A review of the effects of silviculture on timber quality of Sitka spruce

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Summary

This review focuses on timber quality with a particular emphasis on Sitka spruce and sawlog production, although issues pertaining to pulp and panel quality are also dealt with. The review is split into three broad areas. The first covers the factors controlling wood quality that operate within the timber itself and also at the whole-tree scale. These include knots, grain angle, wood density, tracheid length, microfibril angle, juvenile wood and compression wood, tree/log size, growth rate, stem straightness and stem taper. The second section reviews the link between silviculture, site and genetics on these controlling factors and the consequences for wood quality for different end-uses. The silvicultural factors reviewed are rotation length, initial spacing, respacing before canopy closure, thinning after canopy closure, nursing mixtures, pruning, cultivation, weed suppression and fertilizer use. Site factors include site quality, wind, slope, and snow and ice. There is a brief section on the role of genetic improvement on timber quality. Finally, the review provides conclusions and recommends that stands should be identified as being suitable for sawlogs or fibre products and then managed consistently throughout the rotation with a strong focus on the final wood product. For Sitka spruce, the objective of maximizing volume yield appears to be compromising batten performance and buyers should consider premiums for stands where quality has been provided rather than quantity. Long-term forest plans and certification could play an increasing role in providing the assurance that good consistent silvicultural practice had been undertaken throughout the rotation, hence creating the possibility of offering clear premiums for high grade timber.

Introduction

This paper reviews the effects of silviculture on timber quality of Sitka spruce (*Picea sitchensis* (Bong.) Carr.), with emphasis on even-aged plantations in the United Kingdom. The term silviculture is used here in its broadest sense, including any forest management practice which can alter the genetic quality of planting stock, the environmental factors inherent to a site, forest establishment, composition and growth.

The review is divided into three broad areas. The first is a review of wood properties and tree growth characteristics with a summary of the way in which they affect quality for different end-uses. Secondly, consideration is given to the silvicultural, site and genetic factors that affect these wood properties and characteristics. Finally, recommendations are considered concerning the management of the standing crop to best meet the different requirements of 'timber quality' for different end-uses. Throughout this review, particular attention is paid to the timber quality of sawlogs since this will be the critical market sector for UK conifer production over the next 20 years (Forestry Commission, 1996).

Definitions of timber quality

Although widely used, the term 'timber quality' (or 'wood quality') is not easily defined, and perceptions of what constitutes quality can vary between different sectors of the forestry and wood-using industries (Kliger *et al.*, 1994). Mitchell (1961) states that 'Quality is the resultant of physical and chemical characteristics possessed by a tree or a part of a tree that enable it to meet the property requirements for different end products'. This definition is echoed by Briggs and Smith (1986), who describe wood quality as '. . . the appropriateness of the wood for a particular end use'.

A much broader definition is proposed by Zhang (1997) who defines wood quality as 'all the wood characteristics and properties that affect the value recovery chain and the serviceability of end products'. This last definition takes account of attributes which do not necessarily influence the performance of the end-product but which do affect the cost of other operations throughout the wood chain. For example, the diameter of log from which a batten is cut will not *necessarily* affect the batten's serviceability, but it will have an impact on the cost of harvesting, transporting and processing. All these definitions emphasize that quality is a subjective term that depends ultimately on the end-product that the log is converted to.

Within the sawn timber category, the three main uses for British-grown Sitka spruce are construction, pallets/packaging and fencing (McIntosh, 1997).

For construction purposes the principal quality criteria applied by the building industry are:

1 *Dimensions*. The dimensions are crucial to its suitability for use in a specific situation, this has importance that has long been recognized. Construction requires long lengths of timber of known properties. However, with the advent of finger jointing and glulam technology, shorter lengths of timber can now be used and this may become more common in the future.
2 *Stiffness and strength*. Bending stiffness (Modulus of Elasticity, MOE or Young's Modulus) and bending strength (Modulus of Rupture, MOR) are determined by mechanical stress grading.

   Pre-1995, nine strength classes covered all grades and most species from the lowest grade of softwood (SC1) to the highest grade of hardwood (SC9). The most widely used structural grades of softwood were SC3, SC4 and SC5 (British Standard 5268, Part 2, 1991). British-grown Sitka spruce is commonly graded at SC3 and, currently, rarely reaches SC4 (Harding, 1988).

   Post-1995, the SC system was replaced by a new European Standard EN388: 'Structural Timber – Strength Classes' (CEN, 1995). Nine strength classes are used for conifers and poplars, C14 to C40. The new classes, C16, C24 and C27, are approximately equivalent to SC3, SC4 and SC5, respectively.
3 *Dimensional stability*. The changes in dimensions that occur as moisture content varies can result in severe distortion of sawn timber. This can occur when timber is dried to a moisture content appropriate to the end-use environment *or* the 'movement' of timber due to fluctuating moisture content once in service. Differential shrinkage of sawn battens during kiln drying can result in distortions such as twist, bow, spring and cup. In severe cases the battens are classed as reject material under grading regulations. The importance of the straightness of sawn battens after drying is being increasingly recognized and is now considered by some to be of equal importance to mechanical properties (e.g. Walker, 1993; Kliger *et al.*, 1994). The presence of spiral grain, high microfibril angle, compression wood and the transition between juvenile and mature wood will all increase distortions.

Timber for pallets and crates does not generally require the same level of mechanical performance as that used in construction. However, it must be capable of withstanding rough handling, heavy loads and must have an acceptable level of wood density to ensure adequate nail holding. Dimensional stability is of also of some importance, as changes in timber dimensions due to fluctuating moisture content can lead to nail popping and loosening of joints (Harding, 1988).

The most important property for timber in fencing is durability. Sitka spruce has little natural resistance to decay and is classed as non-durable (Harding, 1988), hence treatment with a preservative is required for outside use. Amenability to preservative treatment is therefore an important consideration: Sitka spruce is classed as resistant to treatment, owing to its poor permeability.

Wood properties and tree growth characteristics affecting timber quality

Wood properties

Knots Knot size and frequency affect the quality and value of Sitka spruce timber irrespective of the end-use. Both add to the cost of harvesting, due to the additional time required for snedding an increased number of branches, and processing as well as influencing the solid wood properties.

Knot size and frequency are characteristics used in the visual classification of softwood sawlogs in Britain. Two main grades of sawlog are recognized, 'green sawlogs' and 'red sawlogs'. In order to be graded into the higher value green category, 80 per cent of knots on any individual log must not exceed 5 cm in diameter (Forestry Commission, 1993). In addition to altering quality grading, localized grain deviation around knots in sawn timber results in reduced stiffness and strength (Joxsa and Middleton, 1994; Zhang, 1997). For Norway spruce (*Picea abies* (L.) Karst.), knot area had a greater influence on batten bending strength than on stiffness (Kliger *et al.*, 1995). Brazier (1986) examined the effect of the mean diameter of the two largest knots in each whorl on the stiffness of battens sawn from unthinned Sitka spruce planted in 1935. Mechanical stress grading showed that, as average knot size increased, the average minimum reaction force, i.e. the stiffness, decreased.

Maun (1992) examined the relative effects of different growth characteristics on Sitka spruce batten stiffness. Knot area on the four faces of battens tested showed a strong negative correlation with batten stiffness. Sensitivity analyses enabled the effect of changes in knot area and spacing on the percentage of battens passing SC4 grade to be predicted (Table 1). Thus, a 10 per cent increase in knot surface area would result in a 3 per cent reduction in the out-turn of SC4 (~C24) grade timber, whereas a 10 per cent increase in knot spacing would be expected to result in 4 per cent more SC4 grade timber. Further analysis showed that the combined effect of a 10 per cent reduction in knot surface area and a 10 per cent increase in knot spacing would be expected to result in an 8 per cent increase in the number of battens qualifying for SC4. There appear to be no reports on the relationship between dimensional stability of sawn timber and knots in Sitka spruce, but Cown *et al.* (1996) found that branch (and hence knot) size had a minimal effect on drying distortion in radiata pine (*Pinus radiata* D. Don.).

Large, frequent knots are also undesirable in pulping. Knot wood is significantly denser than stem wood with the result that in chemical processes it is often 'undercooked', whilst in mechanical pulping the knots are resistant to defibration (Walker, 1993).

Grain angle Grain angle is measured relative to the longitudinal axis of the stem of the tree. Although patterns of variation in grain angle within and between trees are highly complex and variable (Danborg, 1994a; Tian *et al.*, 1995), a generalized pattern for conifers in the northern hemisphere is agreed on by several authors (Brazier, 1965; Harris, 1989; Walker, 1993; Zobel and Jett, 1995). The typical pattern is a left-handed angle (or S-spiral) in the rings near the pith; gradually decreasing to straight grained

Table 1: Percentage increase (+) or decrease (–) in the number of battens qualifying for SC4 (C24) structural grade (after Maun, 1992)

	Percentage modifications in growth characteristics			
Growth characteristic	–20%	–10%	+10%	+20%
Knot surface area	+8%	+2%	–3%	–8%
Knot spacing	–7%	–7%	+4%	+7%

and sometimes changing to a right-handed angle (or Z-spiral) towards the bark. The magnitude of the angle is usually greatest in the rings nearest the pith. For Sitka spruce, spiral grain was reported as left-handed near the pith, increasing in magnitude outwards to a peak of ~4° at approximately 5–10 rings, with a gradual decline towards straighter grain as the tree matures (Brazier, 1967).

For sawn timber, the grain angle relative to the longitudinal axis of a sawn batten is determined not only by the inherent grain angle of the tree but also by the taper and straightness of the stem and the sawing pattern used in the sawmill. The interaction between grain angle and out-turn is therefore complex. Brazier (1986), Zobel and Jett (1995) and Desch and Dinwoodie (1996) agreed that as grain angle increased there was a significant reduction in the strength and stiffness of timber. Harris (1989) quoted Kollmann and Côté (1968) who stated that strength in compression, tension and bending all decreased with increasing grain angle, as shown in Figure 1. However, Kliger *et al.* (1995) reported that the magnitude of grain angle had only a minor effect on the bending strength and stiffness of Norway spruce timber from fast-grown plantations. Similarly, Maun (1992) found grain angle to have a low influence on the stiffness of Sitka spruce battens, but suggested that this may be due to the low variation in grain angle in the sample of battens tested. In contrast, a more extensive study by Maun (1998) has shown that grain angle had a highly significant effect on machine grade stiffness. From this it appears that increasing grain angle is likely to have a significant effect on the bending strength and stiffness of Sitka spruce timber and therefore on its suitability for use in construction.

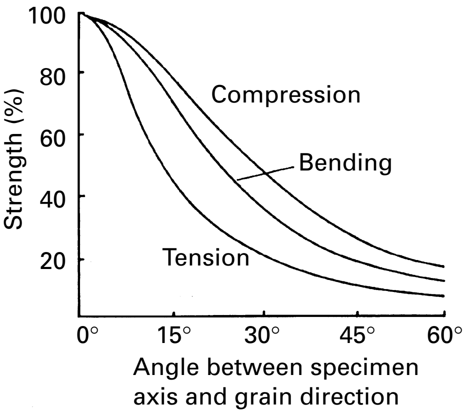

Figure 1. Dependence of strength properties on the angle between grain direction and the specimen axis (after Kollmann and Côté, 1968).

There is general agreement that increased grain angle results in greater drying distortion. (Harris, 1989; Maun, 1992; Walker, 1993; Danborg, 1994b; Cown *et al.*, 1995; Zobel and Jett, 1995). Brazier (1965) developed a Spiral Grain Index, an expression of the average grain inclination at a particular level in a stem. Flat-sawn and quarter-sawn boards cut from European and Japanese larch (*Larix decidua* Mill. and *L. leptolepis* Gord.), which were kiln-dried unrestrained showed a highly significant correlation between twist and the Spiral Grain Index. Cown *et al.* (1996) found that increased spiral grain in radiata pine significantly increased twisting during drying. Similarly, Danborg (1994b) reported that, for Norway and Sitka spruce, the influence of spiral grain on twist was most pronounced in small boards sawn near the pith.

In contrast to sawn timber, high grain angles do not appear to have a significant effect on the suitability of wood for panel board production or pulping.

Density Wood density (or specific gravity) is probably the most extensively studied and widely used indicator of timber quality (Dickson and Walker, 1997; Zhang, 1997). As Walker (1993) stated, 'basic density provides an index of wood quality to which all end-users can relate'. It affects the performance of sawn timber, influences the suitability of wood for conversion to panel products and determines not only the yield of pulp that can be obtained from a given volume of wood but also some of the characteristics of the pulp.

Density has been shown to be positively correlated with the strength and stiffness of small clear samples of wood (e.g. Panshin *et al.*, 1964; Desch and Dinwoodie, 1996), and consequently high-density timber is generally associated with superior mechanical performance. In structural size samples, however, the presence of other strength reducing factors mean that density alone is not always a good predictor of mechanical properties. Wood density is a measure of the amount of cell wall material present but gives no indication of the anatomy of the cell wall nor of its properties. For example, compression wood is denser than normal wood but is weaker.

Brazier (1986) concluded that while density was of significance in affecting wood strength in Sitka spruce, it was not as important as other factors, such as grain angle and the presence of juvenile wood, which lower performance. This has been supported by Zhang (1995), who found that variations in wood density only explained part of the variations in mechanical properties observed in trees of differing growth rates, and that this was particularly evident for *Abies* and *Picea* species. A relatively small change in wood density can be accompanied by a considerably larger change in mechanical properties, with the result that estimates of structural performance based solely on evaluation of wood density may not be reliable (Zhang, 1997). Maun (1992) reported that density was a highly significant, although not the most important, influence on Sitka spruce batten stiffness. Hence, density clearly has an important influence on timber strength and stiffness, but the impact on utilization depends on the integration of other factors such as knots, grain angle and juvenile wood.

Wood density also affects the dimensional changes that occur with changes in moisture content (Walker, 1993). Thicker cell walls associated with higher density wood absorb more water, resulting in greater shrinkage and swelling and therefore greater movement of the timber when in service. In addition, denser wood holds more water in the cell walls, drying takes longer, and thus the cost of the drying operation increases. The practical implications of these effects with sawn Sitka spruce are that variations in wood density across a batten cause differential shrinkage, and therefore distortion, following kiln drying or in service.

For wood-based panels, density is an important quality consideration. The strength of panel products is largely determined by the strength of the glue bond rather than by the strength of the wood (Walker, 1993). Good glue bonds are achieved by maximizing particle-to-particle contact, as measured by the compactness ratio of the board, i.e. the ratio of board density to wood density. To achieve a given compactness ratio, higher wood density will result in higher board density. The production of a high-density board increases the costs of pressing, cutting and transport; light board products are therefore preferred. For a given board density, low density wood therefore produces panels with superior mechanical properties and lower variability than higher density wood (Hsu, 1997).

In pulping, the density of the wood used affects both fibre yield and the strength properties of the paper produced. Higher density wood gives an increased yield of fibre for a given volume (Walker, 1993). In terms of pulp quality, higher wood density results in paper with reduced breaking length and burst strength but increased resistance to tearing (Zobel and Jett, 1995). The thinner cell walls in lower density wood collapse more easily, giving better fibre-to-fibre bonding and producing a higher sheet density. One of the advantages of Sitka spruce for pulp is its low density (390 kg m^{-3} at 12 per cent moisture content) compared with other conifers grown commercially in Great Britain, e.g. European larch 540 kg m^{-3}, Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) 530 kg m^{-3}, Scots pine (*Pinus sylvestris* L.) 510 kg m^{-3} (Harding, 1988).

Tracheid length A characteristic pattern of increasing tracheid length outward from the pith at any one level is generally recognized (Dinwoodie, 1961). In Sitka spruce, average tracheid length is reported to range from 1.3 mm in the first ring from the pith to ~3 mm at ring 36 from the pith (Brazier, 1967). Although for sawn timber, variations in tracheid length *per se* are not generally considered to have a significant impact, short tracheids are associated with high microfibril angles which do reduce timber strength, stiffness and dimensional stability.

Tracheid length is generally acknowledged to affect pulp and paper quality. Walker (1993) stated that a minimum tracheid length of 2 mm is required to produce acceptable Kraft pulp, and that increases in tracheid length up to 3 mm will result in increased paper tear strength. Similarly, Zobel and Jett (1995) reported that increased tracheid length was generally favourable for pulping, resulting in improved burst, tearing and tensile strength of paper.

Microfibril angle Microfibril angle is the winding angle of the cellulose microfibrils in the dominating S_2 layer of the secondary wall of softwood tracheids as shown in Figure 2. The accepted pattern of radial variation in microfibril angle in conifers is from a high value in the rings near the pith, declining gradually towards the cambium. Phillips (1941) reported that microfibril angle in Sitka spruce declined very rapidly from a high value at the pith and reached a more stable 'adult' value at six to nine rings from the pith. Hence, microfibril angle stabilized at an earlier age than that generally associated with the end of the juvenile wood period in Sitka spruce.

Microfibril angle has a significant effect on both mechanical behaviour and dimensional stability of wood, and as such is an important quality characteristic for sawn timber. The stiffness of the cell wall is known to increase enormously from pith to bark as microfibril angle decreases (Walker and Butterfield, 1995). Similarly, Cowdrey and Preston (1966) observed a sixfold increase in earlywood stiffness in one Sitka spruce tree as microfibril angle decreased from 50° to 10° outward from the pith. Cave (1968) also reported a fivefold increase in stiffness in the earlywood of radiata pine over a 40° to 10° range of microfibril angle. Brazier (1986) examined the relationship between microfibril angle and modulus of elasticity (stiffness) of structural-size pieces of clearwood Sitka spruce timber (4000 mm × 100 mm × 50 mm), and found that stiffness increased 2.5 times as microfibril angle declined from 40° to 15° . Maun (1992) also found that microfibril angle had a strong influence on the stiffness of structural size battens.

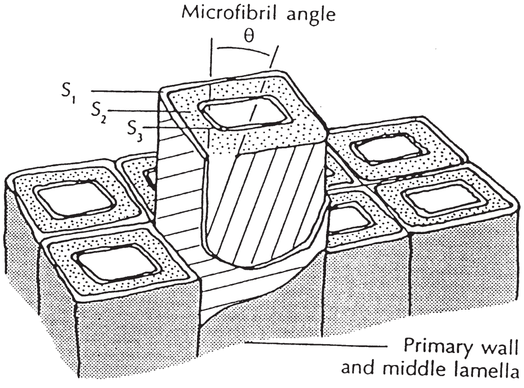

Figure 2. Orientation of the microfibrils in the S2 layer of the cell wall (after Dickson and Walker, 1997).

High microfibril angles also result in increased drying distortion in sawn timber (Briggs and Smith, 1986; Zhang, 1997). This distortion is due to the abnormally high longitudinal shrinkage that results from high microfibril angles, which can be as much as nine times that of wood with low microfibril angles (Zobel and Jett, 1995). When battens contain wood with differing microfibril angles, differential shrinkage occurs, resulting in warp, check, split and twist.

Juvenile wood The term 'juvenile wood' (or 'core wood') is used to describe the wood laid down within the live crown, therefore formed near the tree centre, which differs markedly from the 'mature wood' formed further away from the pith. The term 'juvenile wood' can be confusing (Zobel and Sprague, 1998). It is the age of the *cambium* which determines the type of wood that is formed, with juvenile wood being produced by cambium that is in the juvenile stage (Kucera, 1994). In an old tree, in any given year, mature wood is produced near the base of the stem and juvenile wood formed near the top (Zobel and Jett, 1995) as shown in Figure 3.

Many definitions for juvenile wood have been put forward. Zobel and Sprague (1998) cite Rendle's definition (1959): '. . . the secondary xylem produced during the early life of the part of the tree under consideration and characterised anatomically by a progressive change in the dimensions and corresponding changes in the form, structure and disposition of the cells in successive growth layers. The juvenile period varies according to the species and may be affected by environmental conditions.'

Juvenile wood is generally characterized by low density, thin cell walls, short tracheids with large lumens, high grain angle and high microfibril angle, with the result that it has low strength and stiffness and poor dimensional stability compared with mature wood. As there is no clear separation in the tree stem between juvenile and mature wood, many authors refer to an area of 'transition wood' where the rate of changes in

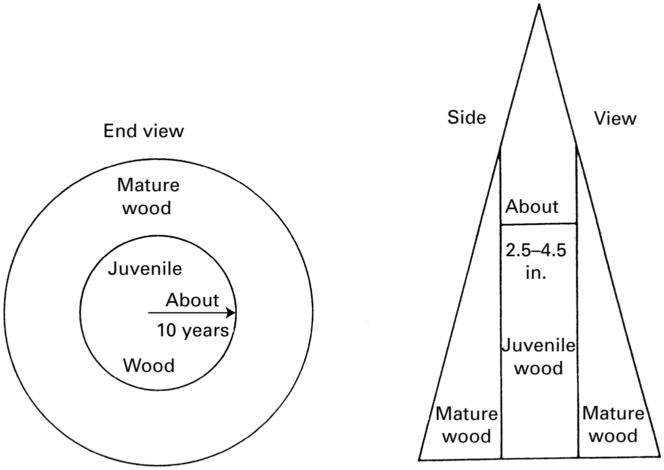

Figure 3. The concept of juvenile wood shown schematically for loblolly pine (*Pinus taeda)* for a cross section and vertical distribution within the tree (after Zobel and Sprague, 1998).

wood properties is less than in juvenile wood, but the more stable properties of adult wood have not yet been attained. In general, juvenile wood is of poorer quality than mature wood for all end-uses.

Although it is not easy to define the boundary between juvenile wood and mature wood, an arbitrary definition of 12 rings from the pith has been used for Sitka spruce (Brazier and Mobbs, 1993). Kucera (1994) suggested that the end of the period of juvenile wood formation at stump height (root-neck) in Norway spruce coincided with the culmination of the period of maximum annual height growth, and supported this theory with data from two experiments. He concluded that the two effects were synchronous growth processes and fundamentally linked by the physiology of the tree. He went on to suggest that in light-demanding species, such as pines, the juvenile/mature wood boundary at stump height will be closer to the pith due to earlier culmination of maximum annual height growth compared with shade-tolerant or shade-demanding species such as spruces or firs. It would be difficult, however, to predict at what period juvenile wood formation terminated further up the stem since this would presumably be linked to the live crown and hence be subject to environmental factors.

Compression wood Compression wood forms in conifers on the underside of leaning stems, on the leeward side of trees exposed to strong winds, in crooked stems, in the lower part of trees growing on a slope and under branches (Nicholls, 1982; Walker, 1993; Desch and Dinwoodie, 1996). Vigorous growth in conifers has also been observed to result in the formation of mild compression wood all round the stem (Walker, 1993). Although the exact mechanism for compression wood formation is not fully understood, its function can be described as to 'act to correct the lean of the stem' (Walker, 1993) or to 'oppose forces deforming the tree and to restore or maintain a specific pattern among tree parts' (Low, 1964). Compression wood is induced where there is an uneven distribution of auxin around the circumference of the stem. In leaning stems there is an auxin gradient around the stem and compression wood forms on the underside where concentrations of auxin are high. Although gravity is thought to play a role in the formation of compression wood, it has been observed to form on the upper side of branches bent upwards artificially, i.e. where it would act to push the branch back down to its original position (Sinnott, 1952).

The structure and chemical composition of compression wood differs from that of normal wood. The tracheids are shorter with thicker cell walls and are more rounded in cross-section, resulting in the formation of intercellular spaces. The S_3 layer is often absent and the S_2 layer is highly lignified with internal helical checks corresponding to the microfibril angle, which is between 30° and 50° (Walker, 1993). As a consequence of its high microfibril angle, compression wood exhibits abnormally high longitudinal shrinkage. Mild or moderate compression wood only occurs in the latewood of annual rings, but in its most severe form it is present across the whole growth ring. In most species it can be recognized by its dark red-brown colour, which reflects the thick-walled tissue present.

The presence of compression wood can have a significant effect on timber utilization. Ni Dhubhain *et al.* (1988) examined the effects of different levels of compression wood development on the mechanical properties of structural-size Sitka spruce battens. They found that while the modulus of elasticity (MOE, i.e. stiffness) decreased with increasing compression wood content, the ultimate bending strength (modulus of rupture, MOR) was not affected. They noted, however, that 70 per cent of the battens that had >10 per cent compression wood ruptured in a brash manner during MOR testing, which indicated that such timber might fail under impact without warning. These findings are in agreement with those reported for other softwood species (Timell, 1986; Walker, 1993; Desch and Dinwoodie, 1996). The excessive longitudinal shrinkage which occurs in compression wood results in increased incidence of drying distortion in sawn timber.

Compression wood can also cause problems in timber destined for pulping. The high lignin and low cellulose content reduces the yield in chemical pulping and the shorter tracheids result in reduced tear strength in mechanical pulps (Walker, 1993).

See Table 2 for a summary of wood properties affecting timber quality.

Tree growth characteristics

All the properties discussed in the previous section are fundamental to the performance of a piece of wood and are determined, in the main, by alterations at the cellular level. In general, silvicultural interventions that can alter one or more of these cellular properties will alter the structural characteristics of the resultant timber. However, there are also timber properties best considered at the whole-tree level that are influenced by the growth and size of the tree. These are summarized in Table 3. Even these large-scale features, with the possible exceptions of tree size and stem straightness, involve alterations at the cellular level.

The effects of silviculture, site factors and genotype on timber quality

Any factor that changes the growth pattern or form of a tree may result in a change in wood quality and properties (Brazier, 1977; Zobel and Jett, 1995). Silvicultural practice, site factors and the genetic quality of planting stock can all affect tree growth patterns, and thus influence timber quality.

Silviculture

Silvicultural practices tend to act indirectly on wood quality through their effect on the growing environment of the tree's crown and roots (Briggs and Smith, 1986; Zobel and van Buijtenen, 1989). Brazier (1977) divided silvicultural operations into two broad types that are used here as a framework for this review:

1. Those which act directly on individual trees, or on groups of trees, such as initial spacing, thinning and pruning.
2. Those which modify the site, and thus act on the crop as a whole, such as cultivation, weed suppression and fertilizer application.

Practices acting on individual trees or groups of trees

Rotation length It has been suggested that 'the most significant feature of softwood plantation silviculture is the effect on wood properties of the reduction in the age at which trees are clearfelled' (Walker, 1993). Increased growth rates brought about by tree breeding and advances in silviculture mean that plantation-grown conifers are reaching a merchantable size at younger ages. In Britain, the move towards shorter rotations is

Table 2: Summary of wood properties affecting timber quality

Wood property and description
Knots
Increasing knot size and frequency increase harvesting and processing costs irrespective of the end-use
Knottiness is used in the visual grading of sawlogs, although the size of the knots in Sitka spruce is not usually sufficient to result in a lower grade
Grain deviations around knots leads to a reduced stiffness and strength. As knot size and number increases the stiffness of a batten cut from such timber drops
Knot wood is denser than stem wood and coloured, this results in increased costs for pulp processing
Grain angle
Patterns of variation of grain angle can be complex but generally decrease from the pith to the bark. For Sitka spruce, the angle is left-handed near the pith, increasing to 4° at 5–10 rings before declining to nearer vertical
Increased grain angle leads to significant reductions in the strength of sawn timber. In addition, grain angle is highly correlated with drying distortions in cut timber
Grain angle does not appear to have an effect on the suitability of wood for panel board or pulp production
Density
Density is the most widely studied general indicator of timber quality and is positively correlated with strength and stiffness of small samples of wood. For larger samples, knots, grain angle and juvenile wood are often more important criteria
For Sitka spruce, density is a highly significant predictor of batten stiffness; the higher the density the stiffer the batten
Higher density wood can absorb more water; hence dimensional stability is poorer for higher density wood due to increased shrinkage or swelling
Lower density wood is preferred for panel-board production since it produces a lower density panel that is easier to process and transport
In pulping, higher density wood results in paper with reduced breaking length and burst strength but increased tear resistance. Lower density wood produces higher sheet density since the cell walls collapse more easily in low-density wood giving better fibre-to-fibre bonding
Tracheid length
In Sitka spruce, average tracheid length doubles from the pith (1.3 mm) to ring 36 (3 mm)
Variations in tracheid length are not thought to have any impact on sawn timber although shorter tracheids are associated with high microfibril angles, which reduce timber strength, stiffness and dimensional stability
Tracheid length is important for pulp and paper quality. Increased length is linked to better burst, tearing and tensile strength in paper
Microfibril angle
Microfibril angle is the winding angle of cellulose molecules in the dominating S2 layer of the cell wall. In Sitka spruce the angle rapidly declines from an initially high value at the pith to a stable mature value at rings 6–9
As microfibril angle drops the cell wall becomes stiffer. This is also reflected in the stiffness of structural battens. In addition, lower microfibril angles give rise to better dimensional stability when timber is dried. Wood with differing microfibril angles is prone to warp, check, split and twist
Juvenile wood
Juvenile wood is associated with the live crown. As branches die there is a transition from juvenile to mature wood
In Sitka spruce, juvenile wood is found in the region surrounding the pith and up to rings 15–20. It is characterized by low density, thin cell walls, short tracheids, high grain angle and high microfibril angle. These give rise to wood of low strength, stiffness and poor dimensional stability. In addition, the short tracheid lengths make it less suitable for pulp
Compression wood
Compression wood differs in structure and chemical composition from normal wood. Tracheid length is shorter and microfibril angle higher with an increased lignin content
The presence of compression wood in sawn timber can lead to sudden failure under bending and the longitudinal shrinkage due to high microfibril angle results in poor dimensional stability when drying
For pulp use, the high lignin content results in reduced yield in chemical pulping and the shorter tracheid lengths to reduced tear strength

Table 3: A summary of the relationships between tree growth characteristics, wood properties and timber quality

Tree character	Effect on wood properties	Effect on timber quality
Tree/log diameter	None	Primarily an economic effect since it determines size of sawn timber that can be cut Has a significant effect on value recovery throughout the wood production chain since unit costs of harvesting transporting and converting large logs are lower
Growth rate (ring width)	Fast growth during juvenile wood formation produces a large juvenile core, therefore a higher proportion of undesirable uvenile wood for a given log diameter In spruces, increased growth rate at any age is associated with lower density wood, due to increased earlywood width without a corresponding increase in latewood (Brazier, 1970a; Zhang, 1995)	Increased proportion of juvenile wood and reduced average density will result in weaker sawn timber with an increased likelihood of distortion when dried For pulp and panel board production, the lower density mature wood is an advantage but the shorter tracheid length of the juvenile core will lead to reduced paper strength
Stem straightness	As stems become less straight there is: increased deviations in grain angle; increased compression wood formation (Sinnott 1952; Harris, 1989; Nicholls, 1982)	Bent stems have a negative impact on value recovery at all stages. The cost of extraction and transport may be increased due to the greater space occupied by bent logs. Debarking can be difficult and may increase costs, depending on the method used For sawlogs – fewer can be cut and their length is reduced. Bent stems result in poorer mechanical performance and increased drying distortion For pulp – increased compression wood leads to reduced pulp yield and quality
Stem taper	Associated with higher grain angles and thus reduced strength, stiffness and dimensional stability (Zhang, 1997)	Increased taper results in reduced recovery of sawn timber
Branching pattern	Increased branching leads to increased knottiness	Angle of insertion affects the area of knot that is present on the face of a batten and the volume of timber affected by the knot Branch size and number also affect value recovery at the harvesting stage as more and bigger branches cost more to remove

also a consequence of the poor stability of stands on exposed sites. Trees felled at a younger age will have a greater proportion of juvenile wood, resulting in inferior mechanical performance and poor dimensional stability, i.e. lower quality in terms of sawn timber markets. The relationship between age and the proportion of juvenile wood is shown in Figure 4; calculated assuming that juvenile wood formation ceases at the age of canopy closure (in this case as top height reaches 7–8 m). Rotation length does not have such a negative effect on suitability for panel or pulp products.

The rise in interest in continuous cover forestry (CCF) (for example, priority point PCE5, Scottish Executive, 2000), with a reduced emphasis on rotation length and felling determined by target diameters or following regeneration events, could be expected to produce larger trees of greater value per unit volume and a reduced proportion of juvenile wood. However, one problem associated with potential delays in regeneration is that, over the period of the delay, the mature trees can become too large for easy handling and milling with current set-ups.

Initial spacing Initial spacing in plantations affects the competition between trees for sunlight, moisture and nutrients and therefore influences tree growth patterns and wood formation (Table 4). Differences in stand density can also affect other aspects of the trees' physical environment such as soil temperature (Zobel and van Buijtenen, 1989) and wind flow (Green *et al.*, 1995; Gardiner *et al.*, 1997). The major effects of wider spacing, which have long been recognized, are increased rates of early diameter growth (due to reduced competition for resources) and longer retention of a deep living crown as suppression of branches is delayed.

Michie (1926) advocated a maximum plantation spacing of 7 ft (~2.1 m), which he considered adequately close to prevent the formation of 'very large knots'. Extensive research has been undertaken concerning the effects of spacing on timber quality of Sitka spruce grown in the British Isles, looking both at wood properties and at technological performance. There is general agreement that trees planted at wider initial spacing tend to have bigger knots, increased ring widths during the period of juvenile wood formation resulting in a larger juvenile core, and reduced average wood density (Brazier, 1970b, 1977; Ward and Gardiner, 1976; Gardiner and O'Sullivan, 1978; Humphreys, 1991; Brazier and Mobbs, 1993). Recent work has shown that there is a strong correlation between wider spacing and larger grain angle for Sitka spruce ($P < 0.05$), with implications for strength and stability of sawn timber (J. Forbes, personal communication, Manchester University). In addition, some authors have suggested that poor stem straightness is also

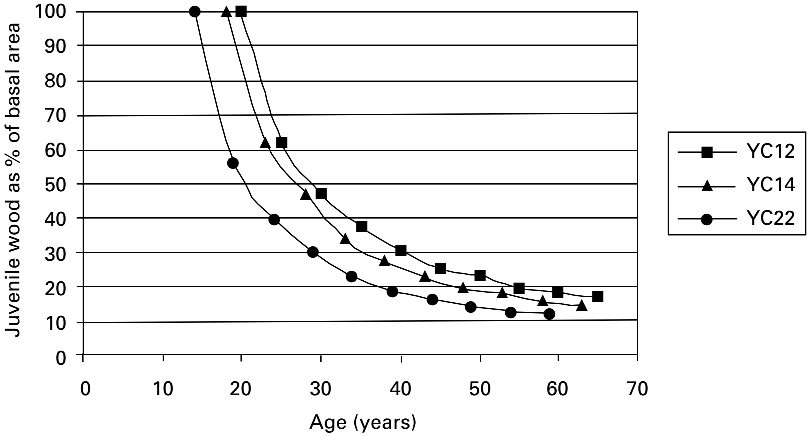

Figure 4. The proportion of juvenile wood at different ages expressed as a percentage of basal area for no-thin Sitka spruce at 2 m spacing (Edwards and Christie, 1981).

Table 4: Studies on the effect of initial spacing on the wood properties of Sitka spruce

Range of spacing/m (stocking/stems ha^{-1})	Age (years)	Effect on wood properties
Pollack *et al.*, 1990 1.83–4.57 (2990–478)	27	Wider spacing gave rise to larger crown diameters, crown area and % of live crown, larger branch diameter at breast height and lower % canopy closure
Brazier, 1970a, b 0.9–1.4–1.8–2.4 (12 300–5000–3025–1720)	35	Density decreased as spacing increased. At wider spacings the largest trees produced the highest proportion of the lowest density wood. Linked to previous work showing that increased vigour resulted in reduced mean density
Humphreys, 1991 1.5–2.7 (4400–1370)	33–46	Wider spacing associated with lower out-turn of SC4 (C24) grade timber, increased juvenile ring width, increased branch size and reduced density. In unthinned stands initial spacing was found to be the single most important factor determining timber strength
Brazier and Mobbs, 1993 0.9–3.9 (12 300–650)	28–57	Wider spacing was linked to: a significant drop in out-turn of higher quality grade logs, principally due to a reduction in stem straightness; an increase in the number of knots exceeding a threshold diameter of 25mm and the size of the largest knots; an increase in the % of juvenile wood due to enhanced growth during juvenile wood formation (radial growth outside the juvenile zone of the butt logs was more or less constant at all spacings); a lower % of structural grade timber (defined as SC3, i.e. C16) Mean batten density was little affected by spacing

associated with wider spacing (Brazier 1986; Brazier and Mobbs, 1993; Walker, 1993), although this is not an area that has been widely researched. However, a recent survey of Sitka spruce stem straightness in southern Scotland found that increased spacing was a significant factor ($P < 0.05$) in the reduction in straightness of the bottom 6 m log (Stirling *et al.*, 2000). Research into the wind loading at different spacing has shown that trees at wider spacing are subject to greater wind loading (Gardiner *et al.*, 1997). The possibility of an interaction between initial spacing and windiness that might affect stem straightness is of particular relevance to upland spruce silviculture and is discussed more fully as a site factor below.

Analysis of Brazier and Mobbs' (1993) results indicated that, to obtain acceptable yields of C16 (SC 3) timber from Sitka spruce, a planting distance of 2 m was the maximum acceptable. This recommendation is the basis of the spacing regime advocated by the Forestry Commission and has been widely practised in the British Isles for the past 15 years.

Interestingly one of the same stands was re-examined by Simpson and Denne (1997) 7 years later. They reported that, in contrast to Brazier and Mobbs' (1993) results, spacing had a relatively minor influence on ring width and specific gravity in juvenile wood. This apparent contradiction was explained as being due to the high levels of self-thinning that had occurred in the 1.4 m and 1.8 m stands compared with the 2.4 m stand over the 7 years. The effect of this self-thinning was assumed to be that fast-growing trees with competitive advantage from an early stage now predominated and hence differences between treatments were reduced. This work emphasized the need for caution when interpreting results and the need to understand the demography of the final standing trees when assessing the effects of silviculture on wood quality.

While there can be no doubt about the general conclusions of Brazier and Mobbs' work (i.e. as spacing increases so the out-turn of structural grade timber falls), so that the recommended 2 m spacing represents the best information currently available, several points should be borne in mind regarding the application of this maxim.

The point was stressed by the authors of the paper that the spacing recommendation was based on timber from unthinned stands. Arguments can be made for either wider or closer spacing in stands that are to be thinned, and these inevitably involve the financial appraisal of different options. The effects of thinning are considered in more detail in the following section. It certainly seems questionable whether a universal initial spacing prescription for thin and no-thin sites is the most appropriate option.

A second point also discussed by Brazier and Mobbs (1993) was that C16 (SC 3) is the minimum grade acceptable for structural purposes. Therefore, if there is a serious intention to produce structural grade sawn timber from British spruce plantations, growers should be aiming for the higher grades of C24 and C27 where possible, in order to compete with imported material. From Brazier and Mobbs' results, this implies an initial spacing of 1 m or less for 95 per cent of the battens to fall within the minimum stress grade for C24 (SC 4) shown in Figure 5.

Finally, certain details of the experimental material should be considered: one site (Brechfa in Wales) is known to have experienced a period of 15–18 years of check (Brazier *et al.*, 1985). This very slow growth during the period of juvenile wood formation will have resulted in a smaller volume of juvenile wood compared with trees grown at similar spacings on other sites. Hence, for logs of comparable dimensions and age, less juvenile wood will be present in trees from Brechfa, with the result that on average battens will have a higher mean minimum reaction force. Since the spacings at Brechfa were 1.4 m and 1.8 m, this may have distorted the reported relationship between spacing and stiffness by making more closely spaced trees appear to be stronger.

The sample stands were representative of a wide range of ages of trees, from 28 to 57 years old. However, there is a general trend of increasing spacing with decreasing age, with four of the seven treatments planted at >2 m spacing being only 28 years old. Given the patterns of variation in Sitka spruce wood properties outward from the pith and the effect of age on the proportion of juvenile wood, it can be expected that had these younger trees been felled and tested at an age closer to the average for the rest of the sites (45 years) then a higher out-turn of Strength

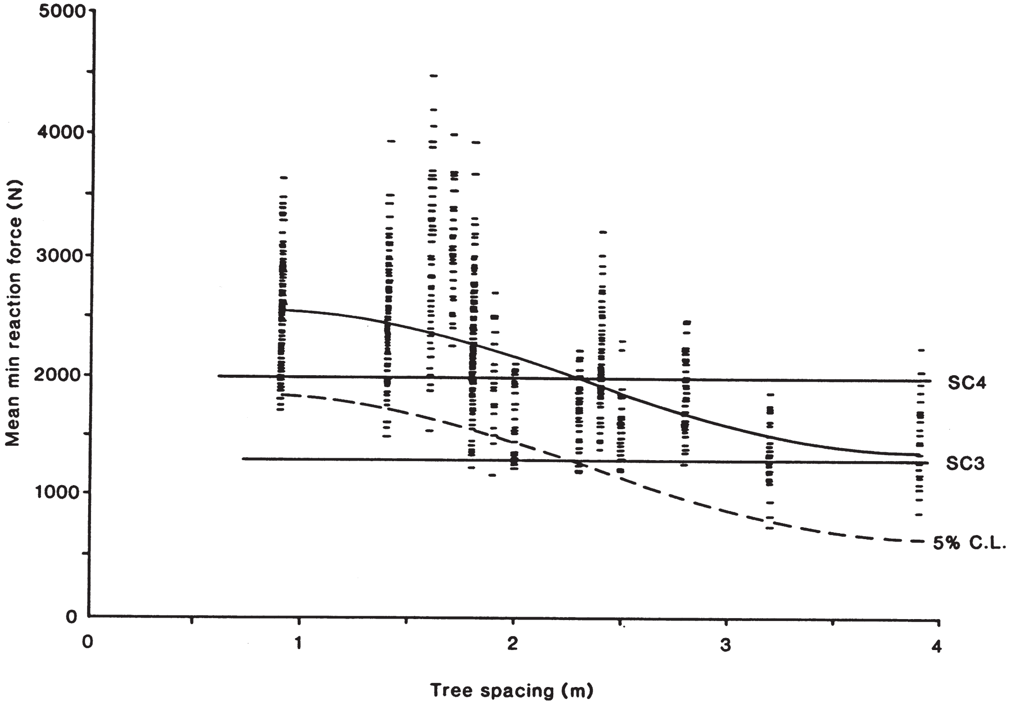

Figure 5. The relationship between initial spacing and mean minimum reaction force. Mean and lower 5% lines are shown and the SC3 and SC4 stiffness levels for machine grading (from Brazier and Mobbs, 1993).

Class 3 battens would have been obtained. It is therefore possible that the relationship between tree spacing and mean minimum reaction force might be distorted in the >2 m spacing range, since the material from these younger plots will inherently have a lower mean minimum reaction force because of their age. The possible effect of age on the performance of timber from trees planted at the same spacing but felled at different ages is hard to ignore. In addition, there has been concern that four of the seven wider spacings were all represented by timber from one site in Northern Ireland, Loughermore, which appeared to have atypical and rather weak timber, thereby unbalancing the results (Schaible, 1994).

One potential advantage of natural regeneration, as opposed to planted material with fixed spacing, is that initial stocking densities are often extremely high (Nixon and Worrell, 1999). Hence competition is intense early in the lifetime of the tree, which reduces the juvenile core and branching to a minimum in the most valuable part of the stem.

Respacing and thinning The modification of the growing space available to trees has a major influence on timber quality. Trees with more growing space will reach a bigger diameter over a given rotation length, thus reducing harvesting and processing costs. Commercial thinning operations aim to improve final crop quality by increasing mean tree size, selecting for better tree form and to provide revenue early in the rotation. Non-commercial respacing or thinning operations are likely to be carried out in two situations. First, where dense natural regeneration must be reduced to the desired number of stems. Secondly, on exposed upland sites where the high risk of inducing windthrow precludes conventional thinning later in the rotation. Such areas represent a significant component of British conifer forests: >50 per cent of Forest Enterprise forests are managed on a no-thin regime (Forest Enterprise, 1996). Recent work has shown that Sitka spruce does not self-thin to the extent predicted in the current standard British yield tables (Matthews *et al*., 1996). Hence not thinning gives rise to a greater number of living trees, at a given age, than previously expected. Therefore, the average diameter at breast height (d.b.h.) of the crop is lower and hence product out-turn is shifted towards smaller diameter timber with negative implications for economic returns.

The timing of thinning influences the effect upon wood quality. When respacing is carried out prior to canopy closure, the trees will retain deep living crowns for longer. Therefore the effects on wood quality are similar to those described for a stand planted at an initially wide spacing, i.e. larger knots, larger juvenile core and greater taper. Respacing carried out after canopy closure means that branch suppression in the lower bole will already have taken place, and hence the branches which take advantage of the additional growing space and increase in diameter will be in the living crown, generally above the valuable lower stem. In addition, juvenile wood formation in the lower bole is likely to have ended, depending on the age of the tree. The increased diameter growth associated with later thinning is therefore less likely to result in an increase in the volume of the juvenile core.

Respacing prior to canopy closure Experiments that examined respacing prior to canopy closure confirmed the assumptions outlined above about its effect on timber quality. A summary of the main findings is given in Table 5.

Deans and Milne (1999) selectively respaced stands of Sitka spruce at 9–11 years old from 2000 stems ha^{-1} to 1500, 1000 and 500 stems ha^{-1} at three elevations in Eskdalemuir, Dumfries and Galloway. In contrast to Rollinson (1988), no significant loss in volume after 15 years was reported for spacings at 1500 and 1000 stems ha^{-1}, except at the highest elevation site. Height growth was unaffected by spacing, although this may have been due to shelter provided by adjacent stands, but taper was significantly greater at lower spacing and there was a strong trend for greater taper at higher altitude. Density measurements of cores taken at breast height showed no significant relationship with spacing, although there was a significant decrease in timber density with increasing stem girth for trees across all sites. An important factor linked to spacing was that branch size and frequency of large branches increased significantly as spacing increased (Deans and Milne, 1999).

An 'oceanic'-type respacing regime (Moore, 1973), designed to be applied to Sitka spruce plantations on upland sites susceptible to windthrow, was also tested at Kershope. It involved respacing final crop trees to 1000 stems ha^{-1} at, or just before, canopy closure by lopping unwanted trees above their lowest live whorl. In theory the remaining live crown of the lopped trees would ultimately be outgrown by the released crown of the final crop trees, but would remain alive for a sufficient time to restrict the lower branches of the final crop. Ford (1980a, b) has presented the arguments for and against this system. Rollinson (1988) reported that, at Kershope, the majority of decapitated trees had produced new leaders from existing side branches and, as a result, many had multiple leaders competing vigorously with the untreated trees. The trees selected to be the final crop had reduced diameter, basal area and volume production compared with the same treatment where whole trees had been removed. However, it should be noted that the treatment was applied when the trees had a mean height of 2.6 m and decapitation was only undertaken at head height. Hence the decapitated trees appear not have been checked back sufficiently for the differences between selected and checked trees to show.

Mitchell and Denne (1995) examined the wood quality of trees from another oceanic forestry trial, where Sitka spruce, planted at 2 m spacing, was selectively respaced after about 11 growing seasons. The stand was on a fertile lowland site, growing at yield class 24, and the remainder of the surrounding crop was thinned selectively according to a conventional regime. Apart from slightly shorter trees in the oceanic treatment there were no significant differences in d.b.h., taper of the lower 8 m of stem, branch size or branch number between the two regimes. Nor were there significant differences in the amount of juvenile wood; ring width and density being similar for the first 20 rings from the pith. These results are somewhat surprising, but the experiment was only on a very small scale, with plots of 0.2 ha, and not replicated. Mitchell and Denne

Table 5: Studies on the effect of respacing on the wood properties of Sitka spruce

Initial stocking/ stems ha^{-1} (spacing, PYear)	Treatments (year respaced)	Expt age (years)	Comments
Kilpatrick *et al.*, 1981 2900 (1.87 m, P1949)	Approx. square spacings/m 1.9, 2.6, 3.7, 4.6, 5.6 (1960)	31	YC 20 Sitka spruce at Baronscourt, N. Ireland Top ht at 31 = 18.5 m Wider spacings were linked to: a large reduction in total volume production for spacings >2.6 m; volume to 20 cm top diameter peaked at 3.7 m spacing linked to an increase in mean tree d.b.h. with spacing; reduced form factors, indicating greater taper; an increase in number and size of branches at >2 m spacing
Savill and Sandels, 1983 As above	As above	32	Based in the same experiment at Baronscourt Wider spacings led to a significant reduction in mean density ($P < 0.01$). The reduction was 9.3% (39 kg m^{-3}) between closest and widest spacing Analysis of variance showed that spacing accounted for 12% of the variation in density, but variation between trees, within spacing was 63% Juvenile core size increased with spacing; estimated as 13 cm at 2900 stems ha^{-1} and 18 cm at 1450 stems ha^{-1}
Rollinson, 1986 3200 (1.8 × 1.7 m, P1967)	Selective and systematic removal of 75% of stems (1975)	17	YC 20 Sitka spruce at Kershope forest, Cumbria. Stocking after respacing = 850–870 stems ha^{-1} Top ht = 9.1–9.4 m The selective treatment showed: gains in volume, basal area production, mean diameter and mean height but these were not statistically significant; fewer forked trees (0.7% compared with 4.8%), smaller diameter branches, but a greater number of branches, reflecting removal of coarse trees with big branches and less vigorous trees with fewer branches

Continued

Table 5: *Continued*

Initial stocking/ stems ha^{-1} (spacing, PYear)	Treatments (year respaced)	Expt age (years)	Comments
Rollinson, 1988 3200 (1.8 × 1.7 m, P1967)	Approx. square spacings/m 1.8, 2.4, 3.4, 4.0, 4.8 (1975)	17	The same experiment as Rollinson, 1986 above Wider spacings were linked to: a loss of total volume production, an increase in mean tree size, mean d.b.h., diameter range, greater stem taper and an increase in the number of branches at a given height and their average diameter (there was little difference in branch size at the wider spacings, perhaps because the branches were all still growing relatively free from competition)

acknowledged these limitations and commented that they partly intended to stimulate further quantitative analyses of the oceanic system. Ideally timber from a respaced crop should be compared with that from an unthinned crop on the same site or with one which is planted at an initially wider spacing. On the exposed upland sites for which the regime was intended, a series of selective thinnings would not be an option.

Respacing before canopy closure therefore generally results in a bigger juvenile core and bigger knot sizes than a no thinning regime at the same spacing under similar site conditions.

Thinning after canopy closure Conventional thinning operations, carried out following canopy closure when the trees being removed are of a merchantable size, also affect wood quality. The remaining trees will increase their growth rate, but as the lower branches have already been suppressed there will be no increase in knot size on the valuable lower stem. The increase in green log volume due to thinning has been demonstrated by a replicated thinning experiment carried out in YC20 Sitka spruce in Ae Forest (Methley, 1995). Details are shown in Table 6.

The drop in green log volume with heavy thinning is primarily due to the fact that the remaining trees are too widely spaced to most efficiently utilize the additional light and nutrients. However, taper is also known to be increased by heavy thinning (Brazier, 1977).

One feature of increasing growing space to trees, independent of the timing of the operation, is that the largest trees tend to have the lowest density and the biggest juvenile core in any one stand. Brazier (1970b) noted this at wide spacings (i.e. 1.8 m and 2.4 m). This was also reported by Savill and Sandels (1983) for each spacing treatment at Baronscourt. From his results, Brazier (1970b) advocated a thinning practice that removed the largest trees to allow the growth stimulus to be concentrated on smaller trees with small, higher density juvenile cores; in essence a target diameter system of thinning control. He observed that there was some evidence that slower grown trees had better stem form and that such a regime would also provide income from the sale of larger dimension thinnings.

A similar effect was found at an experiment located at Bennan Forest, Dumfries and Galloway. A stand of Sitka spruce planted in 1970 on a peaty gley site was thinned in 1986 by either chemical or mechanical methods to provide stocking densities in the range of 2500 to 400 stems ha^{-1}. Assessments were undertaken in 1993 (d.b.h., basal area and volume) and 1995 (density and stem form) (Table 7).

All the parameters in Table 7 show a highly significant effect with spacing ($P < 0.001$). Diameter increased with reduced stocking, whereas basal area, volume and wood density declined with lower stocking. For all parameters there was no significant effect of thinning method but an interaction between stocking and thinning method at $P < 0.05$. Stem form, using a three-point subjective scale, showed no effect of spacing or thinning method.

Once the canopy has closed, the risk of windthrow due to canopy opening increases, and on sites with a high risk of windthrow conventional thinning regimes are precluded. On such sites precommercial thinning or ‘thinning to waste’ may be undertaken. If this is done using mechanical means the felled trees are left on site, but the risk of windthrow is still increased due to opening up of the canopy. This was demonstrated at Bennan where a storm in 1988, soon after respacing was

Table 6: Impact of thinning on cumulative volume production and green sawlog out-turn

Thinning intensity	Cumulative vol. (CV) at 45 years (m^{3}ha^{-1})	Green sawlog vol. at clearfell 45 years (m^{3}ha^{-1})	Green sawlog vol. as % of CV
Unthinned	815	146	18
Light (MT-1/3)*	777	249	32
Management table	717	305	43
Heavy (MT+1/3)	637	253	40

*MT = management table intensity which is 70% of yield class.

Table 7: Summary of the effects of different spacings on diameter, basal area, volume and density for the Bennan Sitka spruce respacing trial (*Forest Research*, unpublished data)

Stocking/ stems ha^{-1}	d.b.h./cm		Basal area/m^2 ha^{-1}		Volume/m^3 ha^{-1}		Pilodyn penetration*/mm	
	Chem†	Mech†	Chem†	Mech†	Chem†	Mech†	Chem†	Mech†
2500	20.2	18.3	67.6	57.5	486	354	17.5	16.4
1800	21.2	21.5	63.4	63.0	462	474	18.5	18.1
1200	21.4	24.5	45.0	58.9	296	429	17.6	19.2
800	26.9	26.5	46.2	39.8	347	279	19.8	20.0
400	28.4	31.0	24.7	16.8	164	111	18.2	21.3
SED‡	1.085		5.46		43.81		0.912	

*Pilodyn penetration is inversely related to wood density. A higher penetration relative to the control plots indicates a reduction in density.

†Thinning method, either chemical (100% glyphosate into cuts on the stem (Ogilvie and Taylor, 1984)) or mechanical (motor-manual).

‡SED's quoted for the interaction between method of spacing and stocking.

undertaken, caused windblow in the mechanically thinned stands but not in the chemically thinned stands. Hence chemical thinning allows the advantages of thinning but reduces the risk of windblow due to avoidance of major disruption of the forest canopy.

Nursing mixtures The use of conifer nurse species, usually pine or larch, to help establish Sitka spruce on nitrogen-deficient sites is common practice on heaths and peatlands (Taylor and Tabbush, 1990). The use of self-thinning mixtures is not necessarily restricted to nitrogen-deficient sites where the nutritional benefits of a nurse species are required. Such mixtures may also be of value on exposed sites where thinning is precluded due to windthrow risk or on sites where it is judged that economic thinning will not be possible due either to market or site constraints, e.g. very steep sites, very soft sites.

With nursing mixtures, it is expected that the nurse species will eventually become suppressed by the Sitka spruce, leaving a final crop of only Sitka spruce. The effect of such mixtures on the wood quality of Sitka spruce in operational plantings was considered by Watson and Cameron (1995). They reported that, after 25–30 years, the incompatible growth rates between the nurse species and Sitka spruce had produced spruce with large, uneven crowns, resulting in greater knot areas and increased compression wood formation. The effect was greater using a Japanese larch than a lodgepole pine (*Pinus contorta* Dougl.) nurse, probably linked to the deciduous nature and lighter shading of the larch compared with the lodgepole pine. The problems reported are similar to those that might be associated with wider and uneven spacing caused by poor establishment success.

Further studies compared the growth rate, stem form, branching habit and wood properties of Sitka spruce planted on a deep peat site either fertilized annually or periodically with nitrogen or in a 1 : 3 mixture, with alternate triplets of spruce and nurse within rows alternating with pure rows of Alaskan lodgepole pine or hybrid larch (*Larix* × *eurolepis* A. Henry) (Cameron and Watson, 1999). The results showed that the greatest growth response was achieved by planting in mixture with hybrid larch, but that this was associated with greater taper, larger knot sizes in the lower stem and greater crown imbalance than the other treatments. By contrast, the use of Alaskan lodgepole pine as a nurse was found to restrict knot size and taper, which would lead to better timber quality.

Pruning Removal of branches from the lower part of the stem by pruning is carried out to limit the extent and size of knots and maximize the amount of clear timber formed. It also has the effect of advancing crown recession, with wood in the pruned section of the stem experiencing a reduced influence of the live crown (Megraw, 1986). It has been suggested that this accelerates the transition from juvenile to mature wood formation (Briggs and Smith, 1986) and thus reduces the volume of juvenile wood produced. There is also some evidence to suggest that pruning reduces the taper of the pruned log for Douglas fir and Corsican pine (*Pinus nigra* var. *maritima* Mel.), although the effect was small, and for Norway spruce virtually non-existent (Henman, 1963). The overall effect of pruning is therefore to improve timber quality in terms of its suitability for structural uses.

However, it seems highly unlikely that the increase in timber quality could offset the cost of pruning operations on Sitka spruce, particularly in the current market situation in Britain where there is no established premium for conifer sawlogs with a high proportion of clearwood. An early study on the economic benefits of pruning (Curry and Endersby, 1965) concluded that ‘in certain circumstances pruning can result in a sufficient improvement in the value of the sawn timber to cover the cost of pruning’. This evaluation was based on visual grading of sawn timber of Douglas fir, Norway spruce and European larch, but there is, as yet, no information about the effects of pruning on the out-turn of mechanically stress graded timber.

Pruning in already established but understocked Sitka spruce plantations, or perhaps in combination with a selective respacing operation, may increase the value of a low quality crop but again this seems unlikely to be an economically viable option. In particular, poor stem straightness is often the greatest defect in such stands and pruning of crooked stems would not be a worthwhile operation.

Practices modifying the site

Cultivation Planting on cultivated ground tends to result in faster initial growth due to improved local drainage, increased soil aeration and weed suppression. Wider growth rings and more vigorous branch growth at the establishment stage will affect wood quality in the juvenile core, but the practical effects of this enhanced early growth on wood utilization will depend largely on spacing, which affects the length of time the tree grows free of competition. More importantly, improved establishment success achieved by cultivation will help ensure that target stocking densities are met.

Indirectly the type of cultivation used can affect wood quality. Spaced furrow ploughing, which was predominant in the 1960s and 1970s, is known to restrict root development in the direction perpendicular to ploughing direction and consequently to reduce tree stability on certain soils (e.g. Savill, 1976). Thinning regimes and rotation lengths on spaced furrow ploughing can therefore be limited by the increased risk of windthrow, with negative effects on timber quality. The move to using scarification and mounding techniques on restocking sites is likely to have a beneficial effect on wood quality, as improved root architecture should increase stability and widen the range of thinning and rotation length options available.

Weed suppression The main effect of weed suppression is likely to be increased early growth and improved establishment success. Dense weed growth leading to patchy establishment, if not beaten up, will result in larger initial spacings in some areas of the compartment with all the concomitant effects on timber quality outlined previously.

Fertilizer application Fertilizer may be applied to relieve nutrient deficiency or increase vigour at different stages of a crop’s growth. The effect of fertilizer application on tree growth characteristics and wood properties depends on the species in question, the type of fertilizer applied, the age of the crop and the conditions in which the crop is growing at the time of application. Elliott (1970) stated that ‘generalisations on the role of a particular nutrient or combination of nutrients are so confounded by site and species effects as to be at best empirical if not dangerous’.

The most obvious effect of fertilizer addition on nutrient-limited sites is an increase in growth rates. This has been demonstrated for different conifer species in different locations (Gentle *et al.*, 1968; Nicholls, 1971; Siddiqui *et al.*, 1972; Erickson and Harrison, 1974; Parker *et al.*, 1976; Smith *et al.*, 1977; Bendtsen, 1978; Hunt *et al.*, 1980; Cown and McConchie, 1981; Shepard, 1982; Ohta *et al.*, 1985) and large improvements in the growth rate and volume increment of Sitka spruce have been shown (e.g. Davies, 1979). Fertilizer applications have shown an average growth response of 5 years (Yang, 1987).

It appears that any addition of fertilizer resulting in increased growth rates of Sitka spruce, in terms of either height or girth increment, reduces the density of the timber. Reductions of 4–17 per cent have been reported for various species in different countries (Klem 1968; Siddiqui *et al.*, 1972; Zobel and van Buijtenen 1989). The effects of fertilizer on Sitka spruce in British conditions were examined by an experiment planted at Wark (Kielder Forest) in 1966. The objective was to identify a successful method of bringing Sitka spruce out of heather check on peat moorland with a range of fertilizer treatments and herbicide applications. Fertilizer and herbicide applications began in 1971, with subsequent fertilizer applications in 1977 and 1985 (Forest Research, unpublished data). An assessment of d.b.h. was undertaken at the end of 1992, when the trees were aged 27 years, and pilodyn measurements of density were obtained in 1994, at age 28 years. The results are summarized in Table 8.

The experiment demonstrated significant effects upon density from both nitrogen (N) ($P < 0.001$) and phosphorus + potassium (PK) ($P < 0.05$). The interaction between N and herbicide was close to significance ($P = 0.053$). Similar effects were shown on d.b.h. with the additional effect of herbicide ($P < 0.001$). The link between faster growth, indicated by a higher yield class and increasing d.b.h., and reduced density is evident. This could be due to either an inherent feature of faster growing trees, i.e. independent of the factor controlling the rate of growth, or that the application of fertilizer has altered the physiology of the tree in some way so as to reduce density. Comparisons between the effects of fertilizers and thinning for spruce and pine show that there are no significant differences in wood structure between treatments given the same resulting growth rates (Klem, 1968). Similarly, a British study looked at nitrogen, phosphorus and potassium applied to Sitka spruce at age 20–25 years found no effect on basic density and tracheid dimensions other than that attributable to increased vigour (Macdonald, 1990). There was, however, some evidence of a greater increase in knot size following application of N than could be explained by the increased growth rate. Therefore it appears that the wood of faster growing trees is less dense than that of slower ones regardless of the factors determining rate of growth. Hence, although the results in Table 8 would suggest that application of N is more strongly linked with a drop in density than PK, this may be due to nitrogen being the limiting factor for growth in this particular set of conditions. Davies (1979) implied that on moderately fertile sites the application of PK alone was needed to produce a rapid increment in growth.

Table 8: Summary of results of various fertilizer and herbicide treatments on heather checked Sitka spruce at Wark Forest (experiment 12/71)

Treatment	d.b.h./cm	GYC*	Pilodyn penetration† /mm
Control	7.4	6	12.88
PK	8.6	8	13.44
Herbicide	10.5	8	14.27
N	10.1	12	14.74
NPK	11.2	12	16.01
SED‡	0.662	–	0.353

*Based on mean heights over all blocks; assessed in 1981 aged 15.

†Pilodyn penetration is inversely related to wood density. A higher penetration relative to the control plots indicates a reduction in density.

‡Standard errors of differences of means for comparison of treatments.

Examination of the intra-ring characteristics of wood formed following fertilizer application has shown that earlywood production tends to increase without a corresponding increase in latewood production, leading to a reduction in wood density (Klem, 1968; Siddiqui *et al.*, 1972; Zobel and van Buijtenen, 1989). Production of latewood cells with thinner cell walls, resulting in greater uniformity within growth rings, has also been reported (Zobel and van Buijtenen, 1989).

Another effect of fertilization on wood quality is the problem encountered with sudden changes in ring widths associated with rapid increases in growth rate. As Klem (1968) noted, this increased heterogeneity in the timber can be of greater importance to end users than the reduction in density or strength. A graphic illustration of this effect can be found in Davies (1979).

A further consequence of the faster growth rates brought about by fertilizer application is a possible increase in the trees' susceptibility to leader breakage, which may contribute to the development of crooked stems. Baldwin (1993) reported that leader breakage affected 74 per cent of 15-year-old Sitka spruce trees fertilized with NPK on a severely exposed site in Galloway compared with only 4 per cent of the trees in the untreated area. He suggested that the longer and probably softer growth of the leading shoots promoted by the fertilizer was more prone to summer wind damage than the shorter less vigorous leaders on the untreated trees. A survey of Sitka spruce stem straightness in southern Scotland found that there had been a decline in average stem straightness in the region since the 1960s (Stirling *et al.*, 2000). This decline is coincident with a large increase in the use of fertilizer as a standard silvicultural treatment in the region (Davies, 1979). It may therefore be possible that the large-scale increase in fertilizer use was a factor in the observed reduction in Sitka spruce stem straightness.

Severe potassium and copper deficiencies are linked to loss of apical control and the lack of fertilizer in these conditions has obvious negative impacts on timber quality for all end uses (Taylor, 1991). Another indirect effect of fertilization could be a reduction in frost hardiness, since Sitka spruce deficient in potassium showed an extended period and greater degree of frost tolerance (Jalkanen *et al.*, 1998). Therefore late frosts could be more likely to cause leader shoot damage in Sitka spruce on nutrient-rich compared with nutrient-poor sites. For a summary of the effects of silviculture on Sitka spruce wood quality, see Table 9.

Site factors

The factors considered here are those environmental influences inherent to the site on which the trees are growing.

Site quality Zobel and van Buijtenen (1989) noted that 'the most difficult environmental characteristic of all to relate to wood qualities is a measure of the overall soil and climate which is often referred to as site index or site quality'. Worrell and Malcolm (1990a, b) showed that the productivity of Sitka spruce, as measured by general yield class (GYC), in upland northern Britain could be predicted on the basis of accumulated temperature and windiness. The variations in growth rate attributable to these climatic variables are likely to result in differences in wood quality, given the known relationship between growth rate and wood properties in Sitka spruce (Brazier, 1970a). Brazier and Mobbs (1993) observed that, as yield class increased, the stiffness of battens dropped, although the differences were small and no information was given on whether this trend was statistically significant. This is most likely due to the reduction in density linked to increased vigour. In addition to direct effects on growth, soil moisture regime is a factor in tree stability and therefore (depending on the windiness of the site) influences the thinning regime applied and rotation length chosen: both these considerations can have a significant effect on timber quality.

Bryan and Pearson (1955) investigated the specific gravity of Sitka spruce grown in Britain. They sampled trees from six different plantations throughout Great Britain and concluded that there was a very close relationship between specific gravity and latitude, with specific gravity decreasing at the rate of 0.011 per degree of increase in latitude. It is not clear whether any effect of differential growth rates or other site differences were taken into account, although care was taken to ensure that density samples were taken to represent wood formed at the same age (i.e. ~30 years). The trend that they identified accords with Zobel and van Buijtenen's statement that 'trees grown at high latitude or high elevation sites usually produce lower specific gravity wood and shorter cells within a given species than wood of that species grown closer to the equator or at lower elevations'. Again, it is unclear whether this statement excluded any effect of differing growth rates. A further investigation into the geographical variations in specific gravity in British forests was undertaken in the 1960s (Jeffers and Dowden, 1964). Ten trees each of seven conifer species from three forests in eleven geographical regions were sampled. For Sitka spruce significant differences were identified in specific gravity between trees, sites and some meteorological regions, although the relationship with latitude was unclear. There is

Table 9: Summary of the effects of silviculture on Sitka spruce wood quality

Silvicultural intervention	Effects on wood quality
Rotation length	Shorter rotation lengths are linked to: increased proportion of juvenile wood hence reduced strength and dimensional stability; greater vigour, which is correlated to reduced density and possibly reduced strength
Initial spacing	Wider spacing is linked to: increased rates of diameter growth and hence larger juvenile rings with associated loss of strength and dimensional stability; longer retention of deep living crown hence larger branching and knots; more exposure to the effects of wind hence increased taper and compression wood; possible reduction in stem straightness; an increase in grain angle, with implications for the strength and stability of sawn timber
Thinning	Prior to canopy closure: the effects are analogous to wider initial spacing with a larger juvenile core, more, persistent branching and increased taper After canopy closure: selective thinning improves straightness and branching characteristics in the standing crop; growth concentrated in the mature wood, however note that the largest trees tend to have the lowest density wood
Nursing mixtures	Incompatible growth rates can lead to large uneven crowns, greater knot areas and more compression wood, analogous to wider uneven spacing Mixtures with deciduous species (e.g. larch) lead to greater taper and larger knots than mixtures with evergreen conifers (e.g. Alaskan lodgepole pine)
Pruning	Reduces the extent and size of knots Can accelerate the transition from juvenile to mature wood Can reduce the taper of logs
Cultivation	Improved establishment success reduces problems associated with wide and irregular spacing Cultivation that reduces stability will reduce rotation lengths; better cultivation will allow other silvicultural interventions
Weed suppression	Poor weed control can lead to problems associated with wide and irregular initial spacing
Fertilization	Increased growth rates lead to a decrease in wood density. Fertilizer application can cause uneven growth and poor dimensional stability in timber Leader breakage may be linked to fertilizer application, leading to reduced stem straightness Severe potassium and trace element deficiencies (e.g. copper) lead to loss of apical dominance and poor stem form Potassium-deficient trees are more frost hardy than non-deficient trees, hence shoot damage and poor form is more likely on frosty, well-fertilized sites

little information, however, about the variations in silvicultural regimes at the different sites, or their age at sampling, which may have masked any underlying relationship.

There is little quantitative information available on any effects of site quality on wood properties of Sitka spruce apart from on growth rate. The Ecological Site Classification (ESC) currently under development (Pyatt and Suárez, 1997) will provide a useful framework within which the effects of site quality on wood properties can be investigated in the future. The classification is based on climate (accumulated temperature, moisture deficit, oceanicity and windiness), soil moisture regime (availability of water and oxygen to plant roots and soil organisms) and soil nutrient regime (availability of major nutrients), all of which can influence wood properties through their effects on tree growth and/or form.

Windiness The windiness of a site affects timber quality both directly and indirectly, and wind is an important influence on timber quality in upland Britain. Direct effects include the development of leaning stems with elliptical cross-sections and compression wood (Jacobs, 1936; Low, 1964) and an increase in taper (Malcolm and Studholme, 1972). At wider spacing, or where spacing has been increased following thinning or respacing, these effects seem likely to be more severe due to the increased wind loading experienced by individual trees (Gardiner *et al.*, 1997). Poor stem straightness has also been associated with windy sites for *Pinus radiata* (Nicholls, 1982) and Sitka spruce growing on exposed sites in Britain may experience repeated leader loss, a contributory factor in the development of crooked stems (Baldwin, 1993).

Indirectly, windiness influences timber quality by limiting the range of silvicultural options that are available to a forest manager. On sites at risk it may not be possible to carry out selective thinnings, rotation lengths are reduced, and therefore stem diameter at clearfell and the relative proportion of juvenile wood are affected by windiness.

In general, therefore, sites with high levels of windiness will tend to produce timber less suitable for higher value markets, such as construction.

Slope Trees growing on steep slopes have been reported to develop 'swept butts' and associated compression wood near the base of the stem in order to maintain verticality (Low, 1964). This will decrease the value of the butt log. In addition to this direct effect, many stands on very steep slopes cannot be thinned because of practical or economic considerations. The opportunity to improve the final crop quality in terms of dimensions, stem form and branching will therefore be lost.

Snow/ice Snow and ice can cause crown damage that may result in the formation of crooked stems as leaders or whole sections of the crown are lost. This kind of damage is likely to be localized and difficult to predict.

See Table 10 for a summary of the effects of site factors on Sitka spruce wood quality.

Table 10: Summary of the effects of site factors on Sitka spruce wood quality

Factor	Effect on wood quality	Comment
Site quality	Higher yield classes show reduced batten stiffness Specific gravity increases as latitude increases Soil moisture can have indirect effects on quality	General trend of reduced strength with increased vigour possibly linked to lower density associated with increased speed of growth Wetter sites will reduce silvicultural options and in windy locations tend to be unstable, hence no-thin
Windiness	Increased wind exposure is linked to: leaning stems with elliptical cross sections; increased compression wood; poor stem straightness; limited thinning	Increased variability in the stem leads to poor dimensional stability and varying strength properties. Compression wood is generally weaker than mature wood and distorts when dried, higher lignin content reduces pulp yields
Slope	Increased slope is linked to: increased compression wood; limited thinning	Similar effect to increased windiness; the two site factors are often linked
Snow/ice	Damage will affect stem straightness and branching	Localized damage, difficult to predict

Genetics

There has been a considerable increase in understanding of the link between genetic variation and wood properties of spruce (for a review, see Rozenberg and Cahalan, 1997). The British Sitka spruce improvement programme has progressed to the stage of offering improved stock to growers (Rook, 1992). Hence in the broadest definitions of silviculture, genetics is becoming an increasingly important factor in stand management. However, Zobel and Jett (1995) comment that wood properties have generally been ignored in tree breeding programmes, with the emphasis being on improving vigour, form (including branching characteristics) and adaptability to a wide range of sites. Many wood properties show significant variation and are known to be highly heritable, making rapid genetic gains a possibility by breeding.

In Sitka spruce, wood density is sufficiently negatively correlated with vigour to make concurrent improvement of vigour and quality an issue (Lee, 1998, 1999). In order to safeguard wood quality the British Sitka spruce breeding programme aims to improve vigour, branching characteristics and stem form while maintaining density at or above the level found in the unimproved population. The most recent family mixtures have shown that such an approach is feasible with reported gains of 22 per cent in diameter and 0 per cent loss of wood density compared with unimproved Queen Charlotte Island stock (Lee, 2001).

Timber from a replicated Sitka spruce seed origin trial planted at Gwydyr Forest, North Wales, in 1950 was examined in order to evaluate the variation in wood properties between origins. Material from three Washington origins (Hoh River, Columbia River and Copalis River) and Queen Charlotte Island (QCI) origin was studied. Significant variation in grain angle between origins was found; timber from Copalis River origin had a lower than average grain angle, whereas that of Hoh River origin was higher than average (Tranquart, 1995). Between-tree variation in grain angle was high, indicating the potential for genetic improvement of this characteristic in Sitka spruce. No significant differences in wood density between origins were observed (Gibson, 1995). The yield of sawlogs and the subsequent out-turn of structural grade timber from the different provenances was examined (Lee *et al.*, 1999). There was a tendency for the Washington origins to yield an increased volume of sawlogs compared with QCI, without a penalty in terms of the proportion of timber satisfying SC 3 (C16). However, there might be a reduction in the proportion of SC4 (C24) timber produced.

For structural grade timber, the emphasis in both genetic and silvicultural research has shifted slightly away from wood density as the main indicator of quality to consider other properties that affect technological performance, such as microfibril angle and grain angle. Cave and Walker (1994) advocated improving wood quality by selecting trees for breeding on the basis of low microfibril angle in the juvenile wood, while Tsehaye *et al.* (1995) propose selection on the basis of stiffness in young standing trees. The use of genetic markers in breeding programmes to improve wood quality is also the subject of ongoing research (e.g. Faivre Rampant *et al.*, 1997; van Buijtenen, 1997).

Conclusions and recommendations

The quality of Sitka spruce timber can only be assessed in terms of the end-use for which it is intended. The most valuable market available for home-grown softwood timber in Britain is structural grade sawn timber, for which there are stringent requirements in terms of the dimensions, mechanical properties and dimensional stability. Sawn softwood has been described as the critical market sector for UK conifer production (Forestry Commission, 1996). Domestic sawlog production is forecast to more than double over the next 20 years (Whiteman, 1996). The lower value pallet, packaging and fencing markets, which currently absorb more than two-thirds of UK-produced sawn timber will not be able to absorb the expected increase in volumes available (McIntosh, 1997). Greater penetration of the higher value construction sector, the most demanding in terms of quality requirements, will therefore be required if British sawlogs and sawn timber are to be successfully marketed. This will only be achieved by increasing market share in the face of strong competition from imported material.

The tree growth characteristics and wood properties which are most important in determining the suitability of timber for structural applications are log dimensions, age of tree, log straightness, knottiness, grain angle, wood density, amount of juvenile wood and amount of compression wood. These characteristics are influenced by the interaction of a range of site and silvicultural factors and the genetic quality of planting stock. The decisions which the forest manager takes can affect all of these wood properties with the possible exception of grain angle. Compared with the wealth of literature on other conifer species, there is a limited amount of information available on factors affecting Sitka spruce timber quality. The general effects of manipulating stocking density through initial plant spacing and subsequent respacing or thinning are well understood, but there is a need for more detailed quantitative information. Although high levels of windiness have been linked to poor stem form and increased incidence of compression wood, to date there have been no detailed studies in this area relating to Sitka spruce. In particular, the interaction of spacing and windiness has not been explicitly examined. Little is known about the effects of fertilizer application on wood quality, other than those attributable to increased vigour. The effects of site factors, as codified by the Ecological Site Classification, are largely unknown. There are high levels of genetic variation in many tree growth characteristics and wood properties, suggesting that significant gains in wood quality might be achieved through tree breeding.

However, it is possible to reach some conclusions about the likely quality of future timber supplies from even-aged Sitka spruce plantations in Britain. Plantations established since the 1960s differ from those from earlier decades in several ways, which are likely to affect the quality of timber produced. A summary of the changes is provided in Table 11.

The use of wider initial spacing, planting on more exposed sites, thinning fewer stands and clearfelling at younger ages can be expected to result in smaller, knottier, more crooked trees with a higher proportion of juvenile wood and a greater incidence of compression wood. This is supported by recent surveys of Sitka spruce stem straightness in southern Scotland, where planting age is a significant factor, with younger plantations showing a reduction in straightness (Stirling *et al*., 2000).

Therefore, there is sufficient information to provide forest managers with broad guidelines. Silvicultural regimes will tend to produce a stand predominately of one product or another. However, in order for these choices to be effective they should be consistent throughout the rotation. This implies a clear understanding of the potential of a site to produce the products required rather than planting an area and waiting to see the mix of products that results. If possible

Table 11: Changes in Forestry Commission silvicultural recommendations for Sitka spruce since 1933 (see Hibberd (1991) and previous editions)

Year	Spacing/m	Fertilization (minor use)	1st thinnings ht/m	Other recommendation
1933	1.7	P at planting	7.5	
1946	1.5	P at planting	12.0	Mixtures with SP; windthrow a hazard
1958	1.6	P at planting	10.0	As 1946, thin every 3 years
1964	1.9	P at planting (K)	8.0–12.0	Introduced management tables and YC; thin every 5 years
1978	2.0	PK at planting (N)	8.0–12.0	As 1964, no-thin regimes
1986	2.0(+)	P at planting	8.0–12.0	As 1978, windthrow hazard classification introduced.
1991	2.0(+)	Regime prescription matched to site	8.0–12.0	As 1986

a stand should be designated as being of 'sawlog type' or 'fibre type' (i.e. pulp or panel) *when established*, since the silviculture required to maximize the return for each type is very different. This raises the issue of what determines stand type, and this involves a number of factors and constraints:

- *Windfirmness*. If the site is exposed and unlikely to be stable over the length of a full rotation then it should be considered for fibre. This can now be predicted with greater accuracy using ForestGALES (Dunham *et al*., 2000; Gardiner and Quine, 2000) a PC-based wind risk model for British forests. This integrates not only the wind environment but also exposure and soil types.
- *Thinning*. Although the decision to thin is linked to windfirmness, and currently the recommendation for upland spruce is not to thin a stand with a DAMS score >17 (personal communication, Barry Gardiner, Forest Research), there are also factors such as accessibility, availability of markets and the willingness of the owner to invest in management. A site that is not destined to be thinned is unlikely to produce good quality timber and should be considered a fibre stand. Whilst there are undoubtedly examples of unthinned stands with good timber, thinning would have concentrated volume into fewer stems, thereby providing financial benefits during harvesting, handling and processing. A half-hearted approach, with delayed and missed operations, is likely to lead to a poor return, with loss of volume in the larger size categories and so a no-thin approach would be preferable.
- *Yield class*. A site with a low yield class (<10) will often not be thinned because the returns for each operation are so low. In addition, the rotation length to achieve reasonable timber sizes is likely to stretch to 70–80 years; therefore, although low YC sites are likely to produce the densest and therefore the strongest wood, on economic grounds they would be better managed as fibre sites or for other benefits. Paradoxically, high yield class sites (>20) would also best be considered as fibre stands because the speed of growth and the associated problems of density reduction and decline in straightness will reduce batten performance. One method of reducing this problem associated with high yield classes would be to increase competition with higher initial stocking. Brazier and Mobbs' (1993) work indicated that a YC-12 site would require an initial stocking of ~1600 stems ha^{-1} for the mean reaction force of the timber to meet SC4 standard, whereas a YC-20 site would require 2060 stems ha^{-1}. The use of natural regeneration on such sites would be one method of achieving high stocking rates (Nixon and Worrell, 1999); alternatively such fertile sites might be best suited to other species.
- *Other constraints*. The economies of scale are more important with a fibre stand than a sawlog type because the value per unit is lower for pulp or panel wood. Therefore, large clear-fell sites would be preferable where such economies are possible. Increasingly, social constraints, in the form of landscape and amenity considerations, are being placed on large clear-fell operations. Another consideration for owners is that cash flow for each site type will be different. Both will require investment at establishment, but a fibre stand will require little further investment before providing a return in one felling operation. A sawlog type will require some additional investment for a pre-commercial thinning but then should provide a steady return from thinnings before being felled.

The silvicultural options for each site type are presented in Table 12.

Most practising foresters will be unsurprised by the silvicultural prescription for quality timber for Sitka spruce. Indeed, a similar prescription could be applied to most other timber species grown in the UK. The traditional emphasis on valuing softwood timber on a volume and form basis (Forestry Commission, 1993) has placed insufficient importance on wood quality amongst foresters. The repercussions of this tradition are now starting to filter through the system and into the market, with increasing concerns being raised by sawmills about the quality of spruce. This review highlights that the biggest, fastest grown trees are not necessarily the best for C16 (SC3) structural grade Sitka spruce and certainly not for higher grades such as C24 (SC4) even though they might match the green log specification. However,

Table 12: Silvicultural recommendations for stands of Sitka spruce either aimed towards sawlog or pulp/panel products

Sawlog type	Fibre type
Establishment	*Establishment*
2 m spacing should be considered a maximum, closer spacing preferred. Natural regeneration would be preferred since high stocking densities possible Establishment success and full stocking crucial Genetic material selected for wood density rather than high vigour should be planted	2 m spacing a minimum, greater than 3 m will reduce total volume production Establishment success crucial for maximum volume production. Planting preferred since further respacing not required Genetic material selected for vigour should be planted
Management	*Management*
Selective thinning Fertilizer used only as a last option to avoid stress Ideally aim to constrain growth rates until juvenile wood is no longer being laid down in the butt, i.e.approximately for the first 15 years Accept that rotation lengths will be longer and possibly thin and fell using a target diameter criterion to match sawlog size requirements	No-thin or systematic thinning Fertilizer applied if volume production shows signs of slowing Minimum rotation length to meet pulp size requirements Clear fell site at first opportunity; the operation should be efficient in terms of speed and hence product assortments kept to a minimum, possible all the crop should be felled and sent as pulp without further assortment Options other than clear-felling unlikely to be economically viable

under the current system, no premium exists for close grown, carefully thinned spruce which has been managed with the aim of maximizing C24 batten output. Indeed, it would be surprising if any forester currently considered out-turn in those terms, but buyers need to because each batten that fails stress grading represents both a cost and lost revenue. Hence buyers need to be more discerning and willing to reward foresters who will compromise annual volume increment to achieve higher-grade timber. However, a discerning buyer will require reliable and validated information about stand history and silviculture. The long-term management plans and auditing required under UKWAS (UKWAS Steering Group, 2000), or other certification schemes, could present a solution to this problem and allow a clear premium to be offered for timber obtained from well-managed stands.

If such clarity of management objectives could be stated, then other forestry management decisions aiming at social and environmental benefits could be more clearly targeted. The slower growth rates and longer rotations desirable for quality sawlogs would more likely provide a pleasing aesthetic environment later in the rotation than the very fast volume growth stands required for pulp production.

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