Alan Crossley, Centre for Ecology & Hydrology

Table 2.1 Dry weight presented as percentages for the chemical components of Scots pine growing in northern Europe (excluding data from Great Britain). The values are medians; where more than two values were found in the literature the probable error is indicated (Räisänen and Athanassiadis, 2013).

	Cellulose	Hemicellulose	Lignin	Extractives
Stem	40.7 ± 0.7	26.9 ± 0.6	27.0 ± 0.0	5 ± 1.0
Bark	22.2 ± 3.2	8.1 ± 0.4	13.1 ± 5.4	25.2 ± 5.2
Branches	32	32	21.5 ± 5.9	16.6 ± 7.1
Needles	29.1	24.9	6.9 ± 0.8	39.6 ± 1.3
Stumps	36.4	28.2	19.5	18.7
Roots	28.6	18.9	29.8	13.3

Growth-related properties

Microscopic or anatomical properties

Scots pine has a similar anatomy to other conifer species (Moore, 2011). A defining anatomical characteristic of pines are large, vertically orientated resin canals (Figure 2.1). The dimensions of softwood fibres (tracheids) affect paper characteristics such as opacity and tear resistance (Dinwoodie, 1965). As Scots pine has been extensively used in paper making, dimensions for its tracheids have been comprehensively reported (e.g., Havimo, Rikala and Sipi, 2009). However, softwood anatomy, particularly in the radial and tangential dimensions (i.e. tracheid widths and lumen

Table 2.2 Fibre characteristics of Scots pine.

Tracheid dimension	Value	Reference
Length (mm)	1.0–2.6	Mencuccini, Grace and Fioravanti (1997)
Radial width (μm)	19–68	Forest Research (unpublished data)
Tangential width (μm)	21–65	Forest Research (unpublished data)
Wall thickness (μm)	0.5–8.5	Forest Research (unpublished data)
Lumen diameter (μm)	19–45	Forest Research (unpublished data)

Table 2.2 is an oversimplification, included for comparison with Sitka spruce (Moore, 2011). It is more usual and more meaningful to see the variation in anatomical properties by their radial positions in the stem, including ring number and inter-ring position (i.e. earlywood or latewood). Cell diameters change notably between earlywood and latewood in the radial direction (Figure 2.2). Cell diameters increase with ring number from the pith, hence tree growth. Cell wall thickness also increases with tree growth (Figure 2.3), most markedly in latewood. A combination of these changes in wood microstructure are observable as changes in solid wood density (see Density, page 14), which is important for a wide range of uses of wood. Microfibril angle (MFA) in the cell walls, another anatomical factor of critical importance for wood or fibre stiffness[3], decreases with tree growth. In Scots pine (Auty, 2011; Auty, Gardiner *et al.*, 2012), similarly to other pines (Jordan *et al.*, 2005; Moore, Cown and McKinley, 2014) and Sitka spruce (McLean, 2008), MFA decreases with increasing ring number and increasing height in the stem (Figure 2.4). These trends in anatomical features cause corresponding trends in the mechanical properties of solid wood (see Bending strength and stiffness, page 18). In particular, as cell wall thickness increases and MFA decreases, there are generally positive effects for the end uses of wood.

Figure 2.3 Variation in cell wall thickness in Scots pine from northern Scotland (Forest Research, unpublished data).

Figure 2.2 Radial variation in typical cell diameters in Scots pine grown in northern Scotland (Forest Research, unpublished data).
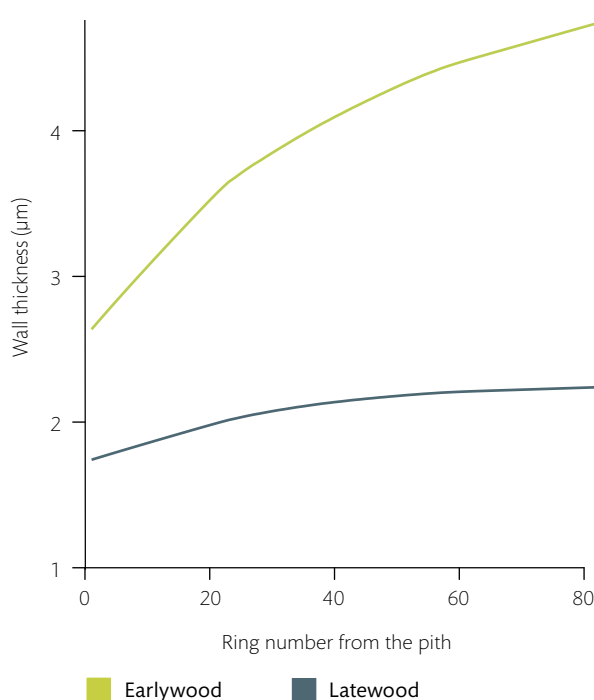
Figure 2.4 Variation in MFA in Scots pine grown in northern Scotland (data from Auty, 2011).
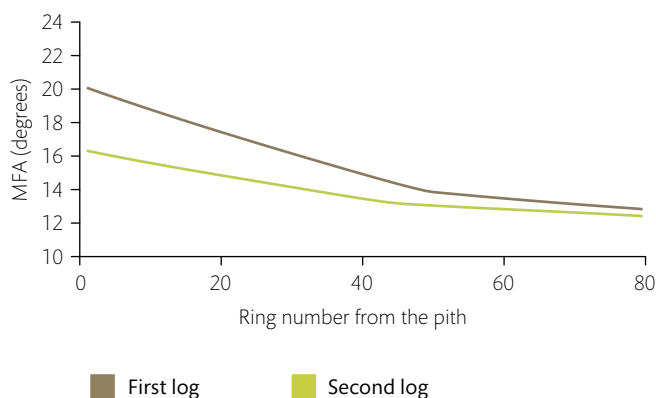
Ring width, earlywood and latewood

Annual rings are formed by the diameter growth of a tree and their size is a visual indicator of sawn wood quality, with narrow rings being associated with higher quality. The most recently formed wood is found on the outside. In Scots pine, like most temperate trees, annual rings are clearly visible to the naked eye, distinct in earlywood and latewood[4]. Typically for most even-aged conifer crops, radial growth is initially rapid and then it slows down. The rapid initial growth stage demands a lot of water, and while the proportion of latewood

3 MFA is the alignment of cellulose fibrils relative to the longitudinal axis of the wood cell. MFA is considered to increase as the cellulose fibrils become less aligned with the longitudinal axis. Lower alignment, equivalent to a higher MFA, indicates there is less reinforcement of the structure, and wood and fibre stiffness decrease accordingly. Therefore, a high MFA causes low fibre and wood axial stiffness (Cowdrey and Preston, 1966).

4 Earlywood is lighter in colour than latewood due to its higher porosity and lower density. Earlywood is formed during spring and has large cells to favour transportation of fluid, while latewood is formed during summer and has thicker walled cells that favour structural support of the tree.

increases slightly in later growth rings, the most noticeable change is the decreasing width of earlywood (Figure 2.5). The rapid initial growth stage is also responsible for lower quality wood known as juvenile corewood (Burdon *et al.*, 2004). The age of transition between juvenile corewood and mature outerwood depends on the definition property used (Moore, 2011), and therefore no particular value for age exists[5]. In typical British even-aged Scots pine forests, this period of rapid radial growth lasts for approximately 40 years, while MFA levels off around ring 50 (see Figure 2.4), considerably higher than the equivalent value (ring 15) estimated for Sitka spruce (Moore, 2011). Elsewhere, much lower values are reported: Auty *et al.* (2014) used an arbitrary 20 years for British Scots pine, while Sauter and Munro (1999) used 22 years for German Scots pine based on latewood density.

Figure 2.5 Typical ring widths of Scots pine from an even-aged plantation in northern Scotland (data from Auty 2011).
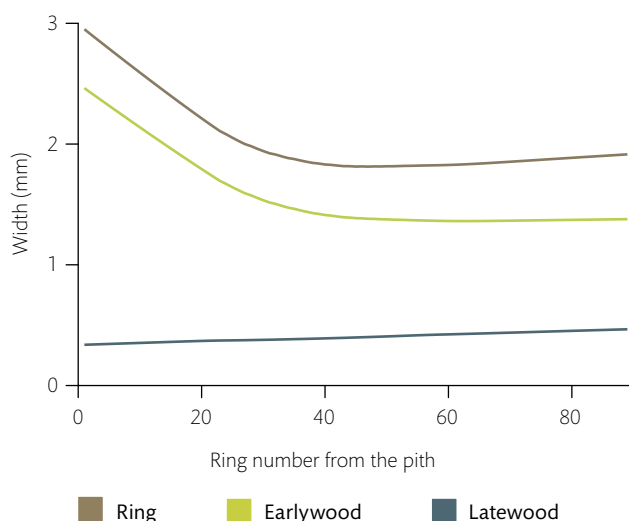
Sapwood and heartwood

The sapwood and heartwood of Scots pine are visibly different (Figure 2.6) due to the presence of extractives (see Chemical composition, page 7). Extractives can offer benefits for wood in service such as increased durability, and in the case of Scots pine they limit the growth of blue stain fungus (see Colour and appearance, page11). In addition, extractives may contain desirable chemicals that can be collected in industrial processes (see Chemicals, page 30). Conversely, extractives can also pose problems for engineered products (Nussbaum and Sterley, 2002) or in pulping (Hillis and Sumimoto, 1989). Therefore, for a number of reasons it is desirable to have information on the

5 Lachenbruch, Moore and Evans (2011) provides further reading on this subject and reviews the range of hypotheses.

amount of heartwood present. Beauchamp (2011) carried out an investigation into the amount of heartwood in Scots pine grown in northern Scotland and showed an average linear decrease in heartwood diameter from approximately 60% of the stem diameter at breast height to 0% when the stem diameter reached approximately 7 cm (Figure 2.7).

Figure 2.6 Heartwood and sapwood of freshly cut Scots pine from northern Scotland, where the heartwood is visibly drier (top); on drying this difference is visible, but less pronounced (middle); however, after continued exposure to ultraviolet light, for instance from the Sun, then heartwood will eventually become darker in colour (bottom).

Figure 2.7 Heartwood profile in a typical 60-year-old, yield class 12, Scots pine tree (Beauchamp, 2011; Fonweban *et al.*, 2011).

Figure 2.8 A longitudinal section depicting the radius of a tree showing the process by which a dead knot is formed (after Fujimori, 2001). The branch stops growing in diameter and forming annual rings (at the end of period a); then after several years it dies (at the end of period b). The branch remains attached to the tree for a number of years while the stem grows in diameter; it will eventually become detached leaving a stub (at the end of period c). Following the death of the branch the adjacent rings curve towards the pith to begin the stub-occlusion process (throughout period d). Once occlusion is complete, clear wood is formed once again (period e). In this example, timber produced during periods a and b will contain sound knots, from period c will contain dead knots, and 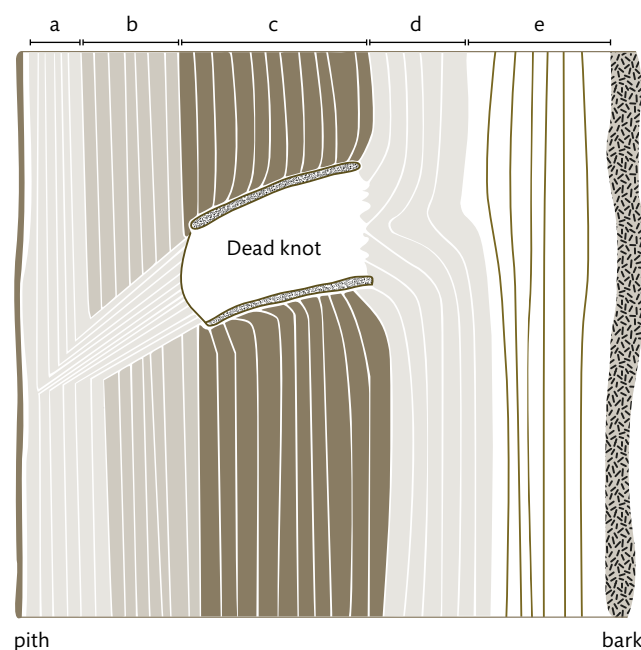from period e will contain clear wood; while timber produced from period d will be free of knots, there will be local deviations in tracheid alignment or grain associated with the stub-occlusion process. The timber produced during period c will have the least desirable sawn wood properties.

Knots

Knots are remnants of branches in sawn wood. Knot geometries are shaped by the branching habit of the species (Duchateau *et al.*, 2013) and the growing conditions of the trees. Knots typically have a detrimental effect on sawn wood by locally distorting the wood fibres proportional to their frequency and size, the latter of which is predominantly determined by branch diameter. Knots are more of a problem in Scots pine timber than in Sitka spruce for two reasons. First, like other pines (Woollons, Haywood and McNickle, 2002; Weiskittel *et al.*, 2010), Scots pine is typically uninodal, which means it normally produces one distinct whorl in a growing season that is free of inter-whorl branches (Auty, 2011). This is beneficial in terms of producing sections of clear wood, but also problematic in that knot clusters are large when they occur. Second, as Scots pine is a light-demanding (shade-intolerant) species, it does not retain a deep, living crown, and its branches die quickly. The stem will continue to grow around the dead branches until they fall off (Figure 2.8). This process leads to large occluded (dead) knots in sawn wood (Figure 2.9). These dead knots are not connected to the surrounding fibre, which reduces the strength of timber; and they can also fall out leaving holes which restrict its use (for example, in Cladding, see page 25). The size of dead knots is affected by the diameter of the branch and the length of time that

the dead branch remains attached to the tree[6]. In addition to creating larger knots, branches of larger diameter have more strength, and consequentially remain attached for a longer period of time when they die (Kellomäki, 1983). Problems associated with dead knots are compounded in Scots pine by knots occurring in clusters. Pruning (see page 22) can be used to effectively reduce the impact of dead knots on sawn timber.

Auty (2011) studied the branching habit of Scots pine growing in typical conditions in northern Scotland. The number of branches produced per year was proportional to the nodal length (i.e. the annual height increment): more branches were produced on longer nodes. On average, four branches were produced per year, and the branch of the largest diameter was found at approximately 70% of the tree height (Figure

6 On average, branches of Finnish Scots pine remain alive for seven years after their active growth has ceased, and the period from branch death to occlusion (i.e. healing) lasts a further 40 years (Makinen, 1999). No comparable study has been made in Great Britain.

Figure 2.9 (a) sound knot; (b) dead or partially inter-grown knot; and (c) encased or bark ringed knot.

2.10). Branch size increased with tree age, and for any given age larger branches were produced on trees of larger diameter. Comparing trees of a similar age and diameter, and grown at a similar spacing, the average branch diameter and number of branches per whorl in northern Scotland (57°N 4°W) (Auty, 2011) is almost identical to southern Finland (62°N 30°E) (Pukkala, Karsikko and Kolstrom, 1992). This suggests that silvicultural choices will have a similar impact across regions. While pruning can be used as a reactive silvicultural technique to reduce the impact of branches, techniques such as spacing (see Choice of silviculture, page 20) and thinning (see Pruning, page 22) can be used to proactively control branches. Breeding trees for favourable branch characteristics (see Choice of genetic material, page 19) could offer another means of branch control in the future.

Figure 2.10 Number and size of branches in a typical Scots pine (derived from Auty, 2011) compared to Sitka spruce (derived from Moore, 2011). The dashed lines indicate the living crown. Scots pine does not produce inter-whorl branches and so has fewer branches than Sitka spruce.
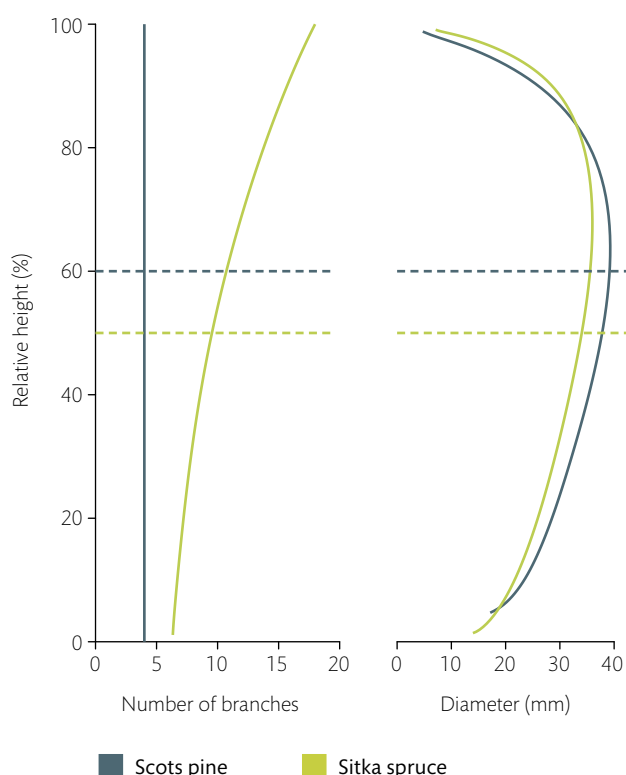
Spiral grain

Spiral grain is the spiral alignment of the longitudinal tracheids relative to the stem axis. The exact cause of formation remains unknown. It is a cause of timber downgrading under visual grading standards (e.g. BS 4978), and is also a cause of distortion on drying. The radial trend in spiral grain in Scots pine (Figure 2.11) follows a similar pattern to Sitka spruce (Brazier, 1967; shown in Moore, 2011). The average spiral grain angle in Scots pine trees growing in northern Scotland reached a maximum of approximately 3° at ring 10 then decreased to an average of around 1° at ring 50. These angles are lower on average than those observed in Sitka spruce for equivalent ring numbers, but there is considerable variation in the angles at each ring number for both species.

Figure 2.11 Radial variation in spiral grain of Scots pine growing in northern Scotland, based on average values for breast height (1.3 m) discs from 66 trees measured by Forest Research. The shaded area represents approximately 70% of the variation.
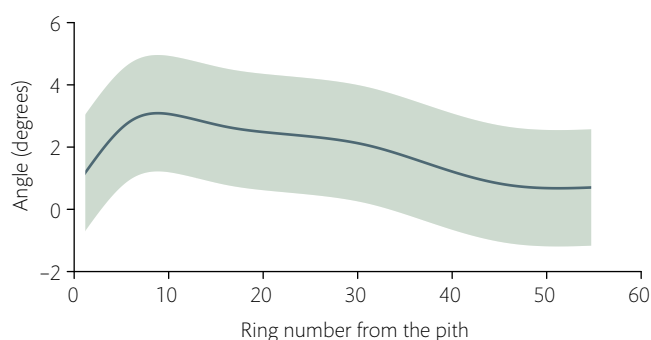
Physical properties

Colour and appearance

The heartwood of Scots pine is normally described as a light reddish brown (Figure 2.6), giving rise to the common trading name of redwood or red deal, although this is more frequently applied to imported wood. The sapwood is a pale yellow. The well-defined growth rings and clear

demarcation of latewood accentuate the grain[7]. Scots pine is generally considered an attractive wood and is therefore found in furniture, although pine furniture sold in Great Britain tends to use imported wood because home-grown softwood is very rarely appearance-graded (see Appearance grade timber, page 24). Resin pockets are medium in size and evenly distributed throughout the end grain (Figure 2.1).

Occasionally the sapwood can appear to be blue as the result of fungi; this is known as bluestain, and it can occur in freshly felled logs in the damp, mild conditions typical of Scottish summers (Figure 2.12). While bluestain can be a niche character feature for timber of certain species, this is not normally true for Scots pine. Bluestain, at least in its early stages, has no effect on the mechanical properties (Humar and Vek, 2008), but its appearance (and in more extreme cases its smell), make it unattractive to customers. A survey conducted by Macdonald and Gardiner (unpublished) demonstrated bluestain to be the primary concern of processors in northern Scotland, where it was perceived to be a more serious defect than knots.

Figure 2.12 Bluestain in a freshly felled Scots pine log.


Image courtesy of Ivor Davies

7 Grain is a term given to the longitudinal alignment of tracheids (e.g. spiral grain), but it is also widely applied to the appearance of cut wood, and in particular to the appearance of growth rings in a longitudinal section (Figure 2.8). The term end grain typically refers to the appearance of growth rings in cross-section (Figure 2.6).

Moisture content

Wood is a hygroscopic material which continually exchanges water with the atmosphere; its moisture content will change with the temperature and relative humidity of the atmosphere around it. When wood is considered green[8] it is freshly cut from a tree. Green wood is full of water and under normal atmospheric conditions it will begin to lose water to the atmosphere. The measurement used to quantify the water present in wood is moisture content, which is expressed as the ratio of the mass of water to the mass of dry wood. There is a large variation in the amount of water in freshly cut Scots pine; recent figures from Finland indicate that the range of heartwood moisture content was between 26 and 44%, and that sapwood moisture content ranged from 100 to 180% (Karttunen, Leinonen and Sarén, 2016). The moisture content of freshly cut wood has an important impact on its mass, and it therefore affects handling costs in cases where mass is used to either estimate volume, or directly as the measure of monetary value; both of which occur frequently in Great Britain. Another important effect of fresh wood moisture content is on calorific value (see Thermal properties, page 18). Eventually, the high moisture content in fresh wood drops significantly, a process that can be accelerated by kiln-drying. At stable atmospheric conditions of relative humidity and temperature, wood will (in theory) reach an equilibrium moisture content relative to those conditions (Figure 2.13; Table 2.3). In reality, atmospheric conditions are unlikely to be stable for long enough for this equilibrium to be achieved.

In atmospheric conditions that are representative of sawn wood in service (indoor or outdoor), equilibrium moisture content is below the fibre saturation point; the fibre saturation point is approximated at 30% moisture content and is the point below which no free water in the wood cell lumens is considered to be present. Below the fibre

Figure 2.13 Illustrative equilibrium moisture contents of wood at various conditions of temperature and relative humidity (after Simpson, 1973; and Glass and Zelinka, 2010).
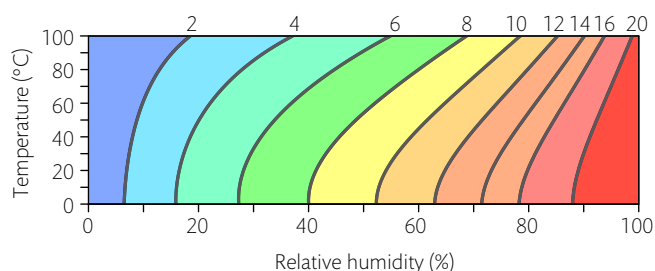
8 Green wood is more liberally applied and is often used to describe wood that has not yet been dried, irrespective of how long ago it was cut.

Table 2.3 Values of equilibrium moisture content for British Scots pine (Ahmet *et al.*, 2000).

Temperature (°C)	Relative humidity (%)		
	35	55	75
10	9.0	12.4	15.1
20	8.2	11.2	14.0
30	7.4	10.6	13.7

saturation point, changes in the equilibrium moisture content signify changes in the fixed water chemically bound to the wood cell walls. These changes in the fixed water content affect the physical and mechanical properties of wood (Table 2.4), with a 1% change in moisture content between 8 and 12% causing a 4% change in the air dry modulus of rupture or crushing strength; a 4% change in moisture content will cause a 16% change in the air dry modulus of rupture or crushing strength. In addition, changes in fixed water content are accompanied by dimensional changes (see Shrinkage, page 16) that must be taken into consideration when using sawn wood, or when applying adhesives or coatings. Moisture also participates in wood deterioration, both directly and by providing the growth conditions for mould (e.g. bluestain, see Colour and appearance, page 11) and wood-decay fungi. Small changes in equilibrium moisture content below the fibre saturation point are therefore very important and attract extensive research.

The same piece of wood at a given set of atmospheric conditions can have a different equilibrium moisture content depending on whether it is in the process of taking water from (adsorption) or giving water to (desorption) the atmosphere. The adsorption or desorption of water can be tracked with a sorption isotherm, and the difference between them is known as hysteresis (Figure 2.14). Therefore, wood moisture content not only depends on atmospheric conditions, but also on the history of those atmospheric conditions.

Wood has a higher moisture content at a given temperature and humidity when drying for the first time, compared to any subsequent cycles of wetting or drying. The initial desorption isotherm is of particular interest when seasoning sawn wood, and needs to be considered in industrial kiln-drying. When drying, the equilibrium moisture content of wood is higher than when wetting, although the difference is temperature-dependent and decreases with increasing temperature (see Figure 2.11 in Moore, 2011). The sorption isotherms equivalent to those produced for Sitka spruce at a range of temperatures (Moore, 2011) are not currently available for British Scots pine, but similar behaviour is expected.

Moisture content collected from 3651 Scots pine wood samples over a range of latitudes in northern Europe (including northern Scotland) during adsorption and desorption were presented by Feilke *et al.* (2011) (Table 2.5).

Figure 2.14 A sorption hysteresis at 32.2 °C for North American Douglas fir (*Pseudotsuga meniesii*) (after Spalt, 1958).
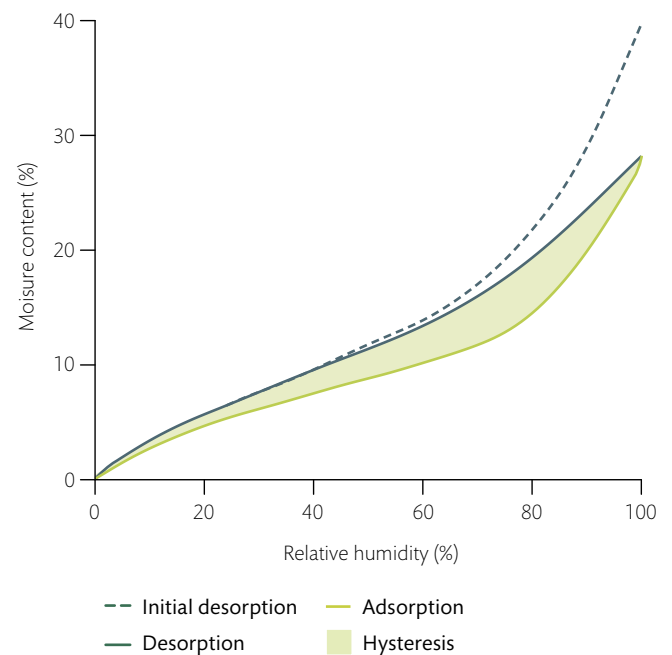
Table 2.4 Strength changes in mechanical properties of British Scots pine associated with changes in moisture content (Lavers, 2002). Changes are not linear throughout the ranges of moisture content and the magnitude of change increases as the wood gets drier. The numbers correspond to the change in the property per 1% change in moisture content within the respective range.

Mechanical property	Mean		Moisture range (%)			
	Air-dried	Green	8–12	12–16	16–20	20–24
Modulus of rupture (MPa)	88.9	46.2	3.79	3.28	2.83	2.38
Modulus of elasticity (GPa)	10	7.31	0.207	0.179	0.179	0.152
Maximum crushing strength (MPa)	47.4	21.9	2.46	2.03	1.67	1.39
Side hardness (kN)	2.98	2.22	0.0534	0.0534	0.0489	0.0445
Shear parallel to grain (MPa)	12.7	5.93	0.634	0.531	0.448	0.359

Table 2.5 Moisture content of northern European Scots pine wood during adsorption and desorption at 25°C. The values represent averages of 3651 samples with standard deviations in parenthesis (Feilke *et al.*, 2011).

Relative humidity (%)	Heartwood		Sapwood	
	Adsorption (%)	Desorption (%)	Adsorption (%)	Desorption (%)
15	4.27 (0.38)	5.61 (0.45)	4.7 (0.26)	5.44 (0.25)
35	6.72 (0.33)	8.24 (0.3)	7.25 (0.24)	8.65 (0.25)
55	9.41 (0.32)	11.24 (0.32)	10.08 (0.26)	12.25 (0.26)
75	13.29 (0.42)	16.00 (0.49)	14.09 (0.34)	16.66 (0.34)
95	22.84 (1.15)		23.83 (0.79)	

A difference can be observed between heartwood and sapwood: sapwood consistently had a higher moisture content under equivalent conditions, but much more so during adsorption than desorption because Scots pine heartwood extractives are known to repel moisture (Venäläinen *et al.*, 2004). The amount of fixed water wood can hold is proportional to oven-dry density: denser wood has more wood material per given volume for water to interact with. The opposite is true for free water: denser wood is less porous and therefore there is less space for water in the lumens. In Feilke *et al.* (2011) the variation in the mass of water contained by individual samples at a particular stage (e.g. adsorption, 55% relative humidity and 25°C) can be almost perfectly described by the variation in their oven-dry densities (i.e. with no water present).

In summary, wood hygroscopicity is complicated, and is still not fully understood after 150 years of global study. Attempts to predict moisture content based on generic tabulated values are prone to error because of the dependence of moisture content on temperature, relative humidity, time, history and biological variation in anatomical microstructures. Whether that error is acceptable depends on the wood's end use, but there are several production processes including kilning, gluing and coating which are affected by moisture content. One objective of industrial wood modification processes (see Wood modification, page 27) is to control wood hygroscopicity.

Density

Wood density changes with moisture content, and therefore it is normally stated along with moisture content, depending on what the wood will be used for. The most common indicators used are air-dry, basic and green (Moore, 2011)[9].

Air-dry density is used in engineering; green density is mainly used in roundwood transport and monetary valuation during harvesting; basic density is used by both processors (to estimate how much dry material is present in the green volume) and scientists (to estimate the amount of carbon stored in trees). Air-dry density is taken to represent density at 12% moisture content; the moisture content of green density and basic density are generally not recorded, even although they also depend on moisture content. Green density and basic density are regarded as representative of wood in trees.

Since air-dry density is used by end users (e.g. in timber grading, see Structural timber, page 25), and because it is linked to a known moisture content, it is the most appropriate density value to gauge the suitability of wood for different end products. Air-dry density has a generally positive relationship with mechanical properties; species with higher densities usually possess superior mechanical properties (Armstrong, Skaar and de Zeeuw, 1984). Because wood material density without voids is constant, any variation observed in wood densities between species are primarily based on anatomical differences, with a smaller effect attributable to extractives.

Relative to British Sitka spruce (Moore, 2011), British Scots pine has higher density: at the accepted definition of air-dry density (12% moisture content), British Scots pine has a density of 510 kg m^{-3} (Lavers, 2002). The basic density of British Scots pine is 418 kg m^{-3} (Macdonald, Gardiner and Mason, 2009). The green density of British Scots pine is 625 kg m^{-3} at 50% moisture content (Lavers, 2002) or 1020 kg m^{-3} when freshly felled (Matthews and Mackie, 2006); the latter value corresponds to the middle of the measured range of Swedish Scots pine sapwood (Skog, Vikberg and Oja, 2010).

The variation in wood density within a species is usually considerable. As the growing environment and climate affect a tree's anatomical features (see Microscopic or anatomical properties, page 7) on a sub-annual basis, it similarly affects density. Density is therefore extremely variable for a species

9 Density is the ratio of mass to volume. Green density is the ratio of green mass to green volume. Basic density is the ratio of oven-dry mass to green volume.

like Scots pine with such a wide distribution. Within a species, this variation in density is often used as a surrogate for mechanical properties because of the comparative ease with which it can be measured. In contrast to Sitka spruce (McLean et al., 2015), the relationship between clear (i.e. knot-free) wood stiffness and density in Scots pine is consistently positive. The relationship between wood density and wood strength is even more apparent (Figure 2.15).

The variation in wood density within a species can be broken down into three components: (1) the regional variation between forest stands; (2) the variation between trees within a stand; and (3) the variation within a single tree. When examining the basic density of timber battens from

six sites in northern Scotland, Macdonald, Gardiner and Mason (2009) showed that the variation within a single tree was the most significant of these three components: it accounted for 90% of the variation. Being able to understand or account for the variation within a single tree is therefore an important first step before other sources of variation are able to be considered. The geographical range in the study by Macdonald, Gardiner and Mason (2009) was small relative to the global distribution of Scots pine, and so it is worth considering other studies spanning a wider range of latitudes. Multinational studies (Grekin and Verkasalo 2010; Feilke et al., 2011) in northern Europe have indicated that Scots pine wood density decreases from south to north. No detailed investigation for countrywide variation in British Scots pine wood density exists. Nonetheless, the northern European studies show a significant variation in density that is not explained by latitude.

Figure 2.15 The relationship of clear wood stiffness (modulus of elasticity) and strength (modulus of rupture) to density in British Scots pine (data from Auty, 2011).

Auty et al. (2014) described the changes in basic density both within and between trees growing in even-aged Scots pine plantations in northern Scotland. Density was observed to increase from the pith to the bark, and to decrease slightly with height in the stem (Figure 2.16). The decrease in wood density with height was noted as negligible in the

Figure 2.16 Variation in wood density of 80-year-old pine trees growing in northern Scotland (after Auty, 2011). Density is presented at 12% moisture content using a conversion detailed in Simpson (1993).
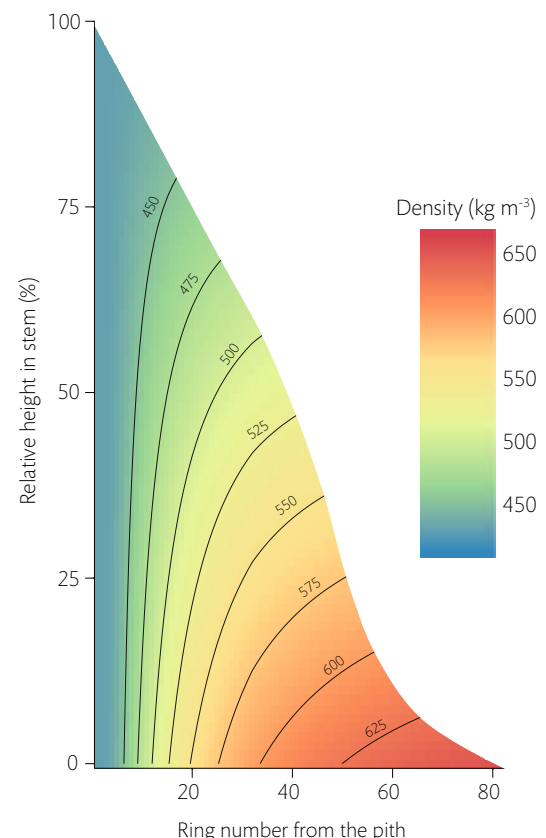
first 20 rings from the pith, then approximately linear in the outer rings (i.e. rings greater than 20 from the pith). The pith-to-bark or radial trend in Scots pine wood density is markedly different to Sitka spruce, where the highest density wood is found within the first seven growth rings (McLean, 2008; Gardiner *et al*., 2011; Moore, 2011). The increasing wood density from pith to bark in Scots pine is mainly due to the increasing relative proportion of latewood (Figure 2.17) and the increasing density of that latewood in individual trees as the forest stand ages.

Figure 2.17 Radial variation in average ring, earlywood and latewood density at 8% moisture content (Forest Research, unpublished data).
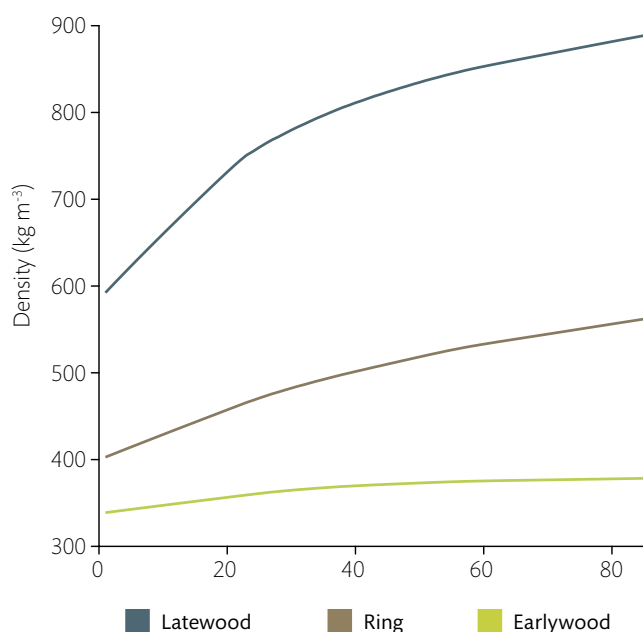
Shrinkage

Wood starts to shrink when water is lost from its cell walls (i.e. below the fibre saturation point). Since the equilibrium moisture content of sawn wood in service is below the fibre saturation point (see Moisture content, page 12), shrinkage is an important consideration throughout the processing and utilisation of wood. Wood shrinkage is anisotropic, occurring at different rates in different directions (Figure 2.18).

Wood shrinkage in the longitudinal direction along the axis of the wood cells is usually 10 times less than shrinkage across the axis. There are also differences in the two traverse axes, where the shrinkage tangential to the growth rings is normally around one and a half to two times that of the shrinkage parallel to the direction of radial growth (Spear and Walker, 2006), which is why roundwood splits on drying. Consequently, shrinkage is either specified by direction (e.g. radial) or as a combination of all three (volumetric).

Figure 2.18 The three axes of wood are described according to the direction of the grain and the direction of growth. The longitudinal axis (L) is parallel to the grain. The tangential axis (T) is perpendicular to the grain and tangential to the growth rings, while the radial axis (R) is perpendicular to the grain and in the direction of radial growth. The three axes are mutually perpendicular to each other.
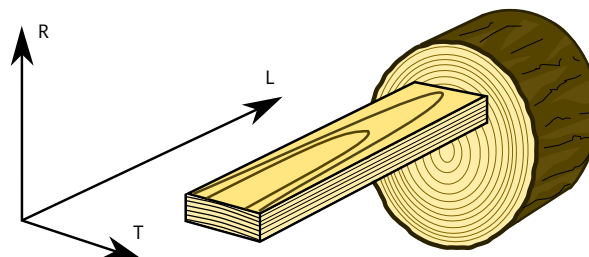
Early studies on British Scots pine determined values of 4.5% tangential shrinkage and 3% radial shrinkage between the green condition and 12% moisture content (Forest Products Research Laboratory, 1965), which are similar to comparably produced values for Sitka spruce (Moore, 2011). It is more conventional to report shrinkage values from green to oven-dry because this avoids any ambiguity over the actual moisture content of the test pieces (see Moisture content, page 12). As shrinkage is linear over this range of moisture contents (see Figure 2.16 in Moore, 2011) the calculation of shrinkage at a nominal moisture content is straightforward. However, a single shrinkage value per species is ultimately misleading because, like all wood properties, shrinkage is variable. Grekin and Verkasalo (2010) studied the radial and tangential shrinkage of Scots pine distributed in Finland and Sweden: shrinkage in both directions increased from the pith to the bark and decreased from the bottom to the top of the tree, mirroring the variation in wood density (see Density, page 14; Figure 2.16). The northern sites had lower density and lower shrinkage, because in wood of relatively lower density there is less wood material to interact with water, and also less material to move (Figure 2.19). The ratio between tangential and radial shrinkage decreased with distance from the pith, and both tangential and radial shrinkage became more stable in the outerwood.

Partly due to the comparative difficulty of measurement and partly because its lower magnitude has a much less obvious impact on end users, the variation in longitudinal shrinkage has been studied less than that of transverse shrinkage; consequentially there is limited information available for Scots pine: Rijsdijk and Laming (1994) produced an average of 0.16% longitudinal shrinkage in Dutch-grown Scots pine between green and oven-dry based on a very small number of measurements (20 pieces). Most of what is known about the mechanisms underlying longitudinal shrinkage in wood

Figure 2.19 The relationship between radial shrinkage and basic density in Scots pine (derived from Mazet and Nepveu, 1991).

Figure 2.20 The relationship of shrinkage to MFA in *Pinus radiata* (Harris and Meylan, 1965).
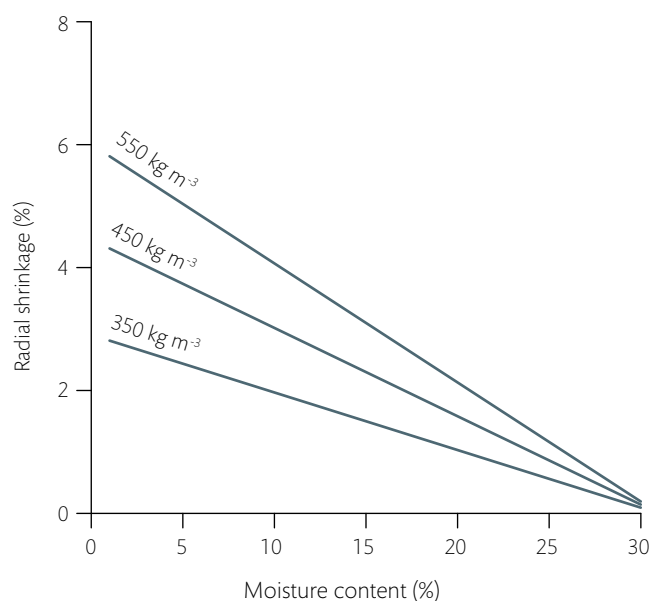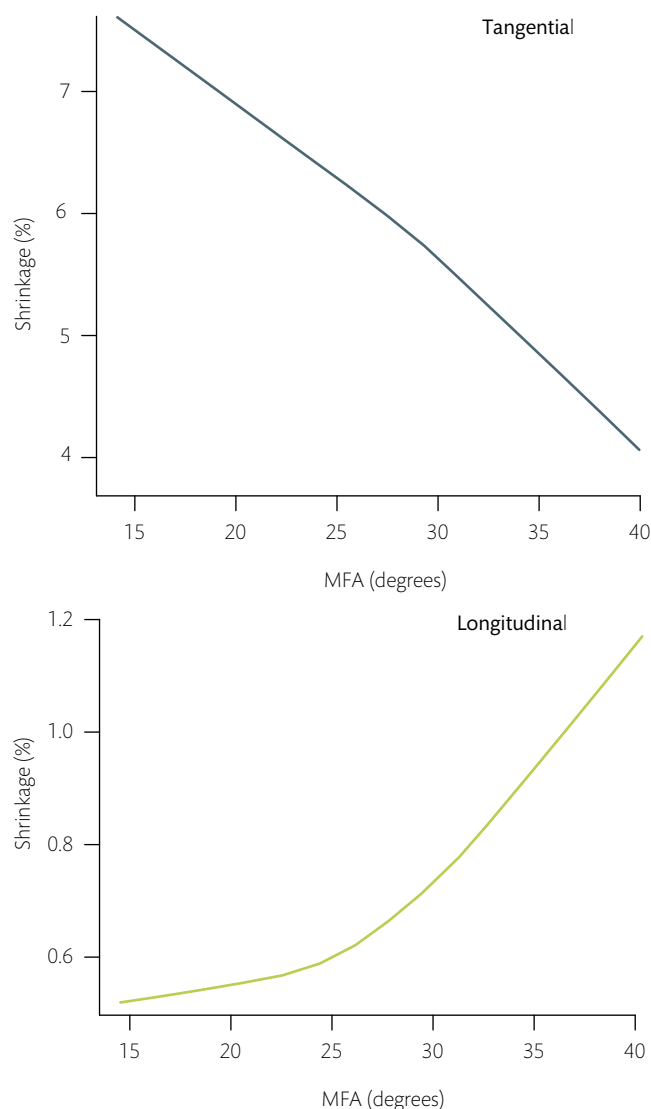

comes from research on radiata pine (Harris and Meylan, 1965; Meylan, 1972). Longitudinal shrinkage is primarily determined by the MFA, where higher angles lead to greater shrinkage. Conversely, higher MFAs restrict transverse shrinkage as their reinforcement effect shifts from along the cell axis to across it (Figure 2.20). Any relationship to wood density is not apparent at the range of MFAs for which longitudinal shrinkage has been studied (Yamashita *et al*., 2008), but compression wood (defined in Moore, 2011), which has a different chemical composition (Brennan *et al*., 2012), has approximately twice the longitudinal shrinkage of normal wood at an equivalent MFA (Harris and Meylan, 1965).

The examples presented here are idealised; in the real world, shrinkage in rectangular boards cut from logs above the fibre saturation point is also subject to local variations in grain angle, both along the axis and with respect to the curvature in growth rings relative to the shape of the boards. This compounds the effects described above and distorts these boards as they dry (see Drying, page 26).

Natural durability

According to the reference tests (British Standards Institute 1994a, 1994b), the sapwood of European[10] Scots pine is not durable (Class 5) and the heartwood of European Scots pine is slightly (Class 4) to moderately durable (Class 3). The variability in heartwood durability is usually linked to position in the stem (Davies, unpublished), suggesting that durability

is affected by tree age. Typically the outer, most recently formed, heartwood is the most durable. The resistance to decay fungi is normally associated with the group of extractives known as stilbenes (Chong, Poutaraud and Hugueney, 2009), which have been shown to be present in much higher quantities in older trees (Venäläinen *et al*., 2003; Hovelstad *et al*., 2006). However, there is considerable variation in stilbene content between individual trees and this appears to have a strong genetic component (Partanen *et al*., 2011). Kiln-drying timber (Sehlstedt-Persson and Wamming, 2009) has been shown to have a negative impact on the durability of Scots pine heartwood, indictating that extractives are partly removed in the process.

Permeability

Both the heartwood and sapwood of pines have higher permeability than spruces (Moore, 2011) as the pits are

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10 A more specific origin is not provided, therefore in principle this includes British Scots pine.

larger and the ray cells are thinner (Olsson *et al.*, 2001). However, pine extractives have a considerable effect on permeability (Olsson *et al.*, 2001). The higher the extractive content, the lower the permeability (Behr, Larnøy and Bues, 2011). Scots pine sapwood is therefore classed as easy to treat with preservatives (British Standards Institute, 1994a), meaning it can be completely penetrated by pressure treatment without difficulty. On the other hand heartwood is classed as difficult to treat (British Standards Institute, 1994a), meaning that 3–4 hours of pressure treatment may result in no more than 3–6 mm of lateral penetration. In sapwood, the relative proportion of latewood has a positive effect on permeability (Zimmer, Larnøy and Koch, 2011), and both of these decrease with the latitude of tree growth.

Thermal properties

The thermal properties of interest were defined in Moore (2011); these are largely independent of species and much more dependent on moisture content. The thermal conductivity of Scots pine (0.14 W m^{-1} K^{-1}) is higher than that of Sitka spruce (0.10 W m^{-1} K^{-1}) due to its higher basic density. The higher density of Scots pine relative to Sitka spruce means that an equivalent volume of Scots pine will also burn for longer.

Mechanical properties

The main mechanical properties that are important for the use of wood were described in the Sitka spruce research report (Moore, 2011). Further detail of these properties are available in Kretschmann (2010) and are summarised for Scots pine in Table 2.6. In all of the reported cases, British Scots pine has more desirable mechanical properties than British Sitka spruce.

Bending strength and stiffness

Strength and stiffness are often confused. Strength is the ability of a material to withstand load without breaking, while stiffness is the ability of a material to resist a load without deforming. Bending strength and stiffness are quantified as the modulus of rupture (MOR) and modulus of elasticity (MOE), respectively. Along with wood density (see Density, page 14) these properties form the structural grading criteria for sawn timber (see Structural timber, page 25). For British Scots pine, the mean MOE of small, clear (defect-free) specimens is 9.5 GPa, and for full-size specimens it is 9.6 GPa. The mean MOR of small, clear specimens is 87 MPa, and for full-sized specimens it is 42 MPa. The MOE is lower but the MOR is comparable with values reported for

Table 2.6 Mechanical properties of wood from UK-grown Scots pine. Values presented are for wood at 12% moisture content.

Mechanical property	Reference	Sample type*	Value
Bending strength (MPa)	Auty (2011)	SC	84
	Macdonald, Gardiner and Mason (2009)	FS	45
	BRE (unpublished data)	FS	39
	Lavers (2002)	SC	89
Bending stiffness (GPa)	Auty (2011)	SC	8.9
	Macdonald, Gardiner and Mason (2009)	FS	9.31
	BRE (unpublished data)	FS	9.59
	Lavers (2002)	SC	10
Work to maximum load (kJ m^{-3})	Lavers (2002)	SC	103
Work to total fracture (kJ m^{-3})	Lavers (2002)	SC	134
Impact bending (mm)	Lavers (2002)	SC	710
Compression strength parallel to grain (N mm^{-2})	Lavers (2002)	SC	47
Compression strength perpendicular to grain (N mm^{-2})	Not available	-	-
Side hardness (N)	Lavers (2002)	SC	2980
Shear strength parallel to grain (N mm^{-2})	Lavers (2002)	SC	13
Modulus of rigidity (N mm^{-2})	Not available	-	-
Resistance to splitting in radial plane (N mm^{-1})	Lavers (2002)	SC	10
Resistance to splitting in tangential plane (N mm^{-1})	Lavers (2002)	SC	13

*SC = small, clear specimen, typically 20 mm × 20 mm × 300 mm; FS = full-sized specimen containing defects, typically 50 mm × 100 mm × 3 000 mm.

Southeast Finland (Malinen and Verkasalo, 2010; Hautamäki *et al.*, 2014). The within-tree variations in both MOE (Figure 2.21) and MOR (Figure 2.22) are closely related to the trends in MFA and density (Auty, 2011).

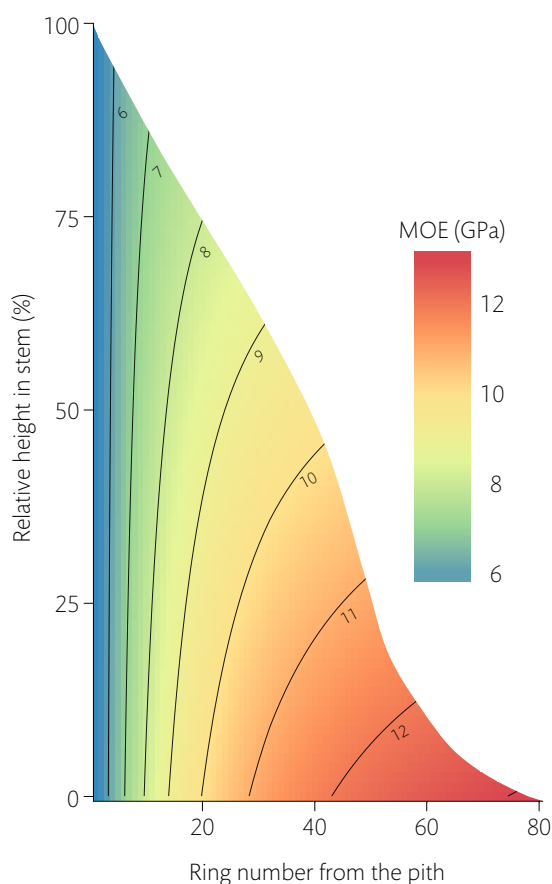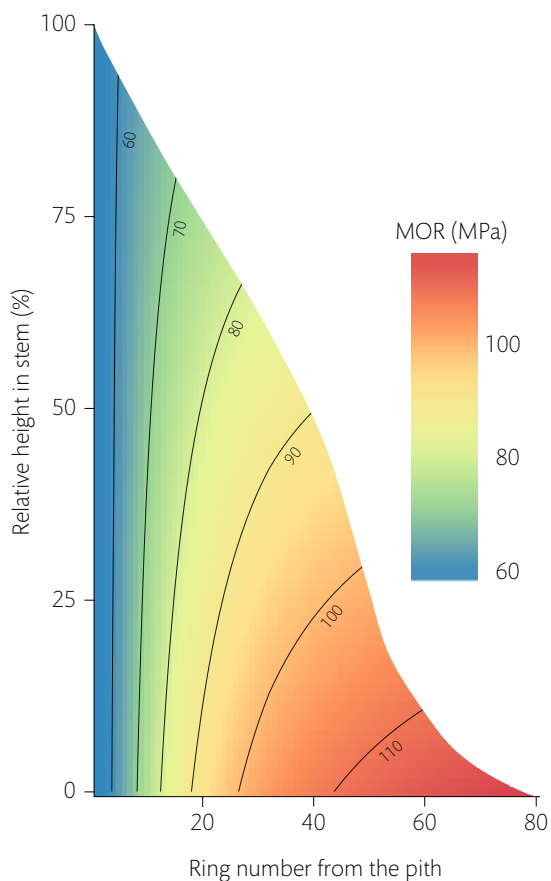**Figure 2.21** Variation in MOE within Scots pine trees growing in northern Scotland (after Auty, 2011).

Effects of site, silviculture and genetics on selected wood properties

Forest location

In addition to affecting tree growth, the location of planted forests has an impact on stiffness and wood density. Anecdotally, slower growth in the north was thought to produce better quality wood, but evidence now suggests it may not be so straightforward. Research that has been completed since the publication of the Sitka spruce research report has shown that the more exposed Sitka spruce sites generally produce timber with lower stiffness (Moore *et al.*, unpublished), with an additional gradual decline in wood stiffness associated with increasing latitude (Beauchamp *et al.*, 2014). No comparable study covering such a broad range of growing environments currently exists for British Scots pine. However, in Scandinavia, the Finnish Forest Research Agency has shown that wood density (Grekin and Verkasalo, 2010), stiffness and strength (Malinen and Verkasalo, 2010) of Scots pine can decrease with increasing latitude. One proposed explanation (requiring more research) is that this could be attributed to the proportion of latewood present in the growth rings, where trees in the north have a shorter growing season and therefore produce less latewood.

In the same study, the amount of within-tree variation in wood properties decreased with increasing latitude, with northern trees having less variation between juvenile corewood and outerwood (Malinen and Verkasalo, 2010). In circumstances where homogeneity of properties is required (such as dimensional stability), this could be a benefit. The impact of latitude on knots is more difficult to quantify, as dead knots from material from southern sites tended to be bigger, but this material also had longer sections of clearwood between whorls due to a larger annual height increment (Verkasalo *et al.*, 2013).

Choice of genetic material

Genetic origin has a significant impact on the growth and wood properties of a tree. In Great Britain, the breeding programme for Scots pine began in the 1950s, just over a decade before the breeding programme began for Sitka spruce. Despite this, due to the lower commercial importance and longer rotation of Scots pine, its breeding programme is not as advanced as the one for Sitka spruce (Lee, 2004): to date selection has only been for height growth and stem form (Lee, 2002), with no consideration of wood properties. Currently there are no plans to move into

Figure 2.22 Variation in MOR within Scots pine trees growing in northern Scotland (after Auty, 2011).

a further cycle of selection. The breeding population that exists has the potential to produce seed orchards for gains of 14–20% in height growth or 5–19% in stem form[11] (Lee, 2002) relative to plants produced from registered seed stands. The currently available and most commonly used orchard material (SP70) is predicted to only achieve an 8% gain in height growth (Lee, 1999). It should be noted that the origins of many of these plus trees are unknown; it is believed that some may have grown from seed imported in the 19th century from France or Germany. Consequently, Scots pine trees from the existing seed orchards are unsuitable for use in the creation of native woodland.

Scots pine breeding programmes in other countries are largely similar to those in Great Britain (Pâques, 2013); the only countries to have entered a second cycle of selection are Sweden, Finland, Lithuania and France. Breeding objectives are broadly comparable to those in Great Britain (i.e. the rate of wood production), with additional interest in improved adaptation to harsh sites in France. While breeding for resistance against tree pests and diseases is becoming a subject of increasing importance, this is not yet a main focus of Scots pine breeding[12]. Genetic differences in wood density (Peltola *et al.*, 2009) and durability (Partanen *et al.*, 2011) have been considered in Finland, while branch characteristics have been considered jointly in Sweden and Latvia (Jansons, Baumanis and Haapanen, 2009). The results from those studies suggest it is possible to simultaneously select for growth and wood properties. Given the problems associated with dead knots in Scots pine (see Knots, page 10), placing more emphasis on branching characteristics would be an obvious target for further genetic improvement of Scots pine sawn wood quality in Great Britain.

Choice of silviculture

The majority of Sitka spruce in Great Britain is grown in even-aged planted forests, but this isn't necessarily true for Scots pine: a survey by Macdonald and Gardiner (unpublished) showed that the majority (57%) of Scots pine in northern Scotland is either designated for or already under continuous cover management. The move to continuous cover forestry (Mason *et al.*, 1999) is an attempt to convert even-aged stands to a more irregular structure, with the main advantages being: more evenly distributed
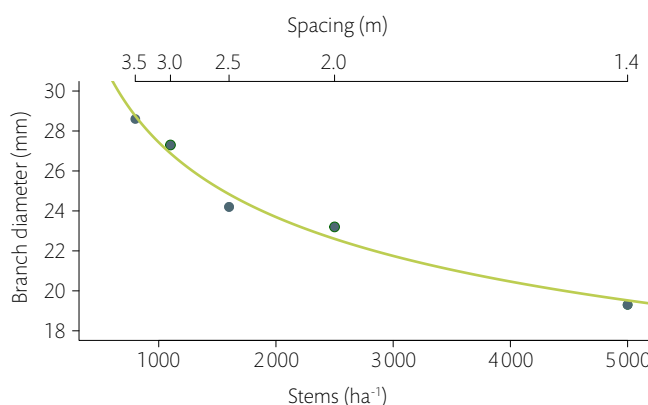
income and expenditure, less ground disturbance and reduced visual impact on the landscape. The effect of this management technique on wood properties is still largely unknown, but since both initial spacing (see below) and age of the crop (see Rotation length, page 22) have a major influence on wood properties, adopting a system in which these vary will most likely increase the variability of wood properties (Macdonald, Gardiner and Mason, 2009). Mason, Hampson and Edwards (2004) illustrate continuous cover management systems applied to native Scots pine.

Initial spacing

Initial spacing is a key silvicultural factor that can influence the growth and wood properties of trees in even-aged planted forests. Our knowledge of the effect of initial spacing on conifer wood properties in the UK is based entirely on work carried out with Sitka spruce (reviewed by Macdonald and Hubert, 2002). In general, closer initial spacing favours better wood properties, while wider initial spacing favours individual stem growth and lowers establishment costs. Consequently, a balance must be found to produce acceptable wood properties with the smallest of compromises on stem growth and cost; for Sitka spruce this is 2500 stems ha^{-1} or 2 m square spacing (Brazier and Mobbs, 1993). There is no separate recommendation for Scots pine, but the mechanical properties of pines have been observed to behave in a similar fashion to spruces, where closer spacing produces wood with higher stiffness (e.g. Lasserre, Mason and Watt, 2005).

As knots play a major role in the sawn wood quality of Scots pine (see Knots, page 10), consideration needs to be given to the effect of initial spacing on branch and/or knot size. With wider spacings there is both less competition for branch space and a longer period until canopy closure. Consequently, branch size (Figure 2.23; see also Egbäck *et al.*, 2012) and the percentage of knotwood (Table 2.7) increases with

Figure 2.23 The relationship of initial spacing to maximum branch diameter in young Scots pine (14–17 years old) in southern and central Finland (data from Salminen and Varmola, 1993).

Table 2.7 Percentage of knotwood within the stem of 44-year-old Scots pine at various sites in Sweden (adapted from Nylinder 1958, in Walker, 1993). The volume of wood fibre disturbed by the knots is not included.

Position as a percentage of stem height	Spacing of trees in stand		
	0.75 m x 0.75 m	1.5 m x 1.5 m	3.0 m x 3.0 m
	17 778 stems ha^{-1}	4444 stems ha^{-1}	1111 stems ha^{-1}
	Percentage of knotwood		
90–100	1.55	1.92	1.98
80–90	1.77	1.94	2.26
70–80	1.63	1.69	1.97
60–70	1.14	1.09	1.51
50–60	0.74	0.88	1.23
40–50	0.52	0.53	0.98
30–40	0.34	0.44	0.97
20–30	0.18	0.3	0.75
10–20	0.11	0.25	0.71
0–10	0.11	0.2	0.55
Average	**0.44**	**0.52**	**0.92**

Figure 2.24 Volume per hectare and mean diameter of stems at breast height (DBH) in 25-year-old Scots pine (yield class 10) at different initial spacings (data from Hamilton and Christie, 1974).
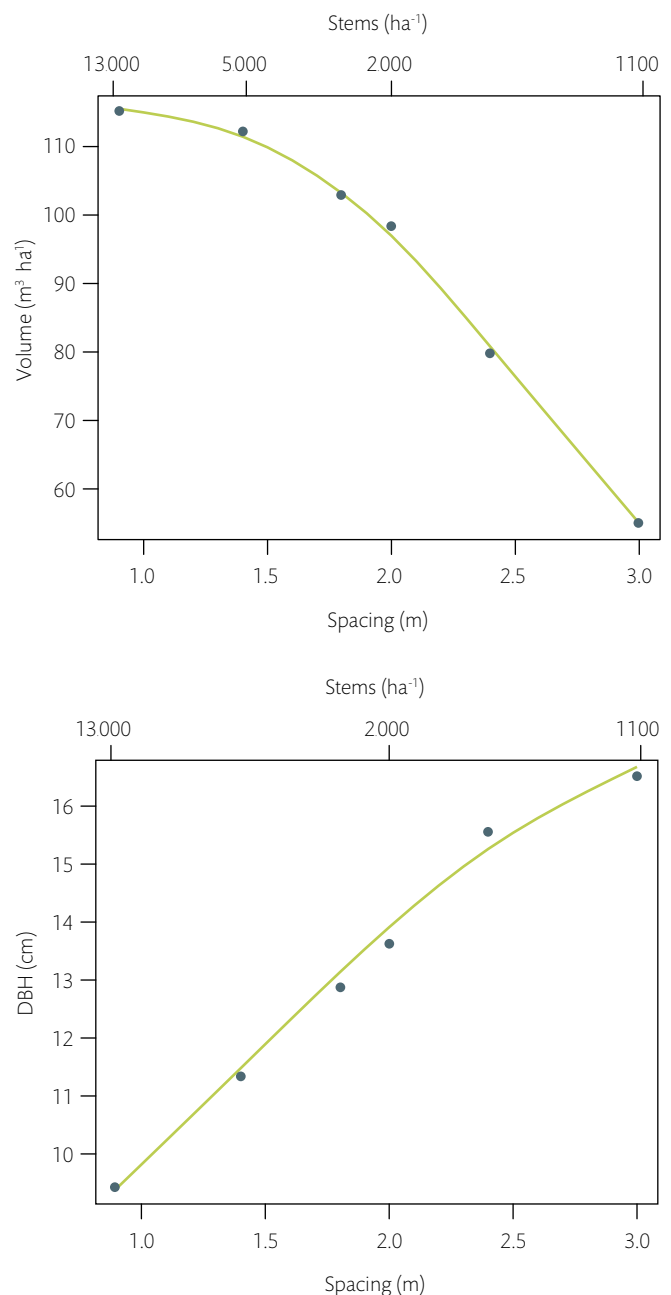
distance between neighbouring trees. The effect of spacing on branch size/knot volume is not linear; decreasing spacing will eventually reach a point of diminishing returns and so an optimal value will achieve a certain threshold branch size: that value would need to balance rate of growth against knot size on a local basis. In Great Britain the requisite field experiments do not exist but computer simulations, such as those presented in Auty (2011), can be used to examine this.

Other benefits of closer spacing, such as straighter stems (Prescher and Erik, 1986; Erik and Persson, 1990) and a higher volume of wood in the earlier stages of the rotation (albeit of smaller diameters) can be considered (Figure 2.24; see also Salminen and Varmola, 1993). The latter in particular could make higher stocking densities more economically attractive if markets emerge that make use of small diameter logs and profits can be made from early thinnings.

Re-spacing and thinning

Thinning is the selective removal of trees to reduce competition and thereby increase the growth of the remaining trees: when thinning is carried out prior to canopy closure, it is termed re-spacing (Mason, 2010). Re-spacing is typically applied to natural regeneration. Re-spacing has the same effect as initial spacing on wood properties (Moore *et*

al., 2009) and branches (Auty, Weiskittel *et al.*, 2012) in Sitka spruce, although no evidence specific to Scots pine exists. In Scandinavian studies (Ulvcrona and Ulvcrona, 2011; Liziniewicz, 2014), thinning has been observed to increase tree diameter growth in Scots pine without any adverse effect on the physical and mechanical properties of clearwood. However, thinning has also been observed to increase branch size (Ulvcrona *et al.*, 2007), which will impact negatively on timber quality. Delaying the first pre-commercial thinning beyond the point at which branch mortality occurs at the crown base should limit knot size in the lower part of the stem (Ulvcrona *et al.*, 2007); alternatively it could be combined with pruning.

Fertiliser application

Fertiliser application is no longer as common as it once was in British forestry, with current practice aiming to apply only where required (Smith and McKay, 2002; Sellers, 2014). Scots pine has a low nutrient requirement, but a phosphate fertiliser is normally applied when creating new Scots pine woodlands in upland Great Britain. Repeated and prolonged fertilisation is not practised in Great Britain and there are no domestic studies available on the effect of fertilisation on the growth and wood properties of British Scots pine. In Scandinavia, repeated fertilisation has been shown to have a negligible impact on wood density and a positive impact on growth (Morling, 2002; Makinen and Hynynen, 2014). No detailed information exists on the effect of fertilisation on branch size, but Malkonen and Kukkola (1991) did report a 25% increase in branch biomass with repeated fertilisation over a 30-year period. This was smaller than the stem increment produced by the same treatment and therefore fertilisation did not cause a net increase in branches.

Rotation length

Rotation length will have a similar effect on Scots pine as that reported for Sitka spruce (Moore, 2011; Moore, Lyon and Lehneke, 2011), where longer rotation lengths will produce higher proportions of outer mature wood. Data from small defect-free specimens produced from 100-year-old Scots pine growing in Tomvaich in Moray (Auty, 2011) showed a 64% increase in bending strength (MOR) from the centre of the tree (position 1) to the outside (position 6), and a 83% increase in MOE (Table 2.8). The overall strength and MOE of timber cut from trees will increase as rotation age increases since there will be proportionally less juvenile corewood (Figure 2.25).

Pruning

Pruning is the removal of branches with the aim of reducing the volume of knots in the lower part of the stem when the tree is harvested. For Scots pine, as with other pine species, knots pose a particular problem for potential uses and may result in visual or structural downgrades (see Knots, page 10), and therefore pruning may be a good management decision.

How effectively knots are controlled depends on how pruning is applied (Figure 2.26). If dead knots are to be completely avoided, branches in the live crown must be pruned, which can reduce subsequent diameter growth in proportion to the amount of crown removal (Henman, 1963). Pruning below the live crown will reduce the eventual volume of dead knots and will not affect growth, but neither

Table 2.8 Mean values of MOR, MOE and air-dry density of small, clear specimens cut from different radial positions within 100-year-old Scots pine trees (data from Auty, 2011).

Property	Radial position					
	1	2	3	4	5	6
Age	<5	<15	<30	<45	<60	>60
MOR (N mm^{-2})	60.0	70.8	80.6	88.3	96.9	98.4
MOE (kN mm^{-2})	5.93	7.26	8.56	9.37	10.64	10.95
Density (kg m^{-3})	428.0	465.9	496.1	527.7	557.8	561.0

Figure 2.25 Effect of rotation length and thinning on the proportion of juvenile corewood by cross-sectional area in the butt log of a Scots pine. The extent of juvenile corewood is assumed to be limited to the first 20 growth rings from the pith.
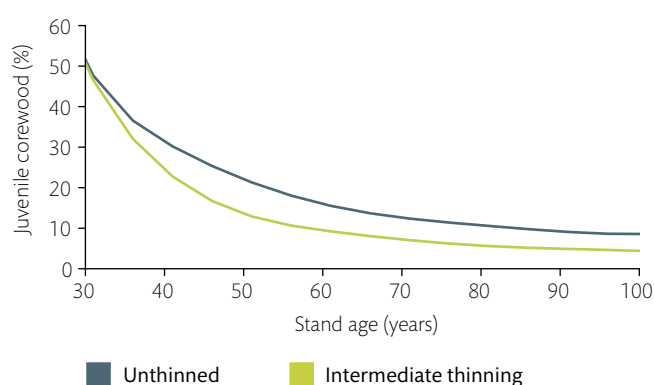
Figure 2.26 How different pruning strategies affect the distribution of knots in conifer stems (modified after Fujimori, 1985 in Fujimori, 2001). Intensively pruning the live crown may impact on diameter growth.
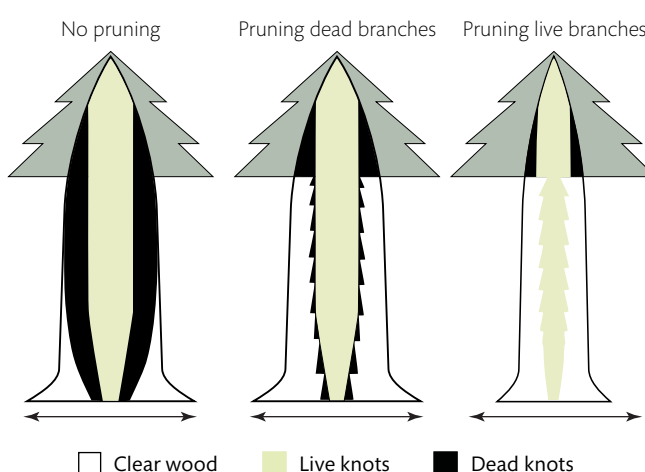
will it completely prevent dead knots. For large-scale conifer forestry, where the management objective is to produce large logs with a high percentage of clearwood in the outer part of the lower stem, the frequency and intensity of pruning can be optimised on a local basis so as to have a negligible effect

on growth while producing a desirable volume ratio of clearwood-to-knotty core. Pruning, however, is an expensive operation, and so the first consideration for the grower must always be a cost-benefit analysis (e.g. Fitzsimons, 1989).

The significant premium for the clearwood of Scots pine could offset the operational costs of pruning; however, the return period on the investment is lengthy because pruning must be carried out several times in early- to mid-rotation. Consequently, British growers are often reluctant to prune. Countries that regularly practise pruning of pine species, like New Zealand, experience much more rapid growth rates that shorten the return period. Also, high premiums are paid for pruned logs (up to 43%), for export and/or domestic consumption (Ministry for Primary Industries, 2015). In Great Britain, if value can be passed along the supply chain to the grower then there are operations that can be carried out to increase the quality of Scots pine product in the forest. From the perspective of a processor, buying pruned material is a risk, because from the outside all pruned logs look the same. Most processors would undoubtedly expect evidence of pruning to a certain specification, and there is currently no such certification scheme in Great Britain.

Effect of pests and diseases

When growing in Great Britain, Scots pine has the potential to contract Dothistroma (red band) needle blight (*Dothistroma septosporum*) (Brown and Webber, 2008). While Scots pine is considered to be at a lower risk than Corsican or lodgepole pine, reported infections are increasing. This fungal disease is a defoliant and will stunt growth if there are successive years of high infection, with mortality possible in the most severe cases. There is no information available on the effect of *Dothistroma septosporum* on wood properties, but there is some from the closely related *Dothistroma pini* in New Zealand on radiata pine. Harris and McConchie (1978) studied the wood properties of young radiata pine trees with various severities of infection by *Dothistroma pini*. They found that the wood density, and in particular the latewood density, of the most severely infected trees increased relative to the fungicide-protected trees during the seven years of the study. On the other hand, diameter growth of the infected trees decreased. Therefore the disease had no negative effect on wood properties. It is worth noting that in New Zealand forest management practices frequently include thinning and pruning which increase airflow and reduce the impact of the *Dothistroma pini* fungus.

3. Suitability for different products

The majority of Scots pine in Great Britain is currently processed into wood-based panels and fencing. Fencing is a valuable domestic market and Scots pine is well-suited to it. End users are concerned about the effects of bluestain and dead knots on various sawn-wood products; consequently, this restricts some possible uses of British Scots pine. Nevertheless, Scots pine has more desirable mechanical properties than Sitka spruce and these could enable the production of timber at higher strength classes. In theory, this could also make Scots pine a more desirable component of engineered wood products, particularly since it can be modified using industrial processes that cannot be used on spruces to enhance its durability and dimensional stability in service. The relatively higher resin content makes Scots pine less desirable for pulping than spruces, but conversely, this makes it more desirable for biorefining.

Introduction

Around 600 000 m^3 of Scots pine is harvested annually in Great Britain, approximately two-thirds of which is in Scotland. Currently, approximately 50% of Scots pine harvested in northern Scotland is processed into wood-based panels, with 40% used for fencing (Macdonald *et al.*, 2008). Only a small proportion was used in higher value applications such as construction, decking or sleepers. This section concentrates on the current and potential uses of Scots pine.

Roundwood

In Great Britain, roundwood was traditionally used for pit props in coal mining, the demand for which has now disappeared. Current long-term uses of roundwood are as pilings and utility poles. Scots pine is unsuitable for untreated pilings in ground contact due to the susceptibility of the sapwood to decay (Reynolds and Bates, 2009). Scots pine can be successfully treated prior to use as utility poles, which command a significant premium at longer lengths meaning suitable trees have a high value. The wooden utility poles used in the UK are usually sourced from Scandinavia or eastern Europe, although home-grown Scot pine poles are available in Northeast Scotland.

Sawn wood

In modern mechanised harvesting, product categories are typically assigned to logs at harvest and then verified at the mill. Straight logs are highly desirable for processing in higher value applications and the potential outturn of straight or sawn logs is a useful gauge of the value of a forest (Forestry Commission, 1993). Describing a survey of stem form of Scots pine in northern Scotland and comparing it to Sitka spruce (Mochan, Hubert and Connolly, unpublished), Macdonald, Connolly and Gardiner (2010) showed that

Scots pine typically has much straighter stems than Sitka spruce, with over 40% of trees producing straight butt logs of at least 4 m in length, and that it is therefore possible to produce a relatively high proportion of sawn logs which are suited to higher value applications.

Appearance grade timber

Appearance grading concerns the classification of wood for non-structural purposes (e.g. furniture) based on appearance; it is not the same as visual grading, which uses appearance to predict structural performance. Joinery or appearance grade timber has a low knot content, straight grain, and is free from fungal attack and discolouration (Figure 3.1). The relevant standard for appearance grading and measurement is BS EN 1161-1:2000 (British Standards Institute, 2003); a detailed guide is available in Brundin and Fröbel (2016).

Appearance grade softwood timber for joinery and furniture production is not currently selected by processors in Great

Figure 3.1 Appearance grades of softwood timber. The highest grade is shown on the left and the lowest grade on the right.

| G4 - 0 | G4 - 1 | G4 - 2 | G4 - 3 | G4 - 4 |

Britain, even although this is a high value application. Macdonald *et al.* (2009) carried out appearance grading on Scots pine timber from northern Scotland and found that 28% could be placed in the three highest European Standard categories (British Standards Institute, 2003). A comparable study of Sitka spruce (Jones, 2006) showed that 25% fell into those same three categories. However, 9% of Scots pine was categorised at the Scandinavian equivalent unsorted (highest) grade, compared to only 4% of Sitka spruce. Automated sawmill sorting for the higher appearance grades of Scots pine could therefore be regarded as having more potential than for Sitka spruce.

Structural timber

Only a very small part of the harvested British Scots pine is currently processed to make structural timber. No studies for British Scots pine measuring its strength, stiffness[13] and density of timber according to BS EN 408 (British Standards Institute, 2012) currently exist, and therefore no information is available on typical yields at different structural timber strength classes according to BS EN 338 (British Standards Institute, 2009). Therefore, it is only possible to speculate based on data from a Forest Research study (2006) consisting of 592 battens from nine sites (eight in Scotland and one in England) passed through a sawmill X-ray and dynamic grader. The grader provides a good estimate of stiffness and density but does not measure strength. Assuming that stiffness is the limiting property for British Scots pine just as it is for other British timber (Moore, 2011; Gil-Moreno, Ridley-Ellis and Mclean, 2016), it is possible to simulate the grading outturn based on wood stiffness (Table 3.1). The results indicate that, based on wood stiffness, Scots pine could be graded higher than British spruce. The highest acceptable grade (based on the number of rejects) to processors is likely to be C22. However, as laboratory data for these Scots pine samples are not available, it isn't possible to verify that the timber will have sufficient strength for a grading of C22. Imported Scots pine is typically a minimum of C24, probably because it has a higher stiffness[14], and therefore local material may not be able to compete unless a buyer insists on home-grown or locally-sourced timber. Otherwise, if strength classes in excess of C16 are sought from British softwood, then Scots pine could meet that demand.

Table 3.1 Estimated grading yields at structural timber strength classes. Scots pine data were estimated from an online timber-grading system, while the Sitka spruce data provided for comparison are from accurate laboratory testing (Moore *et al.*, 2013). The Scots pine yields are therefore indicative rather than observed because measured strength values are not available.

Grade	C14	C16	C18	C20	C22	C24
Scots pine	100	100	100	100	99.8	62.8
Sitka spruce	100	100	92.1	74.9	57.6	29.2

Pallets and packaging

Only a small amount of Scottish Scots pine timber goes into the manufacturing of pallets and packaging (Macdonald and Gardiner, unpublished), and because of the issue with bluestain (see page 12) it isn't always a popular choice. Actually, according to BS EN 12244 (British Standards Institute, 1999), bluestain is permitted in the use of pallets, whereas any other kind of staining is not. This relies on an unrealistic expectation that all users can tell the difference, although most users don't like the appearance of any kind of staining, which is why pallet manufacturers usually want to avoid any staining whatsover. Unfortunately, the methods and locations used for stacking and storing pallets in Great Britain constitute an ideal breeding ground for bluestain, making it difficult to expand the use of Scots pine in this market.

Fencing

Just over 40% of Scots pine harvested in Scotland goes into fencing products, and this is divided almost equally between agricultural and domestic fencing (Macdonald and Gardiner, unpublished). Scots pine has variable natural durability (see page 17) and requires treatment prior to use as fencing, particularly as posts in ground contact. Its popularity in fencing arises partly because it is more permeable than Sitka spruce (see Permeability, page 17), making it easier to treat. Its continued use in fencing is also driven by the large demand for fencing, particularly for livestock, in the regions where it is grown.

Cladding

The design and use of cladding, with a focus on domestic use, is covered in detail by Davies, Walker and Pendlebury (2002). Scots pine is not widely used in cladding. The main home-grown cladding is produced from larch. The heartwood of Scots pine is considered to have similar durability to the heartwood of larch (British Standards Institute, 1994a). However, similar to larch, the sapwood of Scots pine is not durable and therefore preservative treatment or wood modification (see page 27) is required unless the sapwood is

13 An explanation of the difference between strength and stiffness is provided in the Bending strength and stiffness section.
14 British timber is limited to lower grades than other countries in Europe due to its comparatively lower stiffness. Most other European timber is limited by its strength and/or wood density. Therefore, while British softwood timber can have a strength and wood density equivalent to other European timber, its stiffness is lower, and it is specifically this factor which causes lower yields at the higher grades used in other countries.

removed. Because the cladding industry is growing in the UK, there may be potential to expand the use of Scots pine in this application. However, large dead knots could pose a problem for fire performance and would need to be screened in any production line (Davies, unpublished).

Drying

Scots pine is more permeable than Sitka spruce and in theory drying can be performed at higher temperatures. Higher temperatures are normally desirable because of the reduction in the length of time timber spends in the kiln. According to A Handbook of Softwoods (Building Research Establishment, 1977), Sitka spruce is dried according to kiln schedule J (Moore, 2011) whereas Scots pine is dried according to kiln schedule M. However, upon drying discolouration can occur in Scots pine heartwood to a larger extent than spruce (Tarvainen, Saranpää and Repola, 2001), and therefore kiln schedule F is recommended if this is a concern. In practice, kiln schedules need to be modified through local experience (Table 3.2).

As wood dries it undergoes dimensional changes (see Shrinkage, page 16) and as these are not equal with respect to the rectangular dimensions of sawn wood, distortion on drying can be a problem. The type of distortion that occurs depends on uneven shrinkage with respect to the dimensions of the board (Figure 3.2). Twist is the type of distortion that is of greatest concern because it is the most difficult to rectify through further machining or fixings.

The occurrence of twist is higher on boards with a higher ring curvature (hence those cut closest to the pith) and with

Figure 3.2 The four main types of drying distortion in sawn wood.
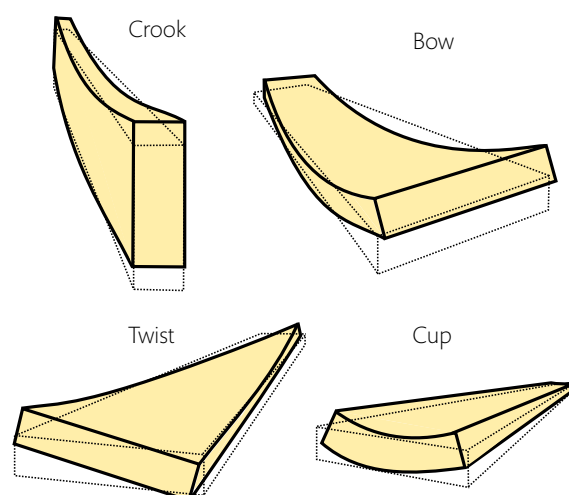
a large variation in grain angle (see Spiral grain, page 11) (Johansson *et al.*, 2001). The impact of distortion can therefore be reduced by using sawing patterns that adapt to the grain and cut sections from the outerwood where shrinkage is more stable, although this would come with a trade-off in terms of volume recovery and efficiency. High throughput modern machinery is not set up in this way and the majority of structural sized boards are cut from the core of the log. Restraining boards during drying allows primary processors to minimise distortion at the kiln; however, large-scale kilning is not normally carried out beyond a target endpoint of 20% moisture content in Great Britain, which is above the moisture content at which most boards will be used in service. Therefore, once this restraint is removed and boards continually interact with atmospheric conditions, any distortion that was previously restricted during kiln-drying will now take place.

Preservation

The natural durability of Scots pine is variable (see page 17). For use in ground contact Scots pine requires treatment (Wood Protection Association, 2012). This process uses the same chemical treatments and techniques which are used for Sitka spruce (Moore, 2011), although incising Scots pine with toothed rollers beforehand is less common as the permeability of its sapwood is much higher and consequently much better preservative penetration is possible without the use of incising. Rhatigan *et al.* (2004) showed that the penetration of the common types of wood preservative was similar for incised Norway spruce and non-incised Scots pine of Austrian origin. A 15-year monitoring trial of British-grown softwoods in ground contact has been set up, and it will test species and preservatives applied both with and without incising (Young, 2015).

Table 3.2 Typical kiln schedules for Scots pine (Building Research Establishment, 1977). Schedule M is recommended for normal drying while the gentler schedule F is recommended if discolouration is to be avoided.

Schedule	Moisture content (%)	Dry-bulb temp (°C)	Wet-bulb temp (°C)	Approximate relative humidity (%)
M	Green	90	81	70
	50	95	78	50
F	Green	50	45	75
	60	50	44	70
	40	50	42	60
	30	55	43.5	50
	25	60	46	45
	20	70	52.5	40
	15	75	57.5	40

Wood modification

Wood modification processes, covered in detail in Hill (2006), have been developed in northern Europe primarily to increase the decay resistance and durability of non-durable species in outdoor applications without relying on a biocidal preservative. Other benefits such as water repellence and improved dimensional stability are usually also achieved, although this is sometimes at the expense of mechanical properties. The high permeability of Scots pine means it is suitable for commercial chemical modification techniques that cannot be used on Sitka spruce, and studies have shown that chemically modified Scots pine wood has enhanced durability (Alfredsen and Westin, 2009) and dimensional stability (Ramsden, Blake and Fey, 1997).

Acetylated Scots pine of Scandinavian origin is available commercially from the same company currently producing acetylated radiata pine. Furylation (i.e. impregnation with furfuryl alchohol) is the second chemical modification process that has been commercialised to date, and furylated Scots pine timber (once again of Scandinavian origin) is available for purchase. British Scots pine is not currently modified with these treatments on a wide scale, although examples do exist (Figure 3.3). There are currently no treatment facilities in the UK.

Thermal modification

Thermal modification is a group of high temperature treatment processes that cause changes to the wood molecular structure without the addition of chemicals (Hill, 2006). Commercial applications of thermal modification are more advanced than modification using chemicals. Thermal modification generally has a negative impact on structural properties (Hill, 2006) and therefore is restricted for use on wood for non-structural applications. While it is theoretically possible to thermally modify Sitka spruce grown in Great Britain, its knots crack if the standard Finnish process is used (Torvinen, 2010), which is why the technology hasn't been adopted in the UK. Scots pine knots also crack, but to a lesser extent. Only large or dead knots pose a problem for Scandinavian material (Syrjanen and Oy, 2001), and therefore material screening is possible prior to treatment. Currently there is a small pilot plant in Wales trialling thermal modification of home-grown larch, but home-grown Scots pine has not yet been trialled.

Engineered wood products

Engineered wood products use wood in the form of veneers, chips, strands or fibres. They are frequently bonded together with adhesives to form composite materials, but they may also be held together with mechanical fixings. The types and applications of engineered wood products vary widely and are constantly expanding, but the general aim is to engineer solutions for applications that are either less cost-effective, or which are impossible to realise with sawn wood from primary processing. Examples of use range from domestic furniture to adventurous architectural designs. More details on the production of engineered wood products, including usage examples and preliminary trials of British timber, can be found in Hairstans (2018).

Wood-based panels

The products generally classified as wood-based panels are plywood, particle board, orientated strand board (OSB) and

Figure 3.3 This Forestry Commission Office at Smithton in Inverness is clad with furylated home-grown Scots pine (Jardine, 2010).

fibreboard[15]. Plywood is neither manufactured in Great Britain nor produced from material grown in Britain. Otherwise the UK produces 78% of its domestic demand for wood-based panels (Wood Panel Industries Federation, 2014). The majority (52%) of Scots pine harvested in northern Scotland currently goes into the production of wood-based panels (Macdonald and Gardiner, unpublished) and OSB due to a large, local manufacturing presence. In Great Britain, particle board and fibreboard are more commonly made from Sitka spruce and/or recycled wood material.

Structural composite lumber

Structural composite lumber includes laminated veneer lumber (LVL), parallel strand lumber, laminated strand lumber and orientated strand lumber. These are listed by order of decreasing component size and mechanical performance. LVL and parallel strand lumber require logs that can be peeled into veneer. As the term lumber suggests, these products are predominately North American in origin; most of them can be made from southern pine, so manufacture with Scots pine is theoretically possible and trials in Finland have used small diameter Scots pine for laminated strand lumber (Heräjärvi *et al.*, 2004). There is only one mass producer of LVL in Europe, which is based in Finland and uses Scandinavian Norway spruce. None of these products are currently mass-produced from British wood of any species.

Glued laminated and cross-laminated timber

Glued laminated and cross-laminated timbers are made from lamellas joined with adhesives (Figure 3.4). Glulam was first patented in 1906 and its invention is regarded as the birth of modern engineered timber for construction,

Figure 3.4 Glulam beams can be either (a) horizontally or (b) vertically laminated; (c) a CLT panel has layers of timber lamellas perpendicularly orientated to the adjacent layers.
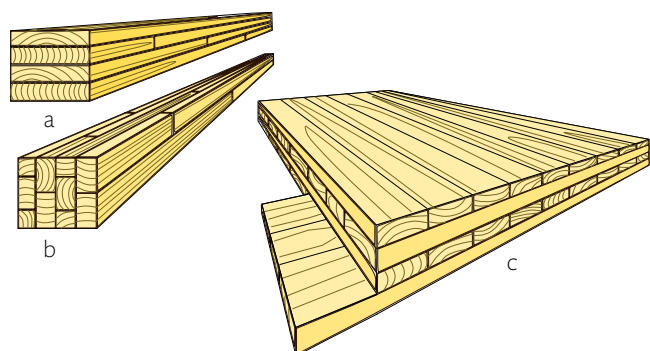

cross-laminated timber (CLT) was developed in the 1990s. Glulam beams have become common exposed features in modern architecture and offer a better strength-to-weight ratio than steel. Norway spruce is the main softwood species used for glulam in Europe; but glulam can be manufactured from Scots pine when durability is a concern, for instance in bridges. However, glulam is not currently mass-manufactured in Great Britain.

CLT panels are one type of massive timber. They are used in the construction of wooden dwellings of ten or more storeys. CLT is currently experiencing a surge in popularity because it is increasingly seen as an efficient means of offsite construction. CLT panels can be large and awkward to transport by road unless their size is restricted. Therefore the scope for local fabrication is higher than that for glulam. Since the Sitka spruce research report was published (Moore, 2011), extensive testing of CLT panels constructed from C16 Sitka spruce has taken place (Hairstans, 2018) and the first UK plant producing CLT with Sitka spruce has been constructed. Trials were also undertaken with Scots pine, Douglas fir, larch, western hemlock and Lawson cypress (Hairstans, 2018). These preliminary trials demonstrated that CLT can be produced from all of these species and that Scots pine products had the lowest stiffness. However, the small sample size and limited range of sample material used in the study means that any comparisons made between species are unlikely to reflect their performances in reality. In theory, Scots pine has better mechanical properties than Sitka spruce (see Structural timber, page 25) and therefore the resultant combination should be better.

Brettstapel

Brettstapel (stacked boards) is the other type of massive timber (Figure 3.5). Unlike CLT, Brettstapel does not usually include the use of adhesives, meaning that it can be considered as having a lower environmental impact, a factor that has become of growing importance in the construction industry. Currently, Brettstapel-only buildings have been erected to a height of four storeys, although a seven-storey building was built in Germany which used Brettstapel in combination with other timber structural elements.

Figure 3.5 Brettstapel is a stack of thin boards normally held together with dowels.
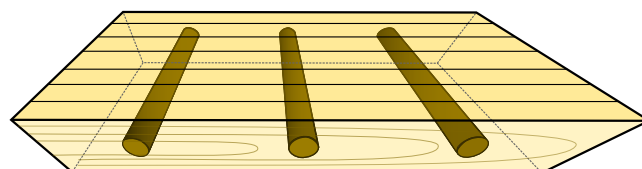
15 For detailed descriptions of these products refer to Moore, 2011.

Brettstapel in name was invented in Germany in the 1970s, although earlier comparable uses of wood do exist. In its earliest commercial form lamellae were nailed together, but dowels have been used since 1999. Dowels are normally made of a hardwood such as beech and are inserted through the lamellae at a lower moisture content than the lamellae, in order that they swell once in place, locking the lamellae together. Products are continually being developed with significant attention being paid to the shape of lamellae (e.g. wavy-edged or tongue and goove) and the orientation of the dowels, which may be perpendicular to the lamellae or angled in a zigzag pattern.

There are currently no mass-manufacturing facilities of Brettstapel in Great Britain but demonstration buildings made with British-grown timber have been constructed, and research about the performance of Sitka spruce and Scots pine in Brettstapel now exists (Hairstans, 2018). As with CLT, the component parts will influence the combined structural performance, so Scots pine could produce panels with a better mechanical performance than Sitka spruce.

Pulp and paper

It is often stated that we are now living in a paperless society, and many forecasters predict that the requirement for wood pulp will go down. Although statistics released by the Food and Agriculture Organisation of the United Nations (2015) suggest that global paper and card consumption is currently at its highest ever, in Europe and North America usage has either peaked or declined slightly. The largest consumption is now taking place in Asia (Figure 3.6).

In the UK, the demand for high quality paper has declined, but the demand for packaging and tissue products has remained stable or increased slightly (Figure 3.7). The delivery of home-grown roundwood to British pulp mills has decreased, countered by an increase in material going to biomass plants (Figure 3.8). The domestic pulping industry is increasingly sourcing fibre from recycled materials, for which it has an adequate domestic supply. Roundwood is still required to produce fresh or virgin fibres that are often mixed with recycled material depending on the product. Annual data from the UK Confederation of Paper Industries suggest approximately 80% of the 1.14 million tonnes of roundwood required are imported (Confederation of Paper Industries, 2013). Scots pine is commonly mixed with spruce pulp in Scandinavian countries, and the fibre properties and pulp characteristics are similar to those of spruce. The main difference is that, due to the increased resin content of Scots pine, it is not suitable for mechanical pulping or the sulphite

Figure 3.6 Global consumption of paper and card (derived from data published by the Food and Agriculture Organisation of the United Nations, 2015).
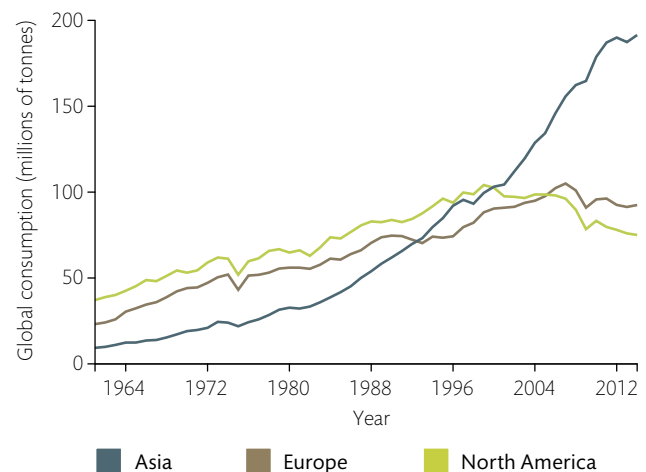

Figure 3.7 UK consumption of paper products (derived from data published by the Food and Agriculture Organisation of the United Nations, 2015).
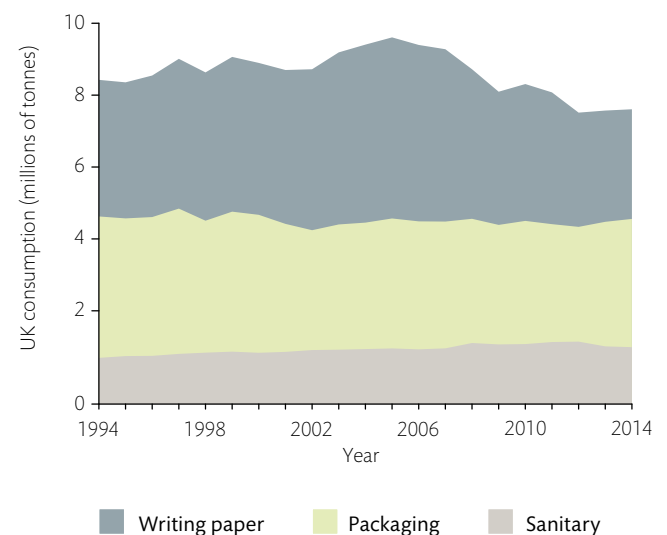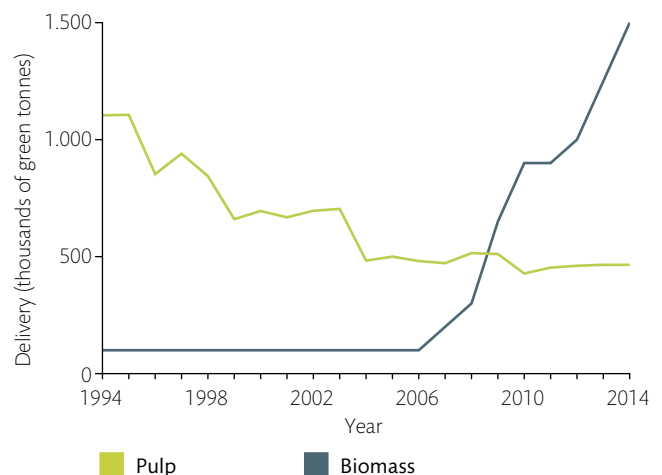

Figure 3.8 Delivery of UK-grown softwood logs to pulp mills compared to biomass plants (Forestry Commission, 2015).

process. It is suitable for the sulphate (kraft) process, but since this is no longer performed in Great Britain, British Scots pine is not currently pulped.

Bark

Scots pine has thicker bark than Sitka spruce; its thickness is on average one and a half times that of Sitka spruce on a mature tree, and it accounts for approximately 15% of the volume of a typical log (Matthews and Mackie, 2006).

Traditionally the inner bark of Scots pine was used by the Sami people as a normal source of food and wrapping material until the end of the 19th century (Zackrisson et al., 2000). Commercially, bark is generally considered as a low value by-product, with domestic markets for garden products (described in Moore, 2011). Potentially higher value uses could include insulation products for construction: insulation made from Scots pine bark has compared favourably with other more commonly used materials (Pásztory and Ronyecz, 2013). The largest developments are in the chemical extractions of bark, where high-value chemicals (see examples below) are obtained, but in relatively greater proportions. Extractives are approximately 25% of the mass of bark as opposed to approximately 5% of the mass of heartwood (Table 2.1).

Chemicals

Many species of pine trees, including Scots pine, have been exploited for chemicals for at least 600 years. In Russia and Scandinavia, Scots pine trees were wounded by debarking in order to produce 'pitch' in large quantities as trees produce resin for sealing wounds. After several years the trees were felled and the wood, particularly the stump, underwent dry distillation into tar that was used to treat wood exposed to the elements, including boat decks, which made it of significant importance to European ships. Stockholm tar, as it came to be known, still exists today as a relatively high value product, although wounding the trees is no longer a stage in the production process. Great Britain was not a large producer of pine tar, it relied on imports instead. The resin (or oleoresin) that was harvested during the wounding of pine trees was also distilled into turpentine, which became the more important of the two products from the end of the 19th century. While turpentine is still produced in some countries by tapping live trees, in Europe it is now largely produced as a co-product of the chemical pulping process. All of the products listed as traditional chemical products are not made from wood, but from bark resins or extractives.

Chemical products are also produced from wood (i.e. cellulose, hemicellulose and lignins, see Chemical composition, page 7). Biorefineries producing multiple chemical products from wood material are a rapidly evolving reality. Bioethanol is perhaps the most well-known product, but it is not necessarily the most valuable. The most successful biorefineries using wood material are producing high value products such as vanillin, a well-known food flavouring, and furfural, an important chemical in agricultural pesticides used more recently in treatments to enhance wood durability (see Wood modification, page 27). Research into high value products from pine extractives is very active: current examples include flavourings, perfumery and pharmaceuticals (Table 3.3). None of these are currently produced using British wood.

New uses (and patents) for wood-derived products are developing rapidly. Typically, wood biomass and biorefining makes use of the lower value feedstock that once went into pulp. Much of this technology has been developed around spruce; however, it is equally applicable to pine. There are currently plans for pilot plants in the UK that will trial domestically grown wood, but the end products are as of yet unknown, as are the demands for feedstock and for the ideal properties of that feedstock. Consequently, the trees we plant today will have a much wider range of purposes than those that we currently harvest, and our silviculture will need to adapt accordingly.

Table 3.3 A selection of chemical compounds identified in the heartwood extractives of mature Norwegian Scots pine (Ekeberg et al., 2006).

Chemical	Common uses
Hexadecanoic acid	Flavourings
Heptadecanoic acid	Adhesives and sealants
Linolenic acid	Pharmaceuticals
Linoleic acid	Paints, cosmetics
Oleic acid	Soldering, soaps, pharmaceuticals
Pinosylvin	Pharmaceuticals
Diethylstilbestrol	Cancer treatment
Palustric acid	Cosmetics
Arachidonic acid	Dietary supplements
Abietic acid	Cosmetics, paints, food packaging, pharmaceuticals
Bis(2-ethylhexyl) phthalate	Plastics, pharmaceuticals
Retinoic acid	Dietary supplements, cosmetics, pharmaceuticals
7-Oxodehydroabietic acid	Pharmaceuticals
Behenic acid	Cosmetics, paints, detergents
ß-Sitosterol	Cholesterol-reducing food additives

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Scots pine is the second most abundant conifer growing in the UK and the only native conifer species grown for timber. It grows well on sites that are too dry for Sitka spruce and it plays a large role in the landscape and rural economy. This Report collates and synthesises research into the production and use of Scots pine timber in Great Britain, drawing where necessary and for comparative purposes on sources from the European continent where Scots pine is better characterised and used in a wider range of applications. It is written for forest scientists, engineers, wood processors and end users of wood products who are seeking to determine the potential end uses of Scots pine. It is divided into three parts: (1) distribution of Scots pine, (2) wood properties and uses of Scots pine, and (3) suitability for different end products. General descriptions of wood properties are not covered in depth, but the wood properties of home grown Scots pine are examined and where appropriate, contrasted with Sitka spruce.

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