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Forest Research

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Distribution of larch

Larch species are naturally found in the temperate cold zones of the northern hemisphere. Larch was first introduced to Great Britain in the 17th century. Starting in the 18th century, larches were the first of the exotic conifers to be used in the UK in extensive afforestation for timber production. Later on, because all larch species are deciduous (despite being conifers), they became favoured for their aesthetic impact on forest landscapes, due to their attractive seasonal colour changes. Until recently, larches were seen as making an important contribution to forest diversification, and there was growing interest in their durable timber. Although they still account for a substantial proportion of forest area in the UK, this is changing because of the impact of *Phytophthora ramorum* (*P. ramorum*), a disease that has resulted in widespread mortality. This leaves the future of larch in Great Britain as highly uncertain, although work continues to explore disease resistance and understand the geographic variation in disease.

Natural distribution

Larch is the common name given to trees of the *Larix* genus. There are at least 10 accepted natural species of larch worldwide, all of which originate in the northern hemisphere. Two species, European larch (*Larix decidua* Mill.) and Japanese larch (*Larix kaempferi* (Lamb.) Carrière), have been introduced to Great Britain on a wide scale. Specimen and arboretum plantings in Great Britain of the common boreal species Siberian larch (*Larix sibirica* Ledeb.) and Dahurian or Asian larch (*Larix gmelinii* (Rupr.) Goepp.) were found to flush too early in mild winters, making them susceptible to damage from frost and cold winds, while tamarack (*Larix laricina* (Du Roi) K. Koch) has proven to be relatively short-lived. Species from more restricted montane and sub-alpine distributions include Sikkim larch (*Larix griffithiana* Carr.), Chinese larch (*Larix potaninii* Batalin), Masters larch (*Larix mastersiana* Rehder & E.H.Wilson), subalpine larch (*Larix lyallii* Parl.) and Western or Oregon larch (*Larix occidentalis* Nutt.). These have not been tested extensively, because when grown as specimen trees they tended to be subject to premature flushing and subsequent frost damage during milder British winters.

European larch

European larch is native to Central Europe (Figure 1). In the Alps and Carpathian Mountains, it is most commonly found at an elevation of 180–2500 m above sea level (asl), and typically constitutes a considerable part of forests just below the tree line. It is also found at lower elevation (180–650 m asl) in the south of Poland.

Japanese larch

Japanese larch is native to the central mountainous areas of Honshu, the largest island of Japan (Figure 2), where it is found at an elevation of 1100–2900 m asl. The natural

Figure 1 Map of the natural range of *Larix decidua* (data from www.euforgen.org/distribution-maps).

Figure 2 Map of the natural range of *Larix kaempferi* based on historical accounts (Hayashi, 1960) and elevation data.

larch forests of Japan were once heavily exploited and those that still exist have, for the most part, been replanted with material from nurseries.

Introduction to Great Britain and hybrid larch

While it is believed that European larch may have first been cultivated in Great Britain in 1629, the oldest surviving larch trees in Great Britain are the 'Kailzie larch' (near Peebles), planted in 1725, and the 'Parent Larch' at Dunkeld, Perthshire, dating from 1738. The Dunkeld tree is one of five seedlings collected from the Tirol (in the eastern Alps) that were planted by the second Duke of Atholl.

Throughout the 18th century, the Dukes of Atholl championed the use of larch as a forest tree, using seed from those five trees. The Dukes were specifically interested in planting large areas of productive forest for profit, with the durable timber intended for boatbuilding (see Boatbuilding, page 24). The 'Planting Dukes', as they became known, established around 4000 hectares of larch forest, transforming Perthshire. It was not until almost 100 years later that this type of reforestation would start to take place more widely across Great Britain.

Japanese larch was introduced to Great Britain in 1861 by John Gould Veitch, one of the first European plant collectors to visit Japan. He found Japanese larch on the slopes of Mount Fuji and sent it back for cultivation in the then famous Veitch family nurseries. As well as apparently being better adapted to wetter climates than European larch, Japanese larch was believed to be more resistant to canker, a major disease that was prevalent in the 18th century in planted European larch forests. Unsurprisingly, given the family's inclination towards larch, Japanese larch was planted on the estate of the serving fourth Duke of Atholl. In 1885, 10 Japanese larch seedlings raised from seed imported from Japan in 1884 were planted near Dunkeld House on the Atholl estate, close to numerous European larch trees. In time, pollen was dispersed by the wind and cross-fertilisation occurred. When gathering the seedlings surrounding the parents it became apparent that they were different in appearance from the Japanese larch trees: the hybrid larch (*Larix decidua* × *Larix kaempferi*, also known as *Larix x marschlinsii* Coaz) had appeared!

Although 'Dunkeld larch' was the first reported cross-fertilisation and a spontaneous hybridisation, the first artificial cross-fertilisation, or intentional hybridisation, of European and Japanese larches was performed by Salomon Kurdiani in Poland in 1914 (Pâques, 2013). Early trials showed that hybrid larch appeared to outpace the growth of both Japanese larch and European larch (Edwards, 1956). This potential heterosis, or 'hybrid vigour', attracted considerable interest both in the British Isles and worldwide, and today hybrid larch is one of the few hybrid species bred commercially for use in planted forests. In addition, hybrid larch is generally considered to be adapted to a wider range of sites and growing conditions than either European or Japanese larch. This is important because site adaptability, particularly with European larch, has often led to problems concerning afforestation with this species (Pâques, 2013).

The site suitability for the three larches in Great Britain is shown in Figure 3, along with the areas where they were being grown prior to the outbreak of *P. ramorum* (page 3). Site requirements are given in Table 1. Overall, Japanese and hybrid larches appear to be considerably better suited to the British climate than European larch, and this is reflected in the overall planted forest area. In 2012, approximately 57% of the 126 thousand hectares of larch consisted of Japanese larch, 30% hybrid larch and 13% European larch (Forestry Commission, 2014a). Difficulties in producing hybrid larch seed and plants (Lee, 2003) have resulted in it continuing to only account for a minor proportion of British larch planting. The current outbreak of *P. ramorum* and associated disease management strategies are now having a very substantial effect on the extent and distribution of larch forests in Great Britain.

Recent effects of Ramorum disease

Ramorum disease (also known as Ramorum dieback) in trees is caused by the oomycete *Phytophthora ramorum* (see Pests and diseases of larch, page 18). Several species of the genus *Phytophthora* (which is Greek for 'plant-destroyer') have caused catastrophic damage to commercially important crops worldwide, including the potato blight that contributed to the Great Famine in Ireland (1845–9). Ramorum disease in trees was initially discovered in Europe and California in the 1990s and was described as a new species of *Phytophthora* in 2001 (Werres *et al*., 2001). In Europe, it was originally found on ornamental plants (rhododendrons and viburnums) in garden nurseries and it

Figure 3 The climatic and soil suitability of Great Britain for each of the three larch species currently used as forest trees, along with the areas in which it was grown on the Public Forest Estate prior to the introduction of *Phytophthora ramorum*. Suitability is based on Ecological Site Classification (Pyatt, Ray and Fletcher, 2001); larch distribution is based on data from the National Forest Inventory.

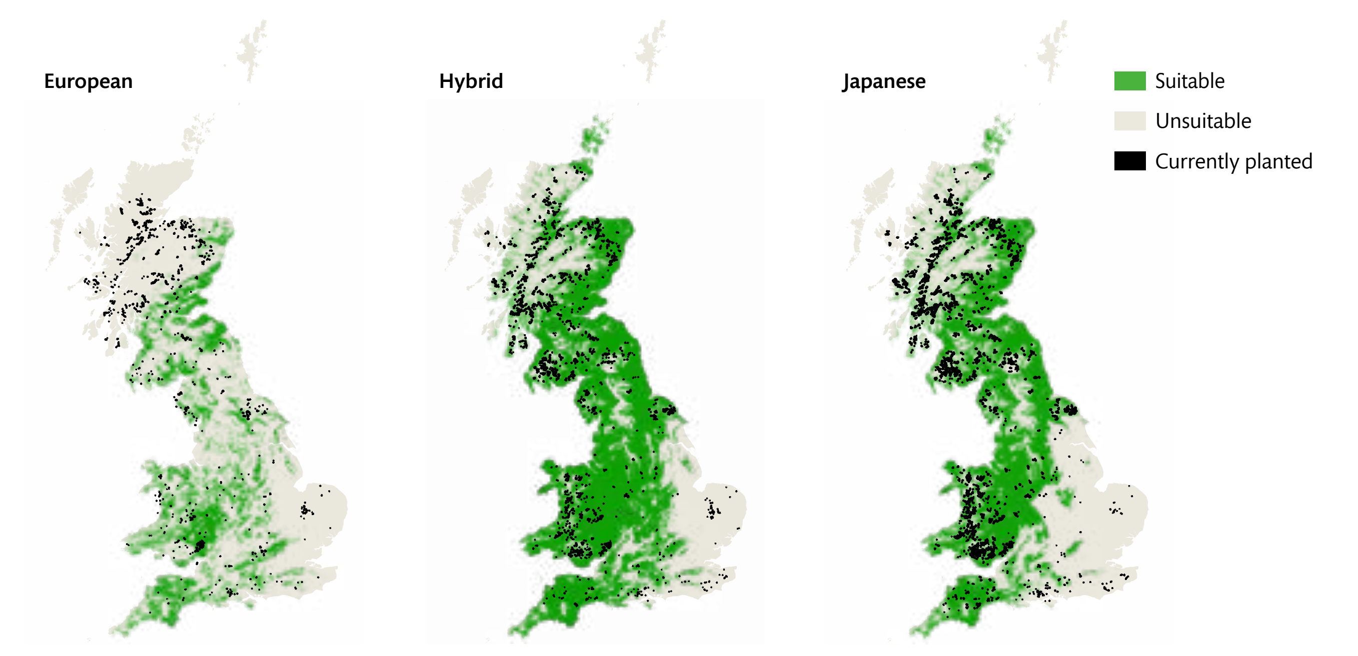


Table 1 Site requirements for growing larch for timber according to principles used in Forest Research Ecological Site Classification (Pyatt, Ray and Fletcher, 2001).

Site property	Species requirements		
	European larch	Japanese larch	Hybrid larch[a]
Exposure	*Sheltered* to *moderately exposed* sites are suitable, but prone to poor lower stem form on exposed sites.	*Sheltered* to *moderately exposed* sites are suitable, but prone to poor stem form on exposed sites.	*Sheltered* to *moderately exposed* sites are suitable, but prone to poor stem form on exposed sites.
Accumulated temperature (annual sum of temperature on days which are >5.0°C)	*Cool* to *warm* (>975 day-degrees >5.0°C)	*Cool* to *warm* (>975 day-degrees >5.0°C)	*Cool* to *warm* (>975 day-degrees >5.0°C)
Frost tolerance	Cold-hardy, but vulnerable to early spring frosts. Frost damage is associated with larch canker. (Flushes earlier than Japanese larch.)	Cold-hardy, but vulnerable to spring and autumn frosts.	Cold-hardy, but vulnerable to spring frosts.
Shade tolerance	Light-demanding	Light-demanding	Light-demanding
Soil nutrient regime	*Medium* to *very rich*	*Poor* to *rich*. Stem form can be poor on rich soil.	*Poor* to *rich*. Stem form can be poor on rich soil.
pH	Slightly acidic to neutral	Acidic	Acidic
Soil moisture deficit (mm)	*Moist* to *dry* (90–180)	*Wet* to *moist* (20–160)	*Wet* to *moist* (20–160)
Soil moisture regime	*Moist* to *slightly dry*	*Very moist* to *fresh* (20–160)	*Very moist* to *fresh* (20–160)
Drainage	Well-drained soils	Well-drained soils	Well-drained soils
Soil types	Prefers deep, well-drained soils.	Prefers well-drained loamy, sandy or clay soils. Best suited to mineral soils of poor or moderately fertile nutrient	Prefers deep, moist, well-drained soils.
Rootable depth (suitable soil types only)[b]	<4.0 m on loose deep soils <2.5 m on intermediate loamy soils.	<2.5 m on intermediate loamy soils.	Not published

[a] Classifications for hybrid larch are not included in Pyatt, Ray and Fletcher (2001). Hybrid larch is often bracketed with Japanese larch for site classifications and those reproduced here are therefore, in part, as additionally provided by Pyatt *et al*. (2003).

[b] From Crow (2005). Larches are generally categorised with 'heart' root systems, where both horizontal and vertical lateral roots develop from the base of the tree. Larches are considered a deep rooting species, but they develop shallow roots on waterlogged soils.

is currently known to have about 150 hosts, including forest tree species. The first global discovery of Ramorum disease on larch was recorded in 2009 in southwest England (Brasier and Webber, 2010), and since then it has spread widely in north and west Britain (Figure 4) as well as into Ireland. Although laboratory tests have indicated that European and Japanese larch are equally susceptible to Ramorum disease, field observations suggest that, compared with Japanese larch, fewer cankers develop on European larch and fewer spores are produced from infected needles (Webber, 2022). However, further research is required to fully understand the impact of different concentrations of spores before any definitive conclusions can be drawn about differences between the species.

Ramorum disease will generally kill larch host trees and, consequently, widespread felling of both infected and healthy trees (for containment) has taken place since 2010 (Webber, 2022), leading to a large amount of larch timber coming onto the market in the UK and Ireland. Prior to Ramorum disease taking hold, larch trees occupied 4% of the total forested area in Great Britain and 10% of the conifer area (Table 2). Webber (2022) estimated that 25% of the larch area in 2012 had been lost to Ramorum disease and the most recent National Forest Inventory data (Forest Research, 2022) show a 20% reduction in larch forest area since 2012 (Table 2). The rate of further spread of Ramorum disease and the future for larches as forest tree species in Great Britain are uncertain, although research is underway to seek disease resistance.

Figure 4 Infection of larch trees by Ramorum disease initially confirmed in 2010 and spread to December 2022. Initially discovered primarily in the southwest of England, the disease is now found in many areas in which larch trees are grown. Since then there has been widespread felling of infected forests.

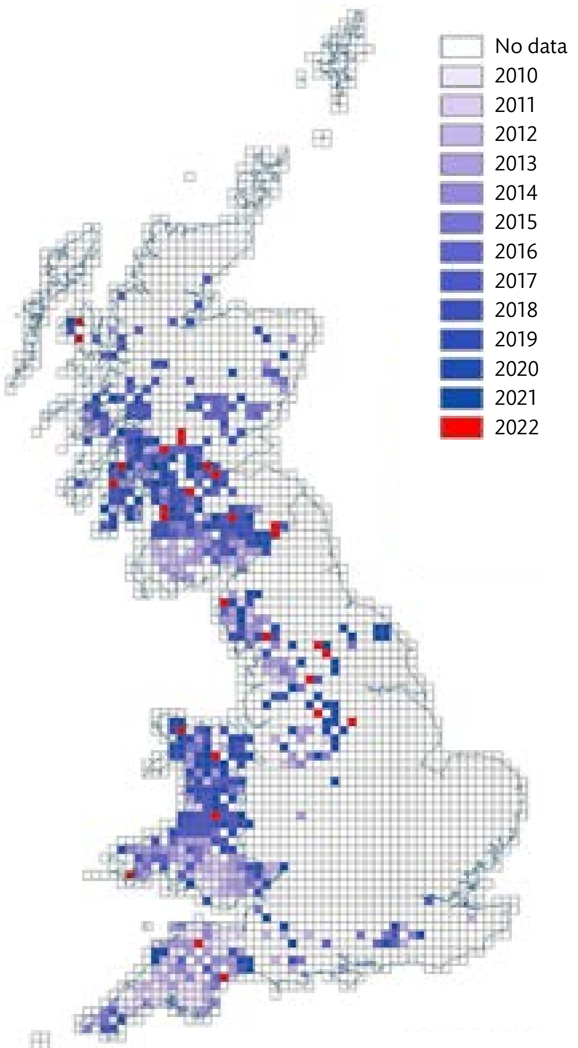


Table 2 Area of larch forests in Great Britain in 2012 and 2022 (Forestry Commission, 2014a; Forest Research, 2022) and the area estimated to be affected by *Phytophthora ramorum* in 2020 (Sketchley, 2019; Webber, pers. comm.).

Total area of forests in thousands of hectares, in 2012	Total area of conifer forests in thousands of hectares, in 2012	Area of larch in thousands of hectares, in 2012	Estimated area affected by *P. ramorum* in thousands of hectares in 2020[a] (% of 2012 larch area)	Area of larch in thousands of hectares, in 2022
1304	307	40	6 (15%)	30
1432	872	66	11 (17%)[b]	57
306	129	20	15 (75%)	13
3042	1308	126	32 (25%)	100

[a] This estimate is the total area on which statutory plant health notices (SPHNs) have been served or which are waiting to be served, based on information in Sketchley (2019) and updated to 2020 with information from Webber (pers. comm.). (It should be noted that areas subject to SPHNs may not have been felled at the time of the survey upon which the 2022 area figures are based.)

[b] Statutory plant health notices are not served in the management zone in southwest Scotland; this figure is the sum of the area covered by the notices and the area of larch trees within the zone, all of which are assumed to be infected.

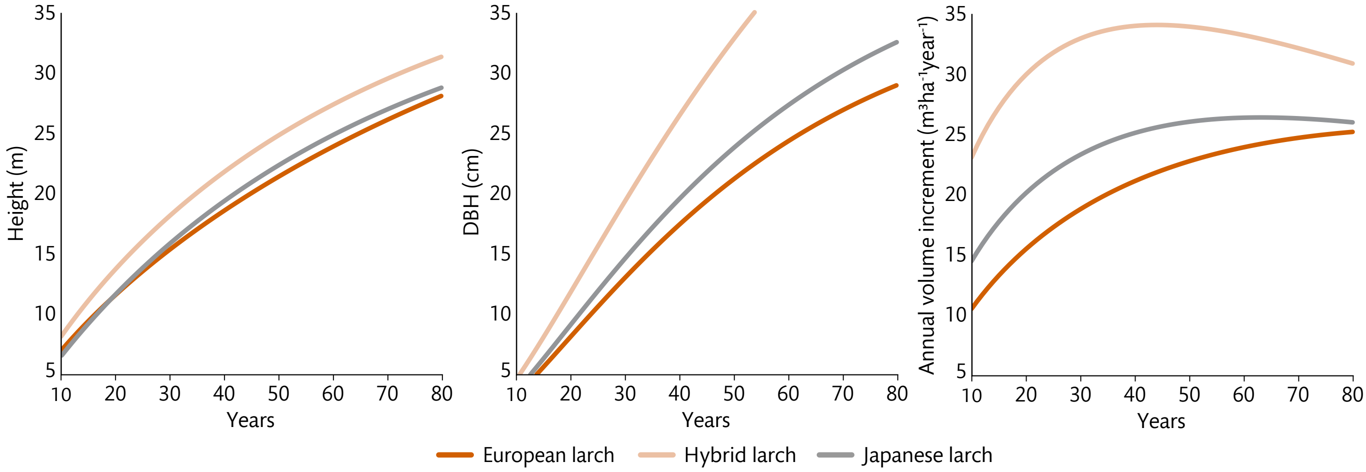
Growth and yield

When considering the growth and yield of British larch it is important to remember that there are two species and a hybrid, each with different growth characteristics, that behave differently according to site type. The forest growth and yield techniques used in British forestry, for the purposes of forest inventory and production forecasting, calculate and model the growth of hybrid larch using Japanese larch because of the limited data on hybrid larch. It is acknowledged that Japanese larch is more productive than European larch: the range of yield classes provided for European larch is 4–12 and for Japanese larch is 4–14 (Edwards and Christie, 1981; Matthews *et al*., 2016). Figure 5 shows the average top height, diameter and volume increment against age for each type of larch based on currently available data from Forest Research's permanent sample plot network.

Although a study of the difference between the growth and yield of the three types of larch has not been conducted in Great Britain, there are indications that hybrid larch[1] grows faster than Japanese larch, which in turn grows faster than European larch (Edwards, 1956)[2]. In Ireland, which also has an oceanic climate, this ranking of the larch species apparently holds true across the range of climates (Walsh *et al*., 2017). A dedicated study in Brittany, France (Ferrand and Bastien, 1985) made use of an experimental forest on one site to quantify the difference in volume produced per hectare between the best provenances[3] of each species at 24 years after planting: hybrid larch (originating from crossings in both Dunkeld, Scotland, and in Denmark) produced the most volume, Japanese larch was intermediate and European larch was the least productive. The hybrid larch produced in Denmark was 30% more productive than Japanese larch and 62% more productive than the best provenance of European larch.

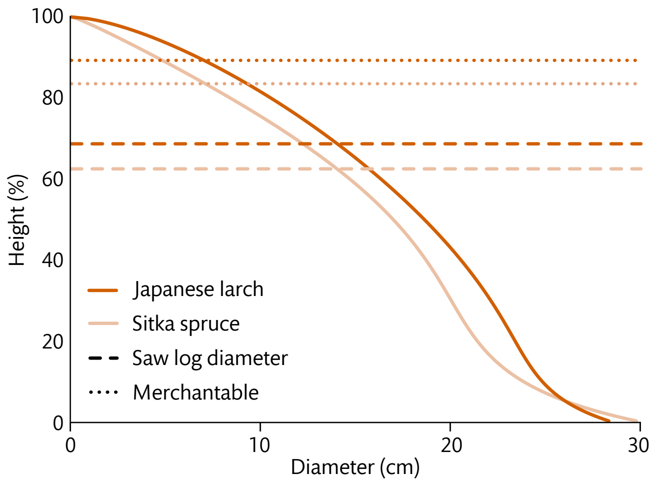
Stem profile is an important consideration for growth and yield modelling purposes. The shape is characteristic of a species, and although the height, diameter and the ratio between them differs between individual trees, the overall shape tends to be the same. The typical profile of a Japanese larch tree is shown in Figure 6, which also illustrates product recovery functions. Here, it can be seen that a Japanese larch tree will have more volume than a Sitka spruce tree of the same height and diameter at breast height, although it will take longer to grow. The relatively higher diameters in the upper stem allow for more of the Japanese larch tree to be considered for merchantable logs. (No comparable data exist for the other two types of larch in Great Britain.)

Figure 5 Average top height (left), diameter at breast height (DBH, centre) and mean annual volume increment (right). Data are from Forest Research's permanent sample plots of the three types of larch grown in Great Britain (Forest Research, unpublished data). There are only eight plots of hybrid larch, compared with 63 plots of European larch and 73 plots of Japanese larch. The largest differences are seen in diameter growth and volume production. The average yield class of hybrid larch is 13 (i.e. a maximum mean annual volume increment of 13 $m^3\ ha^{-1}\ year^{-1}$) with a rotation optimised at 44 years, while European and Japanese larch are both yield class 10. The faster growth of Japanese larch suggests a rotation of around 63 years, while for European larch it is likely to be 101 years for the same volume.



1. The data for hybrid larch are very limited and the full range of growing environments are not covered.
2. This early study considers height growth only in respect to mature forest trees; it also clearly states that there is some uncertainty as to whether all of the hybrid trees were actually hybrids, as they were produced by free pollination (i.e. it was not controlled to ensure one parent came from each species, rather that the two species were in proximity). Nonetheless, the relative differences in height growth correspond to other work.
3. Provenances are trees of the same species from different geographic locations.

Figure 6 The stem profile or taper of a Japanese larch tree in comparison with a Sitka spruce tree of the same height and diameter. The height is typical of a yield class 10 Japanese larch of 65 years. The proportion of the tree length that is suitable for sawn wood products (≥14 cm diameter) and all merchantable logs (≥7 cm diameter) are shown by horizontal lines. This figure was produced by fitting the model described by Fonweban *et al*. (2011) to a small unpublished dataset.



Current and future wood production

Estimates of the current and future areas of productive forest under larch in Great Britain are shown in Figure 7, based on data from the National Forest Inventory. The current extent is largely a reflection of extensive planting that took place from the 1940s to the 1980s, particularly of Japanese and hybrid larch (Figure 8). It is difficult to accurately assess the impact of Ramorum disease on future larch volume production, because of the uncertain spread of the disease and rapid removal of wood after infection. The current best estimates of future available standing volumes of larch wood are presented in Figure 9. Estimates of stocked area and standing volume account for accelerated removals due to Ramorum disease and also for current national restocking policies in Scotland, England and Wales.

Figure 7 The 50-year estimate of the planted area of larches (all species) in Great Britain. Source: National Forest Inventory.

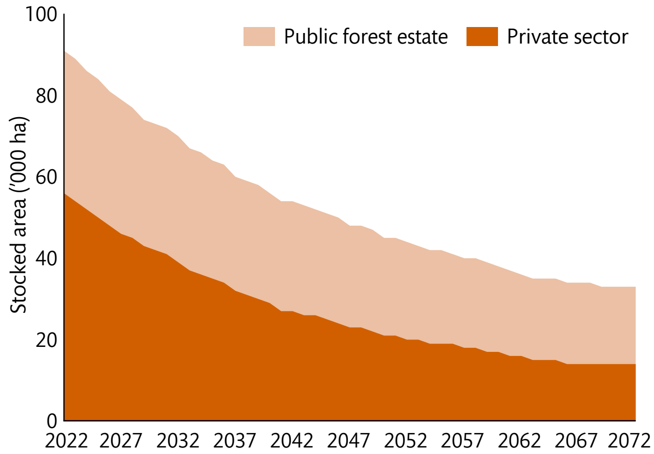


Figure 8 The planting of European and Japanese/hybrid larch in Great Britain, by decade and total area established. Data from Forestry Commission (2003).

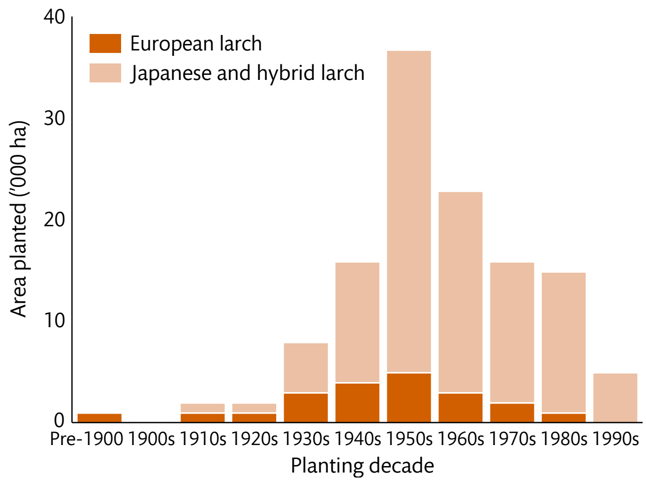
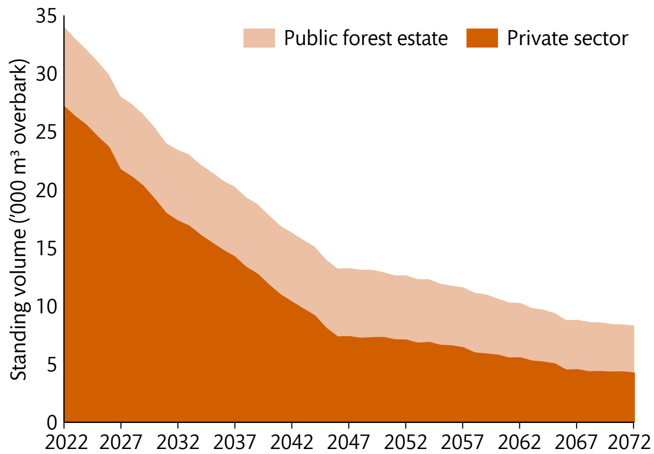


Figure 9 The 50-year estimate of wood availability from larch (all species). Source: National Forest Inventory.



Larch in other countries

Larches are a relatively minor component of European forest cover (Table 3), comprising about 4% of total conifers and less than 1% of the total forested area (Pâques, 2013). They are of regional importance in mountainous regions, such as the Alps, where the predominant species is European larch.

Other countries (including Japan) and particularly those with oceanic climates have favoured Japanese larch. The largest proportion of forested area covered by larch is found in the Russian Federation, where 29% of the total growing stock by volume has been reported as being larch (FAO, 2020j), largely due to the prevalence of larches in Siberia.

Table 3 The proportions of larch in selected countries. Percentages in parentheses represent the relative proportion of larch to the respective national standing volume of softwood timber and the total national forested area.

Country	Standing volume of larch (millions of m^3)	Larch stocked woodland area (thousands of hectares)	References
Great Britain	34 (9%)	100 (4%)	Forest Research (2022)
Austria	69 (6%)	155 (4%)	FAO (2020a), Pâques (2013)
Belgium	3.8 (2%)	8 (1%)	FAO (2020b), Vandekerkhove (2013), Lust, Geudens and Olsthoorn (2000)
Czech Republic	37 (5%)	94 (4%)	FAO (2020c), Köble and Seufert (2001)
Denmark	4.0 (3%)	19 (3%)	FAO (2020d), (Pâques, 2013)
France	Not published	111 (<1%)	IGN (2018)
Germany	102 (3%)	307 (3%)	FAO (2020e), Thünen-Institut (2012)
Ireland (Republic)	5 (4%)	25 (4%)	An Roinn Talmhaíochta, Bia agus Mara (2017)
Italy	87 (6%)	382 (4%)	FAO (2020f), Pâques (2013)
Japan	213 (4%)	1029 (4%)	FAO (2020g), Forest Agency Japan (2019)
The Netherlands	4 (5%)	17 (5%)	FAO (2020h), Lust, Geudens and Olsthoorn (2000)
Poland	45 (2%)	15 (2%)	FAO (2020i), (Pâques, 2013)
Russian Federation	23 672 (29%)	Not published	FAO (2020j)
Slovak Republic	14 (3%)	46 (2%)	FAO (2020k), (Pâques, 2013)
Switzerland	29 (6%)	72 (6%)	FAO (2020l), (Pâques, 2013)

Wood properties and uses of larch

Despite having been in Great Britain for a long time, British larch wood has been less studied than that of spruce or pine. From the limited data that do exist, it appears that wood from British larches behaves in a similar fashion to other British softwoods. However, larch wood is denser and, depending on the species, may also be stiffer and stronger. While the three species of larch have visually indistinguishable woods, there are currently no conclusive British studies about potential differences between the physical and mechanical attributes of the species grown here.

Chemical composition

The basic chemical composition of wood for the three types of larch grown in Great Britain is similar to that of other conifer species, which average about 40% cellulose, 30% hemicellulose and 30% lignin (Fagerstedt *et al*., 2014). Where softwood species do differ is in extractive content, that is, the non-structural wood components, and in larch heartwood these can be about 13% of the dry weight (Gierlinger *et al*., 2004). Their major component is arabinogalactan, which is of commercial importance (see Chemicals, page 26). Gierlinger *et al*. (2004) suggest that there are differences between the three types of larch, with hybrid and Japanese larch having higher amounts of phenolic compounds and lignin than European larch. These phenolic compounds probably help to provide the higher durability in heartwood compared with the non-durable sapwood (see Wood products, page 22 and Chemicals, page 26).

Growth-related properties

Macroscopic or anatomical properties

Larches have a similar anatomy to other conifer species, and it can be extremely difficult to differentiate *Larix* from *Picea* (spruce) with a microscope. As larch wood has predominantly been used for solid wood applications rather than papermaking[4], there are relatively few studies on the relevant anatomical characteristics of larch for these purposes. In Great Britain, the limited anatomical data available originate from one stand of Japanese larch growing in Scotland, which was approximately 50 years old at the time of sampling (Table 4, Figures 10–12).

The data available show that, in common with other conifer species in even-aged planted forests, Japanese larch wood cell diameters and cell wall thickness increase with tree age: for diameter most markedly in earlywood (Figure 10) and for wall thickness most markedly in latewood (Figure 11). No study has been made of the anatomical differences between larch species that matches ring for ring positions within the tree, but an early study of the Dunkeld larch and its two parents (Chowdhury, 1931) suggested that Japanese larch had shorter, narrower and thinner-walled tracheids[5] than European larch, with hybrid larch coming somewhere in between (Table 5). However, as these results are not replicated on a range of sites with multiple trees, they should be treated with caution.

Table 4 Fibre characteristics of approximately 50-year-old Japanese larch grown in Scotland (Edinburgh Napier University, unpublished data).

Tracheid dimension	Value
Radial width (μm)	25–55
Tangential width (μm)	20–63
Wall thickness (μm)	0.4–7.4

Table 5 Differences in anatomical characteristics of the two parent trees of different larch species and the resulting hybrid larch (adapted from Chowdhury, 1931).

Species	Tracheid diameter (μm)	Wall thickness (μm)	Length (mm)
Japanese larch	27–35	2–6	0.5–3.4
European larch	40–50	2–10	0.9–4
Hybrid larch	30–38	2–7	1–5

4. Siberian larch (*Larix sibirica* Ledeb.) has been investigated and used in pulp making to a minor extent (e.g. Uprichard, 2003; Luostarinen, 2011), but none of the larches grown commercially in Great Britain are commonly used for papermaking.
5. Tracheids are single elongated, tubular and tapering cells in the xylem (fluid-conducting tissues) of vascular plants. Their secondary cell wall is thickened with lignin and their primary functions are to provide structural support and upward conductance of water and dissolved minerals.

Figure 10 Radial variation in cell diameter in approximately 50-year-old Japanese larch grown in Scotland (Edinburgh Napier University, unpublished data).

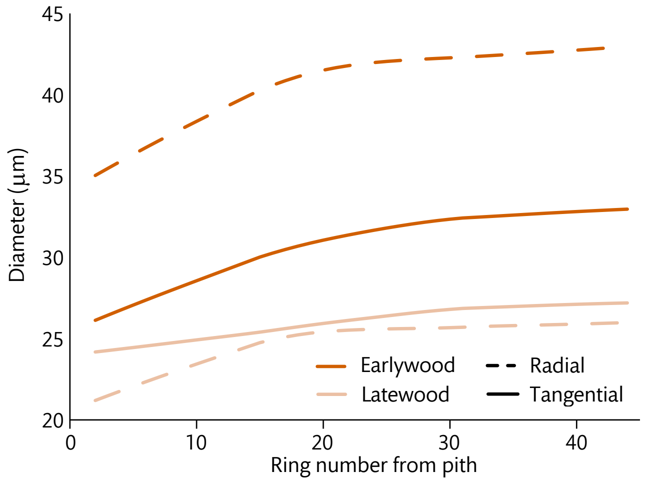


Figure 11 Radial variation in cell wall thickness of approximately 50-year-old Japanese larch grown in Scotland (Edinburgh Napier University, unpublished data).

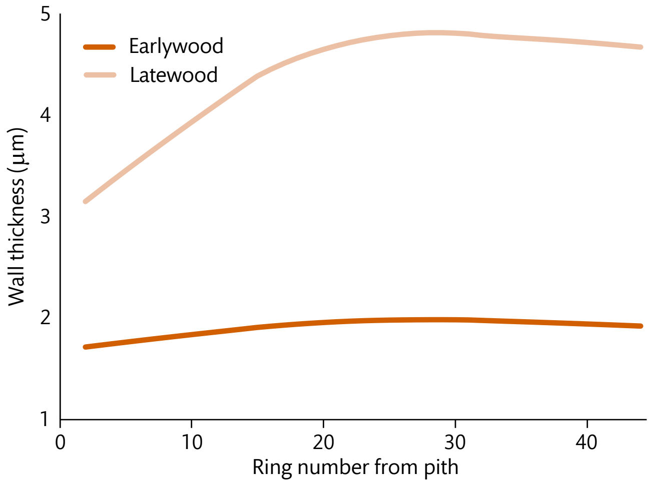
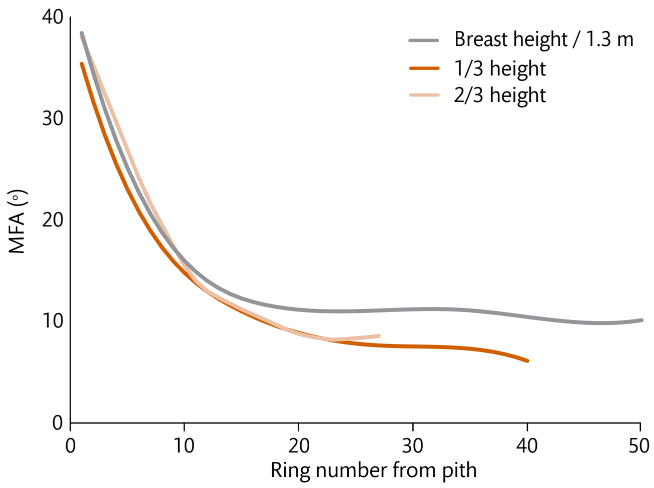


Figure 12 Variation in microfibril angle (MFA) in approximately 50-year-old Japanese larch grown in Scotland (Edinburgh Napier University, unpublished data). 1/3 height and 2/3 height are at 1/3 and 2/3 of the heights of the trees, respectively.

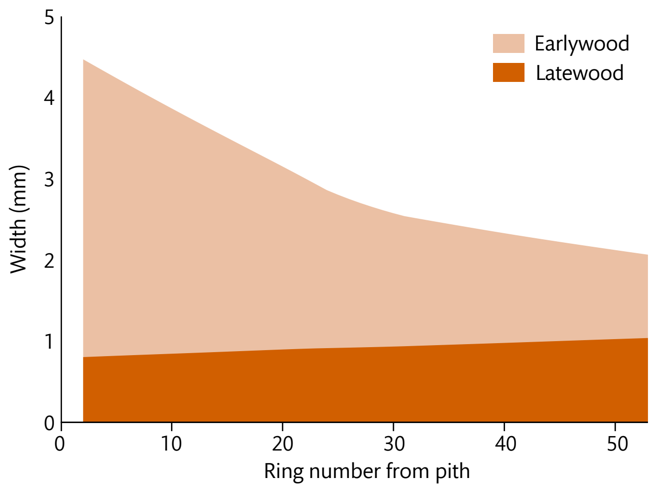


Based on limited data, the radial variation of microfibril angle (MFA) in Japanese larch (Figure 12) would appear to match the general pattern observed in Sitka spruce (McLean *et al*., 2016) and Scots pine (Auty *et al*., 2013), where MFA decreases from the pith to the bark, reaching a stable value in the outerwood. The average MFA values in rings near the pith in the Japanese larch samples were similar to those observed by McLean *et al*., (2016) in Sitka spruce (35°–40°), whereas in Scots pine MFA values close to the pith averaged only around 20°–25° (Auty *et al*., 2013). In Japanese larch there did not appear to be a vertical trend in MFA, unlike in Sitka spruce and Scots pine, where MFA is generally higher in the lower part of the tree. This suggests that wood stiffness in larch will vary radially as with other conifers grown in planted forests, but that there may be no drop in stiffness associated with the first sawlog from the butt.

Ring width, earlywood and latewood

As with other conifers growing in even-aged, planted forests, initial radial growth of Japanese larch is rapid then slows down (Figure 13). What is different from other species investigated in Great Britain to date (Moore, 2011; McLean, 2019) is that the relative proportion of latewood in growth rings appears to be much higher in Japanese larch than in either Sitka spruce or Scots pine, approaching 50% in the outer part of the tree. The data presented here (Edinburgh Napier University, unpublished data) relate to three larch stands in northeast Scotland and are by no means conclusive, but a higher proportion of latewood is typically associated with better mechanical performance and higher wood density.

Figure 13 Ring width of Japanese larch growing in even-aged, planted forests in Scotland (Edinburgh Napier University, unpublished data).



Sapwood and heartwood

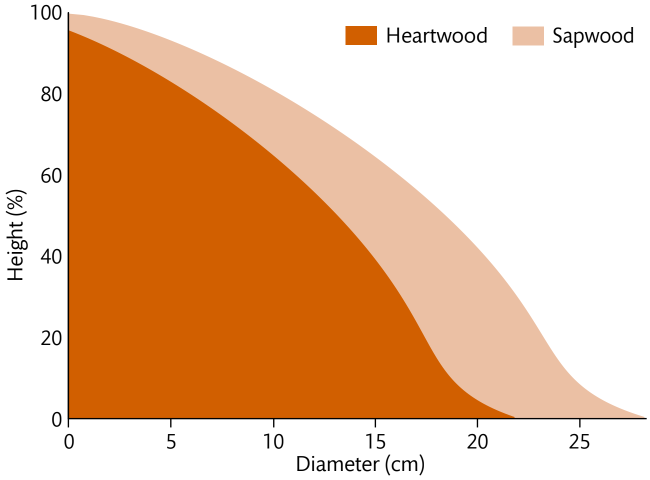
As with Scots pine, the sapwood and heartwood of larch are visibly different due to the presence of heartwood extractives (Figure 14).

There are no published data on the relative amount of heartwood in larches growing in Great Britain, but limited, unpublished data are available, and these can be used to represent a heartwood profile in a typical Japanese larch tree (Figure 15) using similar techniques to Beauchamp (2011). In contrast to Scots pine, of which approximately 60% of the stem diameter is heartwood (McLean, 2019), Japanese larch is almost 88%. The high proportion of heartwood contributes to larch's reputation for greater natural durability, as consequently there is less non-durable sapwood in the cross-section. No study examining the different relative proportions of heartwood between larch species has been undertaken in Great Britain, but there is evidence from Brittany (France) that Japanese larch has about a 10% higher proportion of heartwood based on stem diameter than European larch (Pâques, 2001).

Unreferenced studies cited by Thomas (1964) indicated that light-coloured heartwood was sometimes encountered in European larch and that this exhibited only low decay resistance compared with dark-coloured heartwood.

Figure 14 The lighter (outer) sapwood contrasts markedly with the darker (inner) heartwood in this disc taken from a mature Japanese larch tree.

Figure 15 Heartwood profile, as measured in a 62-year-old Japanese larch tree.

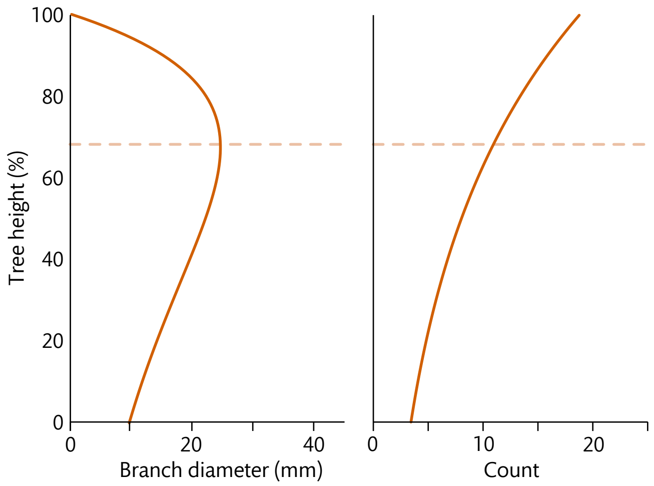


A study by Gierlinger *et al*. (2004) supported this perception, finding that a stronger reddish colour in larch heartwood was associated with greater quantities of phenolic compounds and increased decay resistance. In the boatbuilding industry, a stronger orange colouring of heartwood and a distinct colour contrast between the heart and sapwood are considered desirable characteristics in boat-skin larch, and are also thought to be associated with stronger smelling wood (Grant, pers. comm.).

Knots

As is the case with other softwood species, knots have a detrimental effect on the mechanical wood properties of larch wood, particularly wood strength (Takeda and Hashizume, 1999). The branching habits of larch trees are frequent but irregular in that they do not form obvious nodes or whorls, and therefore knots are relatively frequent and sections of knot-free ('clear') wood are rare. Examination of data collected for Japanese larch growing in northeast Scotland suggests that the relationship between branch diameter and position on the main stem is similar to Sitka spruce and Scots pine (Moore, 2011; McLean, 2019) in that the maximum branch diameter is found at the base of the living crown (Figure 16), although the living crown is apparently higher than in those species. The number of branches that are still attached increases with height in the stem (Figure 16); as larch readily self-prunes, lower branches drop off and dead or unsound knots are a feature of the wood (for an explanation, see McLean, 2019).

Figure 16 Branch diameter (left) and the number of attached branches (right) vary with height in the stem and the position of the base of the living crown (dashed line).



Spiral grain

Tracheids typically run parallel or at a slight angle to the stem axis. Grain is described as 'spiral' when longitudinal stem cells form in a substantial helical orientation; this is considered to be a serious defect in sawn timber, making it prone to twist when drying and difficult to work. Strength properties are reduced and even a small angle has a significant effect on structural performance (Bowyer, Shmulsky and Haygreen, 2007).

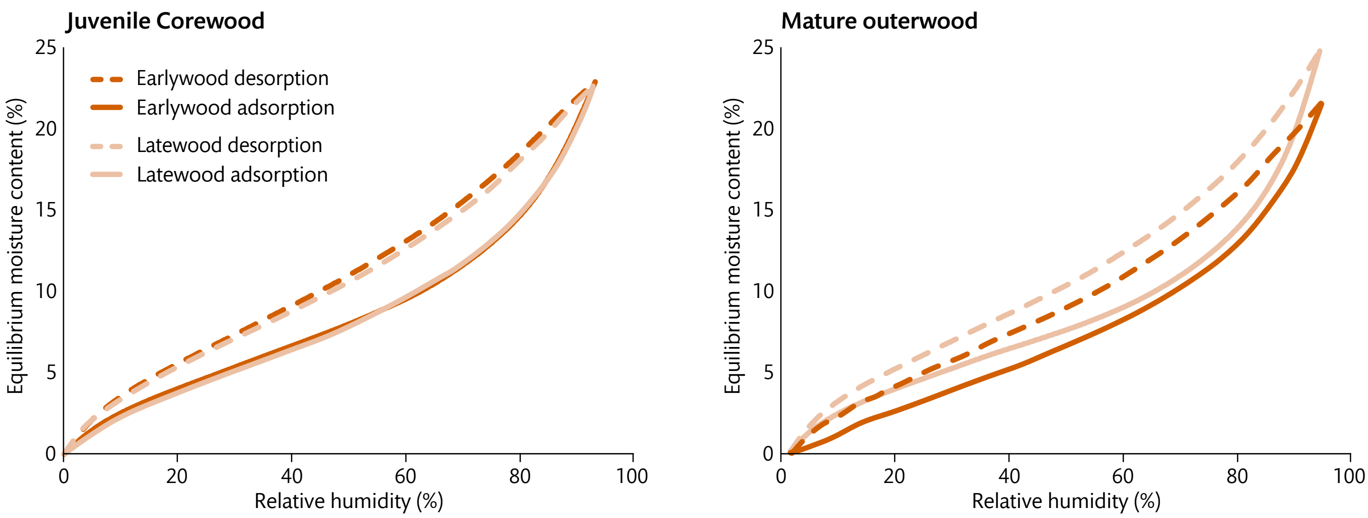
The variation in spiral grain in larches grown in Great Britain has not been fully studied. Data presented for hybrid larch growing in Japan (Fujimoto *et al.*, 2006) suggest that, as is the case with other conifers, spiral grain is generally slightly higher near the pith (around 4.5°) and decreases in the outerwood (around 2.5°) and that the variation in spiral grain between trees is very high.

Physical properties

Moisture content

Larch trees normally have relatively narrower sapwood than other conifers and therefore the moisture content of fresh larch logs tends to be relatively lower; estimates produced by Forestry Commission England and Biomass Energy Centre (2010) suggest that larches have a green moisture content of around 50% (by comparison, Sitka spruce is estimated at 61%). Like all wood, larch interacts with atmospheric water and that interaction will change depending on whether it is taking up (adsorbing) or giving out (desorbing) water. The sorption isotherms that track these two processes are different and that difference is known as hysteresis (see McLean, 2019, or Rijsdijk and Laming, 1994, for further information). Research on Japanese larch growing in Scotland (Hill, Ramsay and Gardiner, 2015) has shown that there is a difference in sorption between earlywood and latewood, in which latewood is less hygroscopic (i.e. it has a lower tendency to adsorb or desorb atmospheric moisture). This difference between earlywood and latewood also increased with ring number from the pith, with the latewood in outer rings being relatively more hygroscopic than the latewood in inner rings. This can probably be explained in part by differences in porosity; the difference between earlywood and latewood density is higher (therefore the difference in porosity is greater) in the outer rings (see Density, page 12, and Figure 17).

Figure 17 Sorption isotherms for earlywood and latewood from a mature Japanese larch tree growing in Great Britain for a growth ring close to the pith (left) and a ring close to the bark (right) (Hill, Ramsay and Gardiner, 2015).



Density

Wood density, defined as mass per unit volume (kg m^{-3}), is generally considered a key characteristic that affects the structural performance of sawn timber, the yield and properties of pulp, the energy that can be derived from wood used as biomass and the carbon stored in trees and wood products.

Because both the weight and volume of wood change with varying moisture content, wood density measurements generally state the moisture content at which they were made; commonly used reference points are air-dry density (mass and volume measured at 12% moisture content), green density (mass and volume measured in freshly felled 'green' wood) and basic density (the ratio of oven-dry mass to green volume) (see Moore, 2011, and McLean, 2019, for a fuller explanation).

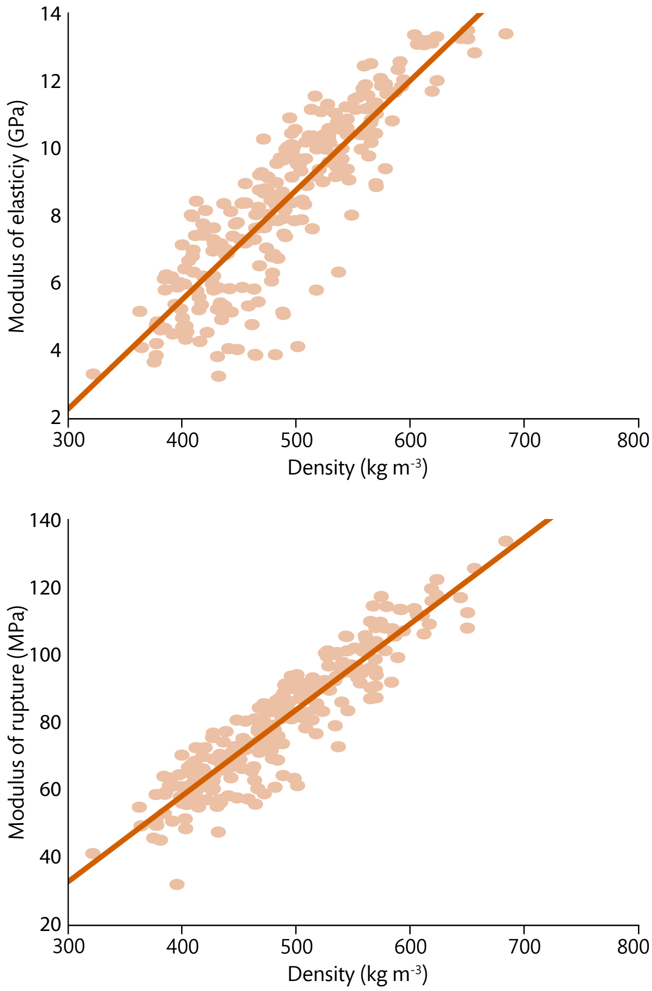
A recent study based on around 1000 pieces of sawn, structural-sized larch timber from trees grown in the UK and Ireland (a mixture of European, Japanese and hybrid), reported average wood density values at 12% moisture content of 480–530 kg m^{-3} (Ridley-Ellis *et al.*, 2022). These values were similar to those obtained in the same study for Scots pine and Douglas fir (480–550 and 450–550 kg m^{-3}, respectively), but considerably higher than those for a mixed batch of Sitka and Norway spruce (380–410 kg m^{-3}).

There is insufficient evidence to confirm any differences in wood density between the three species of larch growing in Great Britain. Lavers (1983) provided average density values at 12% moisture content of 465, 481 and 545 kg m^{-3} for hybrid, Japanese and European larch, respectively. These values suggest that hybrid and Japanese larch have a similar density, while European larch is denser. However, these data relate to a relatively small sample and come from trees grown in different places. It has also been highlighted that the European larch trees available for testing tended to be older (Harding, 1988) and therefore denser. Earlier, unreferenced studies cited by Thomas (1964) had also indicated that European larch was consistently some 13% denser than Japanese larch. Elsewhere, density figures comparable with Lavers (1983) and showing a similar difference between species, have been reported for Japanese and European larch of the same age growing in an experimental forest in Sweden (Karlman, Mörling and Martinsson, 2005), suggesting that there may be a difference between species.

It should be noted that there may also be differences in wood density between provenances (genetic origins) within a species. The most detailed examination of this has taken place with European and Japanese larches growing in Brittany (Pâques, 1996a, 1996b). Regional differences in wood density within the provenance of a species could also be expected to be important (i.e. environmental variation), but data on this do not exist for larches in Great Britain.

In common with most softwood species, the wood density of British-grown Japanese larch is positively correlated with stiffness and strength (Figure 18), with the latter being the stronger relationship and the most variable part being in the juvenile/core wood. These relationships are used in some machine strength grading systems, where the stiffness and strength of sawn timber may be predicted from measurements of wood density and other indicating properties (see Ridley-Ellis, Stapel and Baño, 2016, for further details).

Figure 18 The relationship of stiffness (top) and strength (bottom) to wood density at 12% moisture content for Japanese larch grown in northeast Scotland. Data are derived from small clear wood sample testing (not structural-sized timbers) (Edinburgh Napier University, unpublished data).



The radial pattern of the wood density of Japanese larch (Figure 19) follows the pattern found in Sitka spruce (McLean, Moore and Gardiner, 2016), where, on moving from the pith to the bark, there is an initial decrease in wood density and then an increase. Relative to Sitka spruce (Moore, 2011), Japanese larch apparently has less of an initial decrease in wood density, and the wood density of the Japanese larch outerwood exceeds that of the innerwood, which is not the case in Sitka spruce. There are insufficient data to consider vertical trends in density within a tree, or differences in radial trends, between the three species grown in Great Britain.

Dimensional stability

Below fibre saturation point (around 30% moisture content), wood shrinks as it dries, because water is lost from cell walls, and swells as moisture is gained. The amount of shrinkage that occurs is not the same in all directions: tangential shrinkage (parallel to growth rings) is generally in the range 5–10%, while radial shrinkage (across growth rings) is around 2–6% and longitudinal shrinkage (lengthwise along the grain) is much smaller, only 0.1–0.3% (Walker, 2006). These differences can cause distortion of sawn timber as it dries.

Analysis of data from a study on Japanese larch growing in Scotland (Edinburgh Napier University, unpublished data) suggested that, in common with other softwood species, tangential shrinkage is approximately double that of radial shrinkage (Figure 20). Shrinkage also varied radially, with a general pattern of increasing shrinkage from pith to bark (Figure 20) that approximately followed the radial trend in wood density. This reflects the positive correlation between transverse (radial and tangential) shrinkage and wood density (Walker, 2006; Bowyer, Shmulsky and Haygreen, 2007; Zhang, Ren and Jiang, 2021).

Figure 19 The radial trend in ring density, latewood and earlywood density in Japanese larch growing in northeast Scotland (Edinburgh Napier University, unpublished data).

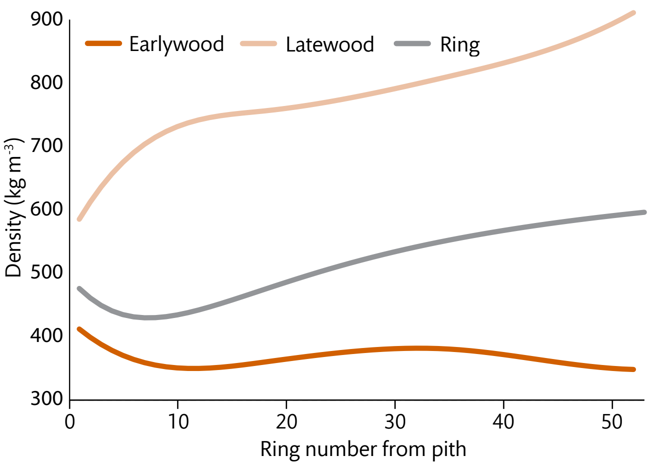
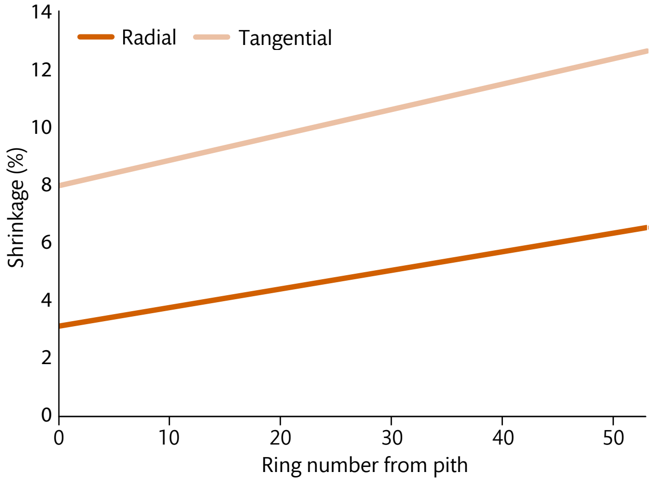


Figure 20 The radial trend in shrinkage of Japanese larch growing in northeast Scotland (Edinburgh Napier University, unpublished data).



Published data suggest that there may be a difference in shrinkage between the three larch species grown in Great Britain. Harding (1988) gives shrinkage values from green to 12% moisture content for European larch of 4.5% (tangential) and 3% (radial), while for Japanese larch the corresponding figures are 3% and 2%, respectively. A similar pattern was observed by Charron *et al*. (2003), who tested trees from the three species growing across a range of environments in Belgium (Table 6). The shrinkage of European larch from green to oven-dry was higher than that of Japanese larch in the radial and tangential dimensions (hence also volumetric shrinkage) and lower in the longitudinal dimensions. This is expected based on their wood density; however, hybrid larch falls approximately mid-way between Japanese larch and European larch based on shrinkage, while having a similar wood density to the Japanese larch samples.

Table 6 Density shrinkage and swelling of samples produced from three species of larch growing in Belgium (Charron *et al*., 2003). Numbers in parentheses are standard deviations.

Property	European larch	Hybrid larch	Japanese larch
Density at 12% MC (kg m^{-3})	642 (78)	526 (59)	526 (80)
Volumetric shrinkage (%)	15.16 (2.88)	13.37 (2.29)	11.84 (1.98)
Longitudinal shrinkage (%)	0.09 (0.72)	0.19 (0.57)	0.4 (0.71)
Radial shrinkage (%)	4.67 (1.32)	3.39 (0.96)	3.10 (1.01)
Tangential shrinkage (%)	7.46 (1.61)	6.27 (1.58)	5.61 (4.37)

MC: Moisture Content

Natural durability

Timber's inherent resistance to fungal decay and insect attack is known as natural durability (Davies, 2016). The true natural durability of larch is a matter of some debate, complicated by the natural variability of wood, and the fact that testing standards cannot replicate the wide range of exposure conditions encountered in service. A full discussion of this topic is beyond the scope of this report, so the following summary is based on the current *European Standard*, *EN350* (British Standards Institution, 2016). Actual experience may vary, and other sources of information may differ slightly (Dauksta, 2011). There is wide variation in decay resistance between individual trees, as is the case for other quality traits. Because this variation arises partly from genetic differences and partly from the effect of the growth environment, it is expected that the natural durability of a timber resource may vary over time, as a result of differences in forest management and climate.

As with all species, the sapwood of larch has no natural durability but, because it is thin (i.e. in the 2 to 5 cm category), this is not a particular problem and it can be excluded or treated. The heartwood of larch has the highest durability of the commercial, home-grown softwoods. The three larch species grown in the UK are rated as moderate to slightly durable against fungi. Research in the UK confirms this, although the inner (juvenile) part of the heartwood may be less durable than the outer (mature) heartwood (Jones *et al*., 2013). The wood is rated as durable against *Hylotrupes* and *Anobium*, but not as durable against termites, or resistant to marine borers. UK-grown larch is at the lower end of the density range listed in EN350 for these species. Siberian larch (both *L. sibirica* and *L. gmelinii*) is listed with similar durability, but higher density.

The three types of larch grown in Great Britain are grouped together in the European standard for natural durability (British Standards Institution, 2016), where heartwood is considered moderately to slightly durable (class 3–4) and sapwood is not durable (class 5). A more detailed investigation into the durability of larches was carried out by researchers in France (Curnel *et al*., 2008). They determined that larch heartwood ranged from very durable (class 1) to not durable (class 5), highlighting that there is a larger range than that found in the *European Standard*. They also found differences between larch species and provenances within species, where Japanese larch was more durable than European or hybrid larch. Chemical analyses of larch heartwood (Gierlinger *et al*., 2004; Pâques, García-Casas and Charpentier, 2013) showed that Japanese larch heartwood generally has higher quantities of phenols (chemical compounds linked to natural durability) than European larch. Hybrid larch comes somewhere between the two parents, being closer to Japanese larch in one case (Gierlinger *et al*., 2004) and closer to European larch elsewhere (Curnel *et al*., 2008; Pâques, 2013). The variation in heartwood content between the three larch species is described on page 14.

Permeability and treatability

Permeability refers to the ease by which a liquid or gas is able to move through wood (Siau, 1984), and this is related to treatability, that is, the ease of penetration by liquids such as wood preservatives (British Standards Institution, 2016).

The heartwood of all three larch species grown in the UK is considered impermeable and is classed as extremely difficult to treat with preservatives, while the sapwood is classed as moderately easy to treat, but variable (British Standards Institution, 2016). As with Scots pine (McLean, 2019), the extractive content of larch heartwood and aspirated bordered pits are likely to contribute to its low permeability and resistance to preservative treatment (Walker, 2006).

Larch can be treated for fire resistance, for both internal and external (leach-resistant) use, although the pressure impregnation of fire-retardant treatments may increase the brittleness of the wood and its tendency to split.

Mechanical properties

The mechanical properties of the three larch species grown in Great Britain are presented in Table 7, in a format comparable with reports for Sitka spruce (Moore, 2011) and Scots pine (McLean, 2019). However, the published data available for larch are relatively limited. The mechanical properties and wood density (see Density, page 12) of British larch have, in general, been found to be better than that of Scots pine or Sitka spruce, although more recent British studies have not taken account of species differences. The earlier tests (Lavers, 1983) suggest that European larch has more desirable properties than Japanese larch, with the hybrid somewhere in between both. A Belgian study (Charron *et al*., 2003), which tested the three types of larch grown in comparable environments, showed clear differences between European larch and Japanese larch, with hybrid larch more closely resembling Japanese larch (Table 8).

Table 7 Mechanical properties of wood from UK-grown larches. Values are presented for 12% moisture content.

Mechanical property	Reference	Species	Sample type: SC or FS	Value
Bending strength (N mm^{-2})	Ridley-Ellis *et al.* (2022)	EL/HL/JL mixed	FS	37–44
	Lavers (1983)	EL	SC	92
		HL	SC	77
		JL	SC	83
Bending stiffness (kN mm^{-2})	Ridley-Ellis *et al.* (2022)	EL/HL/JL mixed	FS	9.5–10.0
	Lavers (1983)	EL	SC	9.9
		HL	SC	8.5
		JL	SC	8.3
Work to maximum load (kJ m^{-3})	Lavers (1983)	EL	SC	0.128
		HL	SC	0.103
		JL	SC	0.101
Work to total fracture (kJ m^{-3})	Lavers (1983)	EL	SC	0.205
		HL	SC	0.139
		JL	SC	0.154
Impact bending	Lavers (1983)	EL	SC	0.76
		HL	SC	0.64
		JL	SC	0.69
Compression strength parallel to grain	Lavers (1983)	EL	SC	46.7
		HL	SC	39.1
		JL	SC	43.0
Side hardness	Lavers (1983)	EL	SC	3650
		HL	SC	3160
		JL	SC	2890
Shear strength parallel to grain	Lavers (1983)	EL	SC	12.4
		HL	SC	11.6
		JL	SC	11.8
Resistance to splitting in radial plane	Lavers (1983)	EL	SC	9.3
		HL	SC	NA
		JL	SC	8.2
Resistance to splitting in tangential plane	Lavers (1983)	EL	SC	10.9
		HL	SC	NA
		JL	SC	10.9

EL, European larch; FS, full-sized/structural; HL, hybrid larch; JL, Japanese larch; NA, not available; SC, small clear.

Bending strength and stiffness

The bending strength and stiffness of larches grown in Great Britain had not been well studied until the outbreak of *P. ramorum* (see Recent effects of Ramorum disease, page 2) led to a sudden abundance of timber resulting from the widespread sanitation felling. The research that has been carried out to date, particularly on full-sized timber specimens, has not investigated the difference between larch species, because their wood is amalgamated into one species group commercially (see Commercial larch species groupings, page 20). It is quite probable that a difference in species exists based on research that has been carried out in other countries (Charron *et al*., 2003), where European larch has been found to have superior bending strength and stiffness compared with Japanese larch and hybrid larch (Table 8).

Data from Ridley-Ellis *et al*. (2022) compared the bending strength and stiffness of larch timber with results for the other main softwood species grown in the UK (Table 9).

Table 8 The bending stiffness and strength of three species of larch growing in Belgium. The figures are for small clear specimens of knot-free wood and have been produced from a limited number of trees of comparable ages growing in comparable environments (Charron *et al*., 2003).

Mechanical property	European larch	Hybrid larch	Japanese larch
Bending strength (N mm^{-2})	112.0 (22.4)	82.0 (18.0)	81.5 (27.0)
Bending stiffness (kN mm^{-2})	12.0 (3.6)	8.4 (2.9)	8.6 (2.8)

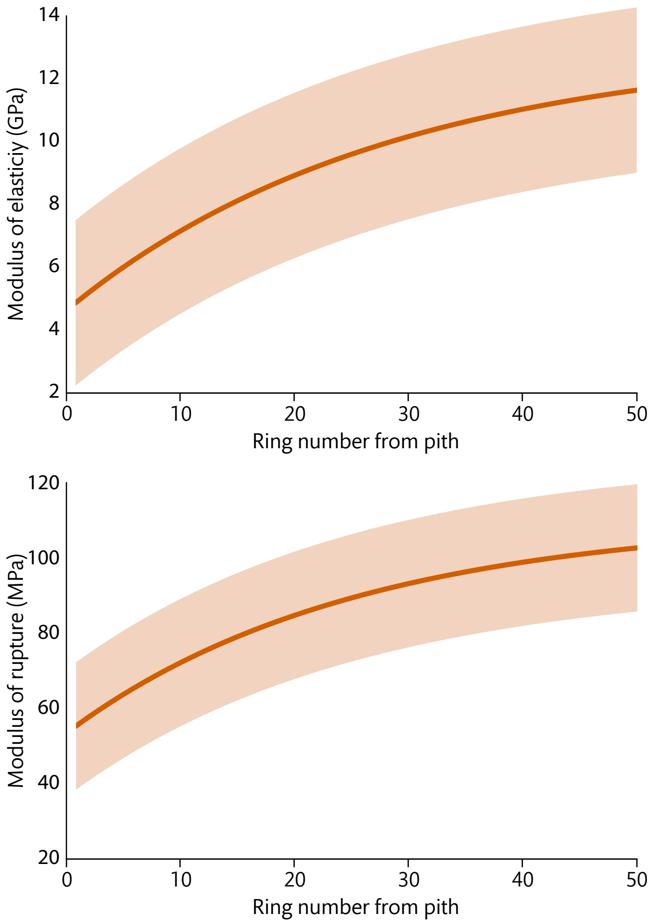
Table 9 Typical average properties of UK and Ireland-grown softwoods before grading, measured at 12% moisture content. Reproduced from Ridley-Ellis *et al*. (2022).

Species	Dataset size	Mean bending strength (N mm^{-2})	Mean bending stiffness (kN mm^{-2})
European, Japanese and hybrid larch	~1000	37–44	9.5–10.0
Sitka and Norway spruce	~2000	30–33	7.5–8.5
Scots pine	~500	36–46	8.5–10.0
Douglas fir	~700	28–50	8.5–13

On average, the larch timber tested was 10–15% stiffer and stronger than the combined Sitka spruce and Norway spruce dataset. Compared with Scots pine, the bending strength of larch was broadly similar, while stiffness was at the upper end of the Scots pine results. Data for Douglas fir suggest a wide variation in the properties of this species, with the lower end of the range of typical values falling quite far below those for larch, but with the top end exceeding the best typical stiffness and strength values achieved for larch.

Based on the data that are available, the pattern of radial variation in bending stiffness and strength of Japanese larch appears to follow the same pattern as that found in Sitka spruce and Scots pine (Moore, 2011; McLean, 2019), being lower in the centre of the tree and increasing towards the outside (Figure 21).

Figure 21 The radial variation in bending stiffness (top) and bending strength (bottom) measured in small clear wood samples of Japanese larch growing in northeast Scotland (Edinburgh Napier University, unpublished data). The dark line represents the mean value in each ring and the shaded area represents the distribution around the mean.



Effects of site, silviculture and genetics on selected wood properties

Forest location

The natural environment impacts on the growth and wood properties of planted conifers. No study has been made of these environmental impacts on larches growing in Great Britain, or conclusively elsewhere. Conversely, there are several studies on the genetic variation associated with provenances (see Seed origin, page 17). Provenance variation may be considered as evolutionary adaptation to local climates and the differences are genetic rather than physiological responses to environment. It has been observed that European larch has a high sensitivity to the growing environment (Giertych, 1979; Lines, 1987) and that provenances will not grow well outside of the climate to which they have adapted.

Genetic origin

Seed origin

In addition to the environment, genetics determine the growth and wood properties of conifers in planted forests. There are several studies on the growth and wood properties of European and Japanese larch provenances in Europe (reviewed in Pâques, 2013) and Japan (Takata *et al.*, 2005). Considering all factors, the best European larch provenances suggested by Lee (2003) for growing in Great Britain were from the Sudetes Mountains in the Czech Republic, although stem form, which is important for timber, is apparently better in the provenances from the lowlands of the Eastern Alps (Lines, 1987). For Japanese larch, the best provenance for planting in Great Britain is considered to come from the Nagano district (Lines, 1987). For use in Great Britain, the current recommendations (Forest Research, 2023) are to source material from British registered seed stands (see Forest Reproductive Materials [arcgis.com] for the online register) or, if importing, European larch from the Czech Republic and Japanese larch from the central part of the natural range.

Tree breeding

There are two main strategies for breeding larches in Europe: improve European larch in its native range, or use hybrids as a means to try and adapt the species to low altitudes (<400 m asl) and oceanic climates (Pâques, 2013). Because hybrid larch grows faster (see Introduction to Great Britain and hybrid larch, page 2) than either Japanese larch or European larch, and in other respects offers the potential to have the best traits of the two parent species combined into one (Pâques, 1989), it has been the focus of the British larch breeding programme.

As described by Lee (2003), there are difficulties in producing hybrid larch for breeding: scions from plus trees of both species need to be grafted then cross-fertilised under strict control, which is challenging because of the different (asynchronous) flowering times for European and Japanese larch and difficulties in storing pollen. In addition, the number of seeds produced per cone is low (often fewer than 10, compared with more than 30 for Sitka spruce).

From the 1960s to the 1980s, a total of 527 European larch and 328 Japanese larch plus trees were selected for the breeding programme and were copied by grafting scions onto rootstock maintained at a manageable size to enable controlled pollination (Lee, 2003). In total, 71 progeny tests were planted in 18 different series (planting years), of which 43 provided reliable data for 200 European larch and 50 Japanese larch plus trees. The best performing 100 European larch and all 50 Japanese larch plus trees are maintained by Forest Research in clone banks, retaining the possibility of future production of hybrid larch families should there ever be a demand.

Estimated gains from controlled pollination between plus trees, followed by vegetative propagation, are in the order of 15–20% for 10-year height and 20–25% for stem straightness, depending on the relative importance placed on each trait (Lee, 2003). These potential gains are much greater than those offered by seed orchards, which also have the disadvantage that only a proportion of the seed produced is hybrid larch, with the remainder being either pure European larch or pure Japanese larch (Ennos and Qian, 1994). During the 1990s, the Forestry Commission used controlled pollination combined with vegetative propagation from cuttings to produce hybrid larch. Although the programme was discontinued because of low rooting percentages and poor plant quality, more recent research has provided best practice guidance on the production of hybrid larch from cuttings (Perks *et al.*, 2006).

The main focus of breeding larch in Great Britain is now most likely to shift towards resistance to *P. ramorum* (see Recent effects of Ramorum disease, page 2) and research on this topic has already begun.

Silviculture

In Great Britain, larches have often been planted for aesthetic reasons. Their deciduous nature is seasonally appealing and, interspersed with evergreen trees, can result in more visually diverse, attractive landscapes. They were also used to provide firebreaks, as the dropped needles will suppress flammable grasses.

Much of the research into larch silviculture in Great Britain has focused on nursery production and the early establishment phase, as summarised by Perks *et al.* (2006). A key concern has been poor establishment success, with losses of up to 50% reported (McKay and Howes, 1994). Recommendations for improved establishment include undercutting and wrenching of plants in the nursery to improve the root:shoot ratio, restricting lifting in the nursery for direct planting out to October and March and using winter weed control to improve survival (Perks *et al.*, 2006).

Spacing at planting influences tree and wood properties, which affect timber utilisation, and studies with conifers have shown that wider spacing, in general, results in greater stem taper, increased branch (and knot) sizes and a larger juvenile core compared with closer spacing (e.g. Brazier, 1977; Moore *et al*., 2009; Auty *et al*., 2012). The current practice in Great Britain of establishing larch at the same spacing as other conifers, with a target of 2500–2700 stems ha^{-1}, is at the higher end of international practice. In a review of international plant spacing recommendations for conifers, Davies and Kerr (2015) found that the recommended initial stocking densities for larch generally ranged from 1000 to 2500 stems ha^{-1}, although 3333 stems ha^{-1} was recommended for Japanese larch in Germany, to restrict branchiness. It was noted that in several countries there was an expectation that pruning would be required to produce high quality timber from stands established at lower stocking densities.

As noted by Davies and Kerr (2015), there have been few scientific studies examining the effects of initial spacing on timber quality in larch. Hamilton and Christie (1974), reporting on tree growth data from a series of trials planted in the 1930s at spacing ranging from 0.9 m x 0.9 m (11 960 stems ha^{-1}) to 2.4 m x 2.4 m (1682 stems ha^{-1}), found that increasing the spacing resulted in increased diameter growth and a higher rate of taper in the lower part of the stem. Similar results for diameter growth have been reported in international studies in European larch (Table 10; Morrow, 1978) and Japanese larch (Table 11; Fujimoto and Koga, 2010), with the latter also reporting a corresponding increase in branch diameter.

General guidance on the silviculture of larches in Great Britain is provided by Savill (2013), who notes that as light-demanding species (Hale, 2004), larches should be thinned heavily and early, maintaining at least one-third of the total stem length as live crown. Savill also emphasises that the stem form of larches is generally variable, so selective thinning should be practised to improve the quality characteristics of the final crop. Studies of thinning in Japanese larch (Koga *et al*., 1997) have indicated that while thinning increased diameter growth and volume increment, there was no significant effect on wood density.

Table 10 The effects of tree spacing on the growth of European larch grown in New York, USA (Morrow, 1978).

Trees per hectare	Age (years)	DBH (cm)	Branch diameter (cm)
2470	21	14.7	1.6
1680	21	16.5	1.9
1080	21	18.5	2.2
550	21	22.1	3.0

DBH: diameter at breast height.

Table 11 The effects of tree spacing on the growth of Japanese larch, grown in Hokkaido, Japan, (Fujimoto and Koga, 2010).

Trees per hectare	Age (years)	DBH (cm)	Height (m)
1000	22	20.3	18.9
500	22	25.7	18.6
300	22	27.6	18.75

DBH: diameter at breast height.

Pests and diseases of larch

Ramorum disease in larches (Figure 22) has become a serious threat to their continued use in forestry in Great Britain. Strict management and sanitation felling operations have led to a large influx of larch timber on the market. There is currently no research specifically investigating the impact of *P. ramorum* on the growth[6] and wood properties of larch. However, because *P. ramorum* affects the living parts of the tree (i.e. the bark and foliage), there is no reason to expect that it directly affects the wood[7] already produced prior to infection. The special licences required for processing larch wood from infected forests have been put into place to restrict the spread of spores, not because there is an impact on wood properties. The potential for in-forest heat treatment of infected larch bark by aerobic composting in windrows has been investigated by Green (2014). However, the method was not found to be sufficiently effective in killing the spores of *P. ramorum* for the removed bark to be used as a mulch, without the risk of spreading the disease.

6. *Phytophthora ramorum* is generally accepted to rapidly kill the host rather than slow the rate of growth; if resistant trees are found then a study could be made.
7. Wood is technically dead from the moment it is finished being produced by the vascular cambium. The one exception is ray cells in the sapwood, which forms a comparatively small component of the larch cross-section (see Sapwood and heartwood, page 10). The main risks associated with *Phytophthora ramorum* and wood are actually related to the unwanted transportation of spores that could cause infection elsewhere. However, these spores will not survive the wood-drying process.

Figure 22 (a) Discolouration of larch foliage caused by girdling of branches by *P. ramorum* lesions. (b) Profuse resin production associated with *P. ramorum* lesions.

European larch can also be particularly susceptible to larch canker, which is caused by the fungus *Lachnellula willkommii*, although Polish studies have indicated that there are provenance and age effects with respect to susceptibility (Kulej, 2006). The pathogen is believed to be native to Japan but has affected European plantations since the 19th century. Infection causes perennial cankers that girdle or distort branches and stems (Figure 23). There is believed to be an association between frost damage and larch canker. Hybrid larch is occasionally susceptible, but Japanese larch is rarely affected.

Figure 23 Larch canker on stem showing sooty coloured resin exudation, fruiting bodies and stem deformation.

All three types of larch can be killed following attacks by the larch bark beetle *Ips cembrae* which preferentially attacks trees under stress.

Suitability for different products

Current larch timber production in Great Britain and Ireland consists mainly of Japanese and hybrid larch. Pallets, packaging, fencing and other outdoor uses are all important markets, with the natural durability of the heartwood valued in a range of applications. Larch grown in Great Britain is also used in external timber cladding on buildings, although much of this market has been, until recently, supplied by imported Siberian larch. In construction, larch is often used in exposed, heavy structures which make use of its strength and the natural durability of heartwood. Following recent studies, larch timber can be seen to achieve high yields of C22 in strength grading, which is typically better than spruce wood. Larch has been shown to be technically suitable for engineered products such as glulam beams or solid wood panels (nail-lam or dowel-lam), and may also be suitable for some joinery applications, especially flooring. The relatively high extractive content of larch offers the potential for chemical production, especially from waste material such as bark, brash and knots, although the development of this market seems likely to be limited by phyosanitary restrictions on the movement and processing of larch bark and brash, in response to *P. ramorum.*

Traditional uses of larch in Great Britain

Larch has a very long history of use for objects and medicine. During the last glacial period, European larch was widespread across the continent, making it a useful fuel resource for the Neanderthal population (Basile, Castelletti and Peresani, 2014). The oldest surviving larch artefact found to date is the approximately 11 000-year-old Shigir idol, discovered in the Middle Urals in 1894 (Zhilin *et al*., 2018).

Modern use of larch in Great Britain began in the 18th century, following the planting of European larch as a timber tree by several private landowners. By 1808, pressures on the supply of oak due to the Napoleonic wars attracted government attention (Holmes, 1975) and soon after, John Murray, the 4th Duke of Atholl, persuaded the Naval Board to trial larch for shipbuilding. After initial trials that showed promise, in 1816 it was agreed to construct a new sloop *HMS Atholl* at Woolwich dockyard entirely from Scottish-grown larch. The *HMS Atholl* served for 40 years, far outlasting a warship of the same class, *HMS Niemen*, which was built from 'Baltic fir' (Scots pine sourced from Baltic ports), which decayed rapidly while in service. However, reports from the dockyard noted issues associated with excessive shrinkage and a tendency to warp during the seasoning of larch (Laslett and Ward, 1894) and, in any case, the age of wooden fighting ships was coming to an end, although larch continued to be used for components and for merchant vessels and smaller boats.

The expansion of the railways in Great Britain provided a huge opportunity to use home-grown larch as railway sleepers, but by this time larch canker was causing significant problems for timber quality and reputation (McIntosh, 1860), which further encouraged the planting of Japanese larch. Nevertheless, the relative durability and strength of the timber was an advantage, and it has found multiple uses over the years, despite never fully achieving its envisaged potential.

Because European, Japanese and hybrid larch are often processed and sold together, and the differences between them are small compared with the general variability in wood, their characteristics and uses are described here together.

Commercial larch species groupings

Species and mixture codes (European Committee for Standardization, 2019) are presented in Table 12.

Larch is not always named consistently in the timber trade but, for the UK and European market, the following can be said:

- UK and Ireland-grown larch is a mixture of three larch types: European (LADC), Japanese (LAKM) and hybrid (LAER), but is often referred to simply as 'larch'. However, the modern resource is mostly Japanese and hybrid larch, especially in Ireland, and is given the code WLAD (European Committee for Standardization, 2019).

Table 12 List of European standard timber codes for larch species and mixtures.

Code	Species scientific name	Species common name
LADC	*Larix decidua*	European larch
LAKM	*Larix kaempferi*	Japanese larch
LAER	*Larix x marschlinsii* (syn. *Larix x eurolepis)*	Hybrid (or Dunkeld) larch
LAOC	*Larix occidentalis*	Western larch
LASI	*Larix sibirica*	Siberian larch
LAGM	*Larix gmelinii*	Dahurian larch, but also known as Siberian larch
WPSM	*Species combination*	Douglas fir-larch
WLAD	*Species combination*	Japanese and hybrid larch

- The commercial larch in Europe (excluding Ireland) is mostly European larch (LADC), but also involves timber from plantations of Siberian larch in Finland, Sweden and Estonia, and Japanese larch from Spain.
- Western larch (LAOC) is marketed as a component of the confusingly named North American species combination 'Douglas fir-larch' (sic), which is given the code WPSM. However, the most well-known of the imported larches is 'Siberian' larch. The name Siberian larch is used to refer to *Larix sibirica* (LASI), but also to *Larix gmelinii* (LAGM). The latter, sometimes called Dahurian larch, is also native to Siberia. These are different species, but they do naturally hybridise where they meet.

Most of these four-letter species codes are from the list of standardised names for commercial wood species in Europe (European Committee for Standardization, 2003), although LASI appears in the glulam (glued laminated timber) standard (European Committee for Standardization, 2013) and WLAD and WPSM are given in the structural timber standard (European Committee for Standardisation, 2019).

Prior to sanctions imposed on Russian timber imports into Europe in 2022, imported Siberian larch was the main direct competitor to home-grown larch for the higher value markets, except for mainstream structural timber, which was mostly imported pine, spruce and fir.

Appearance, processing and drying

Colour, appearance and texture

The appearance of Japanese larch and European larch wood is similar and so is the wood of hybrid larch. Larches have very easily distinguished annual rings, with a clear demarcation between earlywood and latewood. The overall colour is usually reddish, although it can sometimes look very similar to spruce. The heartwood is a reddish-brown to yellow in colour and is usually easily distinguishable from the lighter coloured, white or pale-yellow sapwood (Chapter 2, Figure 14). Larch sapwood typically occupies a relatively narrow proportion of the stem, in cross-section (see Sapwood and heartwood, page 10).

The wood can show a lot of character, especially when flat-sawn. Grain is generally straight. The wood has a medium-to-fine texture and can have a slightly oily feel, although unfinished surfaces also easily give very small splinters that can cause skin irritation. It has a distinct resinous odour when being worked.

Working qualities

Dry larch saws, machines and finishes reasonably well, although split and loosened knots can cause problems. The wood can spring off the saw because of growth stresses, and resin pockets can also be problematic when present. Cutting edges must be kept sharp to avoid earlywood tearing, and clogging of saw blades may occur, especially in green timber. In sawmilling, this build-up of extractives on the saw means lower production rates than are possible with spruce (as it can cause inaccurate cutting and shorter service life), but this can be mitigated with increased lubrication (Dauksta, 2011). Because of the higher density and hard knots, it requires more tool maintenance than spruce. Being a dense timber, it also tends to split in nailing, unless pre-drilled, especially near board ends. It can be stained, varnished and painted similarly to pine, but the marked difference between latewood and earlywood can cause a slightly uneven sanded surface to the touch. The wood glues well if properly dried, although the high extractive content can cause issues for high performance applications, unless there is pre-treatment (Künniger *et al.*, 2006). It can be finger-jointed for structural as well as non-structural uses. Its acidity is similar to spruce and is considered less corrosive to metal fasteners than Douglas fir, although care is needed when choosing fixings for external cladding (Rothoblaas, 2023).

Larch bark and sawdust can cause skin problems for some people (Woods and Calnan, 1976), and as with other wood species, fine dust in particular can cause respiratory problems (Imbus and Stave, 2016).

Despite the reputation for twist and warping on drying, it can be kiln- or air-dried well if cared for properly, and the overall moisture movement is similar to other commercial softwoods. The main issue for UK mills is that it dries differently from spruce, requiring a different schedule (Pratt, Coday and Maun, 1997) and preventing the timbers being processed together. It can start to dry out quite quickly after cutting, causing distortion, splitting, checking and the loosening of knots.

Density and embodied carbon

The overall mean density of the currently harvested home-grown larch resource is ~515 kg m^{-3} with a coefficient of variation of ~11%. Because of the way timber density varies between trees and stands, the mean density of batches of home-grown larch timber can be expected to vary from 470 to 530 kg m^{-3}. This means that 1 m^3 of UK-grown larch timber at 12% moisture content represents 770–870 kg of sequestered CO_2 (European Committee for Standardization, 2014).

Although this mean density is much higher than for UK-grown spruce (mean ~400 kg m^{-3}), a randomly chosen piece of spruce still has an ~10% chance of being denser than a randomly chosen piece of UK-grown larch.

Wood products

Pallets and packaging

Despite the tendency to split on nailing, the manufacture of wood packaging material is an important market for home-grown larch, especially lower-grade logs. For use in pallets, larch performs similarly to Douglas fir and Scots pine, and is superior to silver fir and spruce in strength. The natural durability of larch heartwood is also an advantage for some uses and, unlike Scots pine, it is not susceptible to blue stain.

Fencing and other outdoor timber

Outdoor wood, in various agricultural, domestic and municipal applications, is another important market for home-grown larch because of its natural resistance to rot, with the heartwood classed as moderately durable (British Standards Institution, 2016). This includes fencing, barriers, gates, decking, garden buildings, benches, tables, trellises, playground equipment and sleepers for landscaping.

Cladding

The use of larch as external cladding for buildings is a high profile, high value use (Figure 24). When uncoated and unstained, the wood weathers to an attractive silvery grey. Alternatively, it will take exterior grade stains and oils, but because of the resinous nature of the wood, it is best left natural. Screw fixings and simpler overlapping profiles are

Figure 24 The headquarters for NatureScot in Inverness uses locally sourced larch for the external cladding and solar shading.

Courtesy of Keppie Design

recommended, to better accommodate moisture movement of the wood (Timber Development UK, 2022). However, a substantial part of the cladding market is accustomed to being served by imported Siberian larch, which is considered to be less knotty, and the heartwood has been shown to have greater natural durability than other larch species (Jebrane, Pockrandt and Terziev, 2014). Nevertheless, home-grown larch is suitable for external timber cladding, provided it is specified and installed in line with best practice guidance (British Standards Institution, 2014; Timber Development UK, 2022); there are several fine buildings in the UK clad with home-grown larch. Larch is also used for roofing shingles.

Structural timber for buildings and bridges

Larch has particular advantages for exposed, heavy structures, where the inherent strength and natural durability of heartwood are useful. Large sizes of sawn timber are available, making it suitable for agricultural buildings and light bridges. However, one notable counter example is the gridshell roof of the Savill Building, Windsor Great Park (Figure 25), which is made from small dimension interlocking larch laths.

Until 2011, the only option for structural grading of UK-grown larch was visual, which can achieve the strength classes C16 and C24 (European Committee for Standardization, 2012). These are also the commonly specified strength classes in the UK for light timber construction, but larch is at a disadvantage against the lighter softwoods (spruce, pine and fir), which do not suffer the same splitting problem when nailing.

Grading studies were conducted in response to the outbreak of *P. ramorum*, to allow larch to be used in higher value applications. The first of these, using test data from the Building Research Establishment and the UK Timber Grading Committee, allowed machine grading with bending-type machines (the Techmach Cook Bolinders and the MPC Computermatic Micromatic). The second study was conducted by Edinburgh Napier University in 2014, and used new test data to develop machine settings for Microtec grading machines (including the Goldeneye 702) and Brookhuis grading machines (including the handheld MTG). In 2020, these were supplemented with additional test data from the University of Galway, to extend the growth area to Ireland (the larch properties in the UK and Ireland were confirmed to be very similar, as was already shown to be the case for spruce and Douglas fir). In 2018, a further study, with separate testing performed by the Research Institutes of Sweden, added settings for the Dynalyse Precigrader. In 2022, grading settings for larch and Douglas fir combined were developed by University of Galway and Edinburgh Napier University (Gil-Moreno, Ridley-Ellis and Harte, 2023; Ridley-Ellis, Gil-Moreno and Harte, 2023).

Figure 25 Interior photograph of the Savill Building Visitor Centre in Windsor Great Park (Crown Estates) featuring a timber shell roof. The building was designed by Glen Howells Architects.

Courtesy of Warwick Sweeney / Howells

UK-grown larch can now be graded with several different grade combinations, up to C35, including the trussed rafter grade TR26. The characteristic (fifth percentile) density of ungraded UK-grown larch ranges from about 400 to 420 kg m^{-3}. Characteristic (fifth percentile) strength ranges from about 19 to 22 N mm^{-2}, and mean stiffness ranges from about 9 to 11 kN mm^{-2}. Stiffness tends to limit the strength grading, but larch can achieve C20 or C22 as a single grade with minimal machine reject. With the right grading machine, yields of about 30% C27 with 70% C16 and minimal machine reject are achievable.

Density is by far the least critical property and even ungraded it is higher than the C40 requirement. One consequence of this is that larch graded to the usual C-class strength grades is considerably heavier (typically up to 20%) than the mean density of the strength class. In many structures, it is the connection design that governs member sizes, and this is based on the grade density. Therefore, to make better use of the actual inherent properties of UK-grown larch, four special strength classes have been developed by Edinburgh Napier University for potential future use (Table 13; Ridley-Ellis, Adams and Lehneke, 2016). These four classes are named Napier, followed by L (for larch) and a letter A, B, C or D denoting the level (A being the highest and D the lowest). The grading works in pairs. A with C aims to split the yield roughly 25% to A and 75% to C. B with D aims to split the yield roughly 50% to each.

In full-sized structural timber, the correlation between strength and stiffness is reasonably good, meaning that grading machines based on stiffness work well. However, in contrast to data derived from small clear wood test samples (Figure 18), in structural samples neither strength nor stiffness have been found to be strongly correlated with density. The coefficient of variation for strength (~30%) is fairly typical for a European softwood, and for stiffness (~25%) it is slightly higher than typical. The density of clear wood, which is the reference density for structural timber, is about 5% less than the average density of the whole board (including knots).

Boatbuilding

Good quality, relatively knot-free larch wood is used for building yachts and other small boats (Figure 26). Larch planking over oak was the traditional method of constructing Scottish fishing boats in the 19th century. It can withstand the sun and sea spray without splitting or cracking, and still remain watertight.

Although it may be difficult to source suitable wood, larch is good general boatbuilding timber. It is good for frames and beams and is acceptable for planking. For larger vessels, Thomas Laslett, who was timber inspector to the Admiralty, reported that larch was very suitable for the parts of the frames of a ship in which a light material is considered desirable. He also remarked on the good durability, but

Figure 26 Boatbuilding: boat-skin larch is used where skippers still specify wooden hulls for their fishing boats, such as this one at Isle Ewe Boats, Aultbea.

Courtesy of Mr Alasdair Grant.

Table 13 Larch strength classes developed by Ridley-Ellis, Adams and Lehneke (2016).

Strength class name	Fifth percentile bending strength (N mm^{-2})	Mean bending stiffness (kN mm^{-2})	Fifth percentile density (kg m^{-3})	Approximate yield (%)
Requirements for grade combination option 'NapierLA' with 'NapierLC'				
NapierLA	30	13	480	25
NapierLC	21	9	400	75
Requirements for grade combination option 'NapierLB' with 'NapierLD'				
NapierLB	28	12	440	50
NapierLD	20	8	390	50

noted that excessive shrinkage caused problems in keeping decking and planking weather- and water-tight (Laslett and Ward, 1894). Advice for managing larch for shipbuilding, including the bending of young trees for knees, was laid out in detail by Matthew (1831), who, in a letter written to the Naval Board in 1824, stated that 'Larch has been in general use on the Tay for boatbuilding for 20 years past. At present, no other timber is employed there; in lightness, durability and strength it excels every other for that purpose' (The Patrick Matthew Project, 2018).

Engineered wood products

Larch is not an important species for fibre, strand or particle board manufacture in the UK, but it does go into chipboard production within a general mix of wood types. In other countries, larch species are used to manufacture plywood and engineered wood products like laminated veneer lumber (LVL). Larch is not a species that has been much researched for thermal or chemical wood modification. Indeed, several modified wood products compete with larch in markets such as cladding and decking.

Glulam, cross-laminated timber and other solid wood products like nail-lam (nail-laminated timber) and dowel-lam (known as Brettstapel, which is a method of solid timber construction that does not generally use glues or nails; Figure 27) are attracting increasing attention in the UK, and home-grown larch has been shown to be technically suitable (Hairstans, 2018). However, there is currently no mainstream mass timber production facility in the UK capable of supplying the volume market, and spruce is the primary focus for developing one. Even so, Brettstapel and nail-lam do have potential for small-scale production with larch because they can be manufactured by small businesses with comparatively little capital investment.

Figure 27 The merits of varying forms of mass timber products.

Courtesy of Hairstans, R., Smith, R. and Wilson, P. (2018).

The current standards for production of glulam (European Committee for Standardization, 2013) and cross-laminated timber (European Committee for Standardization, 2015) specify only European, Siberian and Dahurian larch. Japanese and hybrid larch are missing from these lists, but this is due to a lack of data and experience at the time the standards were written rather than because those species are somehow different. The larch glulam on the European market is made from those listed larch species, but Japanese larch is used for glued laminated products in Japan (Dauksta, 2014).

Other uses

Home-grown larch may be suitable for some joinery products, particularly flooring, because it is relatively hard-wearing compared with other softwoods, and can be a visually appealing alternative to oak. However, as with similar products, it has been usually produced with imported Siberian larch. In other countries larch species are used for carpentry, furniture, internal wall panelling and doors.

Historically, larch has also been used for pit props and piles (famously, some of the piling used in Venice). It is still listed in the European standard for wood sleepers and bearers for railways (European Committee for Standardization, 2011).

European and Japanese larch are not listed in the British standard for production of scaffold boards (British Standards Institution, 2009), although it does list *Larix occidentalis* as part of the Canadian species combination of 'Douglas fir–larch'.

Home-grown larch is listed as a species for tiling battens in the British standard for roofing and tiling (British Standards Institution, 2018), but is not commonly used in practice and may be removed in a future revision of the British Standard.

Larch is listed in the British standard for wood poles for overhead power and telecommunication lines (British Standards Institution, 1984), and roundwood larch poles are used for event yurts and tipis.

Biomass for energy

Seasoned larch wood burns well with good energy release because of its high density and extractives content. For industrial biomass energy, the choice of species makes little difference to the amount of energy produced because the calorific value of wood is mostly a function of density and moisture content. For a softwood, larch has a high calorific value per green tonne when felled, similar to birch, oak and Douglas fir at approximately 2700 kWh per green tonne (Forestry Commission England and Biomass Energy Centre, 2010).

Bark

Larch has thicker bark than Sitka spruce, Norway spruce, Scots pine and Douglas fir. European larch has slightly thicker bark than Japanese and hybrid larch (Matthews and Mackie, 2006). The main use for bark from British sawmills is in the horticultural sector, where it can be used for mulching, landscaping and soil improvement, although phytosanitary measures against *P. ramorum* now limit the movement and processing of larch bark, including certain restrictions on sawn wood with residual bark. In-forest aerobic composting of larch bark has been found to be insufficiently effective in killing spores of *P. ramorum* for removed bark to be transferred or sold (e.g. for horticultural products such as mulch [Green, 2014]).

Larch bark, which is rich in extractives, was used for traditional medicine. It has potential for extractive commercialisation, as well as new products such as bark panels for insulation (Kain *et al.*, 2018) or for improved indoor air quality (Tudor *et al.*, 2020).

Chemicals

The potential for the use of extractives, especially from waste material such as bark, brash and knots, or as a pre-treatment step in a biorefinery, is an active area of research (Adams, 2015). Larch is of particular interest, not just because of the quantity of extractives, but because of their type and ability for most to be removed with water as the solvent. The most commercially important extractive is arabinogalactan, which is present in heartwood in large quantities. Arabinogalactan has multiple uses, including as a food additive, animal feed, in cosmetics and medicine. Venice turpentine, which has applications in art and hoof care for horses, is distilled from liquid tapped from larch trees. Larch is also one of the sources of rosin for bowed string instruments and larch essential oil is used in aromatherapy and perfumes.

Pulp and paper

Larches are not preferred pulpwood species because of the coloured heartwood and high extractives content, but can be used if processing younger trees by adapting the pulping process and perhaps performing a pre-extraction step for extractives valorisation. However, this is not of commercial importance in Europe, where there are abundant supplies of more suitable species, such as spruce, pine and birch.

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Larch trees are an important component of the forest landscape in Britain, valued for their aesthetic appeal and for their strong, durable timber, which can be used in a wide range of applications. Since 2009, infection of larch trees by *Phyophthora ramorum* has resulted in widespread mortality and necessitated extensive felling of both infected and healthy trees for disease control. Despite this, it is expected that larch timber from trees grown in Britain will continue to be harvested, processed and utilised for many decades to come. This report collates and synthesises research into the production and use of larch timber in Great Britain, drawing on information from a range of published and unpublished studies. 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 larch. The report is divided into three parts: (1) distribution of larch, including introduction of different species into Great Britain and the current extent of the resource, (2) the chemical, physical and mechanical properties of larch wood and their variation, and (3) suitability of larch timber for different end products.

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