Forestry Commission

Forest Yield

A handbook on forest growth and yield tables for British forestry

Productivity and yield class

Yield tables, such as in Forest Yield, are routinely used in making decisions about forest management such as commitments to future levels of timber production and scheduling thinning and felling operations. In order to inform such decisions reliably, an essential first step in applying yield tables involves assessing the productive potential of the stands of trees being managed and using this information in selecting the most appropriate yield tables for predicting the future development of the stands.

In British forestry, the productive potential of forest stands is assessed in terms of potential volume productivity and, in particular, cumulative volume production and the related parameters of Local Yield Class and General Yield Class (see 'Yield class', page 24). In everyday forestry practice, General Yield Class, which is usually obtained from simpler assessments of stand top height rather than directly from volume, represents one of the most important parameters for making decisions about forest management.

This section describes these various measures of stand productivity and how they are calculated.

Measuring volume productivity

An important measure of volume productivity in forestry is cumulative volume production. Cumulative timber volume production is the standing volume per hectare attained by a forest stand in a given year plus the sum of per hectare volumes removed as thinnings up to that year. By convention, volume of dead trees is not included. Cumulative volume production represents the total production of timber volume from a stand up to a given year in the stand's development.

An example of cumulative volume production as measured in a permanent sample plot of even-aged Sitka spruce is given in Table 5. As an illustration of how cumulative volume production is calculated, in Table 5 cumulative production up to age 44 years is:

$$369 + 34 + 33 + 49 + 24 + 35 + 61 + 53 = 658 \text{ m}^3 \text{ per hectare}$$

Strictly speaking, cumulative volume production is not a meaningful physical or biological variable. The main applications of cumulative volume production are in economic analysis and in support of practical forest management. In essence, cumulative volume production represents the out-turn of commercial stem volume from a stand up to a given year in the stand's development.

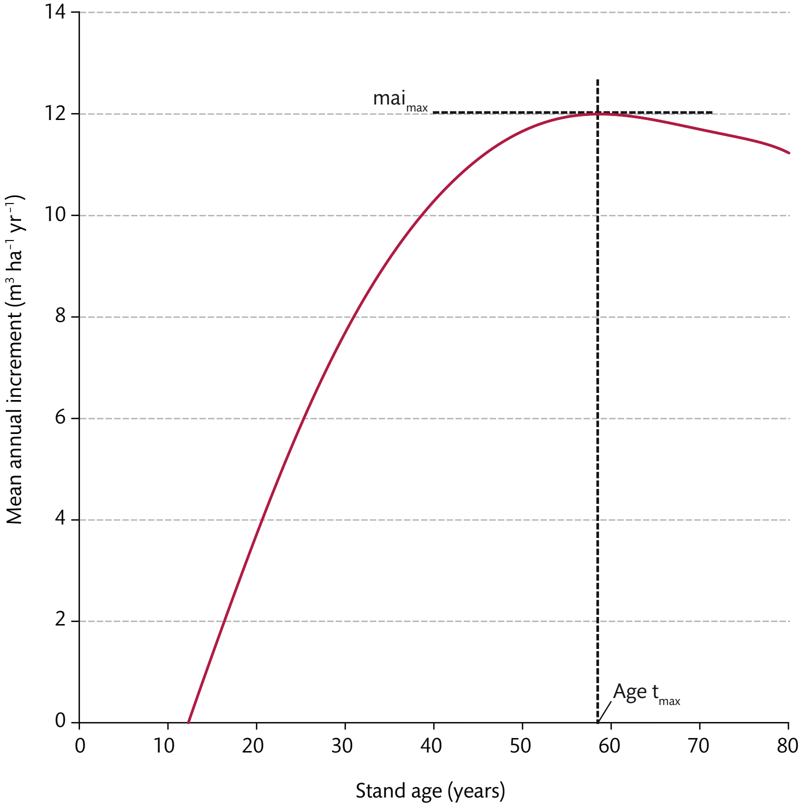
Mean annual increment (MAI) is the average rate of cumulative volume production up to a given year. In even-aged stands MAI is calculated by dividing cumulative volume production by age. For example, for the Sitka spruce stand in Table 5, the mean annual increment up to age 44 years is $658 \div 44 = 15.0$ m^3 per hectare per year.

Table 5 Standing volume and production over time in an even-aged stand of Sitka spruce (permanent mensuration sample plot 1222, Brendon, Somerset, established 1948, felled 1986 at age 57).

Year	Stand age (years)	Top height (m)	Volume per hectare ($m^3\ ha^{-1}$)			Mean annual increment ($m^3\ ha^{-1}\ yr^{-1}$)
			Standing after thinning	Removed as thinnings	Cumulative volume	
1948	19	8.6	103	34	137	7.2
1951	22	10.0	-	33	-	-
1953	24	11.1	121	49	237	9.9
1958	29	14.5	-	24	-	-
1963	34	16.0	262	35	437	12.9
1967	38	17.8	272	61	508	13.3
1973	44	21.3	369	53	658	15.0
1978	49	23.4	396	59	744	15.2
1986	57	-	531	-	879	15.4

For an even-aged stand of trees, MAI follows a characteristic pattern of development with respect to stand age. This pattern is described in Figure 1. In the early years of stand development, MAI rises steadily from zero to a maximum value. For typical even-aged conifer stands grown under UK conditions, this maximum value is usually reached after several decades. From this point on MAI declines steadily, although the rate of decline may be slight in the years immediately following attainment of maximum MAI. The existence of a stand age t_{max} for which MAI takes a maximum value mai_{max} may be regarded as being of great commercial significance in the management of even-aged stands particularly if the aim is to maximise volume production while also ensuring sustainable yield. Specifically, if mai_{max} occurs at a predictable stand age t_{max} then a forest manager may choose to clearfell the stand at this age, i.e. the forest manager can choose to manage the stand on a rotation equal to age t_{max}. The average rate of volume production over the rotation period t_{max} will then be mai_{max}. The forest manager can then replant or regenerate a new stand on the clearfelled site and, if this new stand is of the same tree species and also grown over a rotation period t_{max}, then average rate of volume production of the new stand will again be mai_{max} provided that the fertility of the site has not been depleted and environmental conditions have not changed. Clearly, managing a stand on this site using any rotation period other than t_{max} will result in a lower average rate of volume production, because the MAI achieved by an even-aged stand on this site must be lower for a stand age other than t_{max}.

Figure 1 Trajectory of mean annual increment of cumulative volume production for an even-aged stand. The example curve is based on the Forest Yield table for Sitka spruce, yield class 12, 1.7 m initial spacing and intermediate thinning.

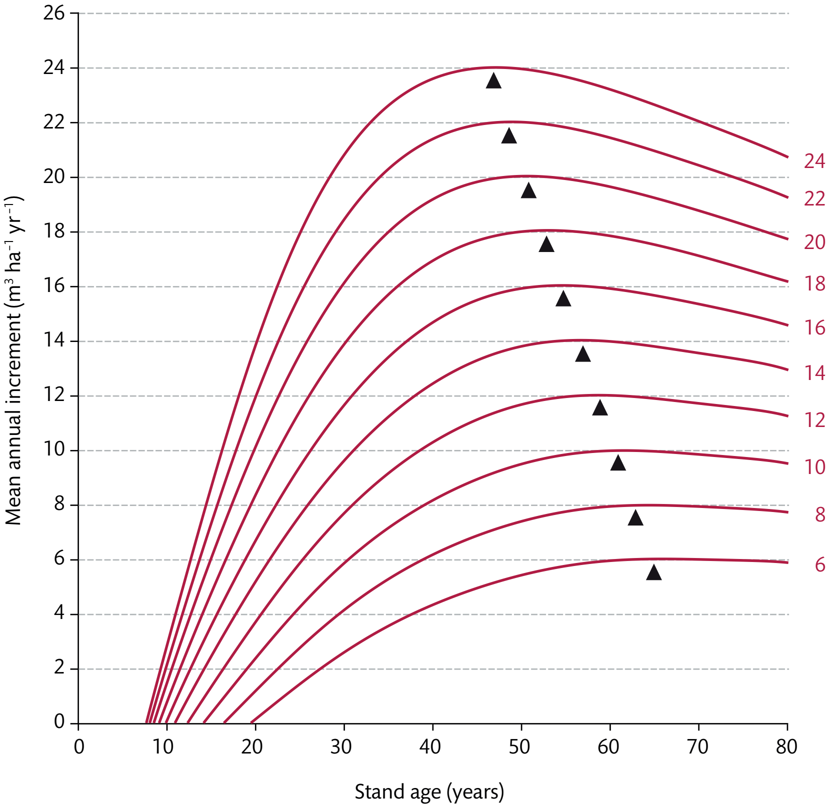


Yield class

Future volume production can be predicted by referring to an appropriate yield table. Yield tables are based on characteristic growth curves for a given species and management regime, including curves for describing the development of MAI and cumulative volume production. Examples of such curves are given in Figures 2 (MAI) and 6 (cumulative volume).

It is possible to construct a curve for MAI development (and an equivalent one for cumulative volume) with any selected value of maximum MAI. However, for ease of use, the curves referred to in yield tables are restricted to a particular set of maximum values.

Figure 2 Illustration of a set of growth curves for describing development of mean annual increment with respect to stand age, showing 10 distinct productivity classes (yield classes). The curves shown are based on the Forest Yield tables for Sitka spruce, 1.7 m initial spacing and intermediate thinning.



By convention in British forestry, to simplify interpretation and reporting, MAI curves usually have maxima equal to even numbers, e.g. 2, 4, 6... m^3 per hectare per year. This maximum value can be used as an index to identify each of the different curves – this index is known as yield class. Yield class is thus an index measure of forest productivity based on the maximum MAI of cumulative timber volume achieved by a given tree species growing on a given site and managed according to a specified prescription. It is measured in units of cubic metres per hectare per year. In Figure 2, there are 10 MAI curves representing yield classes of 6 to 24, which cover the productivity range commonly observed for Sitka spruce in Britain.

A common misunderstanding is that yield class represents the maximum potential volume productivity that a tree species can achieve on a given site. The values of yield class referred to in Forest Yield often do not represent maximum potential productivity on a given site. In many cases, yield class may be close to maximum potential productivity on a given site, but in some cases yield class is defined very differently, depending on how stands of a particular tree species are typically managed. These points are discussed in detail in the section on 'Dependence of yield class on management prescription' (page 36).

Local Yield Class

The yield class of a stand can be assessed by directly monitoring cumulative volume production and comparing it with standard growth curves. An estimate of yield class derived in this way is known as 'Local Yield Class' (LYC).

In Figure 3 cumulative volume measurements from Table 5 are plotted to allow comparison with the model curves. The first measurement of cumulative volume at age 19 is closest to the model curve for yield class 18, but later measurements are around the curve for yield class 16. This illustrates how yield tables can be used to predict future growth for an actual stand, and also shows the limitations of such a prediction. On the one hand, making a prediction is a very simple procedure – the curve that best represents, i.e. is closest to, the measured cumulative volume is selected, and this curve can be used to estimate the future cumulative volume increment in the stand. On the other hand, a prediction made in this way will only be an approximation of the actual development of cumulative volume in a particular stand because, in general individual stands will not grow exactly according to the pattern described by the model curves.

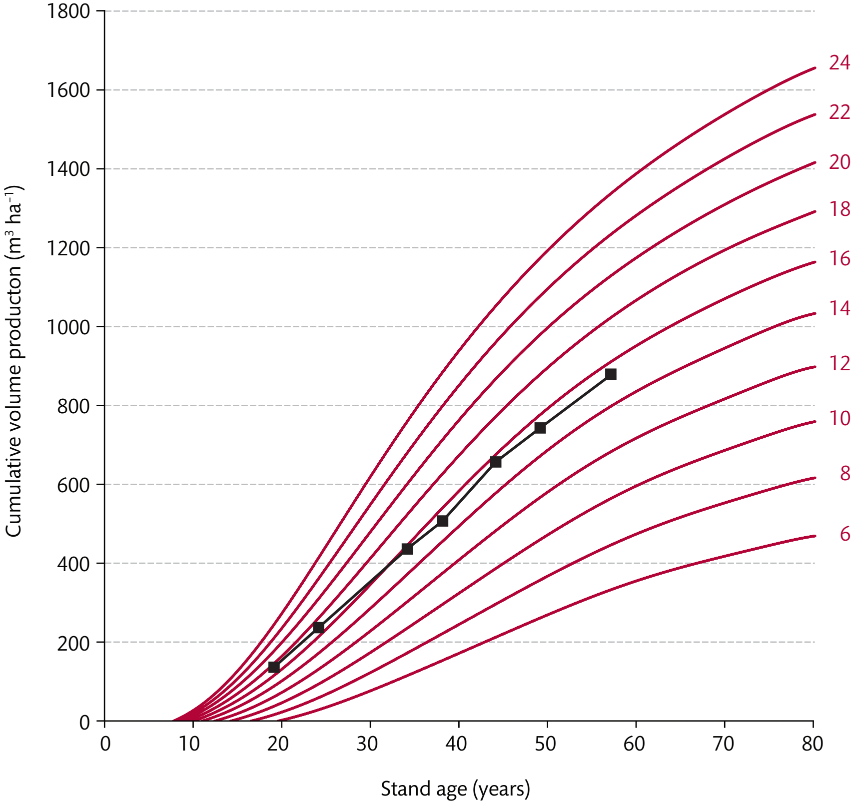
General Yield Class

A big problem with an approach to yield class estimation based on assessment of cumulative volume production is that cumulative volume is difficult and expensive to measure. As a consequence, estimating yield class from direct measurement of cumulative volume is rarely attempted in practice. However, studies of forest growth have shown that cumulative timber volume production is closely related to the development of top height in most tree species when grown as even-aged stands.

For example, the relationship assumed between cumulative timber volume production and top height in the yield tables for Sitka spruce is shown in Figure 4. It is striking and very useful that this relationship can be described with reasonable precision by a single curve, which was called a 'master table' relationship by the original developers of the yield tables[2,3].

[2]Christie, J.M. (1972) *The characterization of the relationships between basic crop parameters in yield table construction.* In: Proceedings of Third Conference of Advisory Group of Forest Statisticians (IUFRO), Jouy-en-Josas, 7–11 September 1970. INRA Publication 72-3. Institut national de la recherché agronomique: Paris, pp. 37–54.
[3]Hummel, F.C. and Christie, J.M. (1957) *Methods used to construct the revised yield tables for conifers in Great Britain.* Report on Forest Research 1957. pp. 137–141. HMSO, London.

Figure 3 Illustration of a set of growth curves for describing development of cumulative volume production with respect to stand age, showing 10 distinct productivity classes (yield classes). The curves shown are based on the Forest Yield tables for Sitka spruce, 1.7 m initial spacing and intermediate thinning. The black points illustrate cumulative volume as measured in an actual stand (see Table 5), which can be compared with the model curves.



Master table relationships such as the example in Figure 4 played a major role in simplifying the construction of yield tables during the 1950s right through to the 1990s. Such simplifications were essential in making the task of yield table construction possible because, during the key development phase from 1950 to 1980, the modelling approach involved:

- charting the development of stands of trees by manually plotting sample plot data on graph paper;
- establishing relationships between variables such as age, top height and cumulative volume using hand-drawn curves based on the graphs;

- manual calculation of values in the yield tables, sometimes with the assistance of mechanical calculators.

Master table relationships were not only easier to characterise than families of curves such as in Figure 3, they also made the process of hand calculation of yield tables less error-prone, for example making it easier to ensure that yield predictions in tables for different yield classes were consistent with each other, as illustrated in Figure 5a-c. In the figure, values for cumulative volume against age are constructed by finding values of top height for different ages, and then using the master table curve to convert the top heights to cumulative volumes.

Figure 4 Illustration of the 'master table' relationship between cumulative volume production and top height development assumed in the Forest Yield tables for Sitka spruce (1.7 m initial spacing and intermediate thinning).

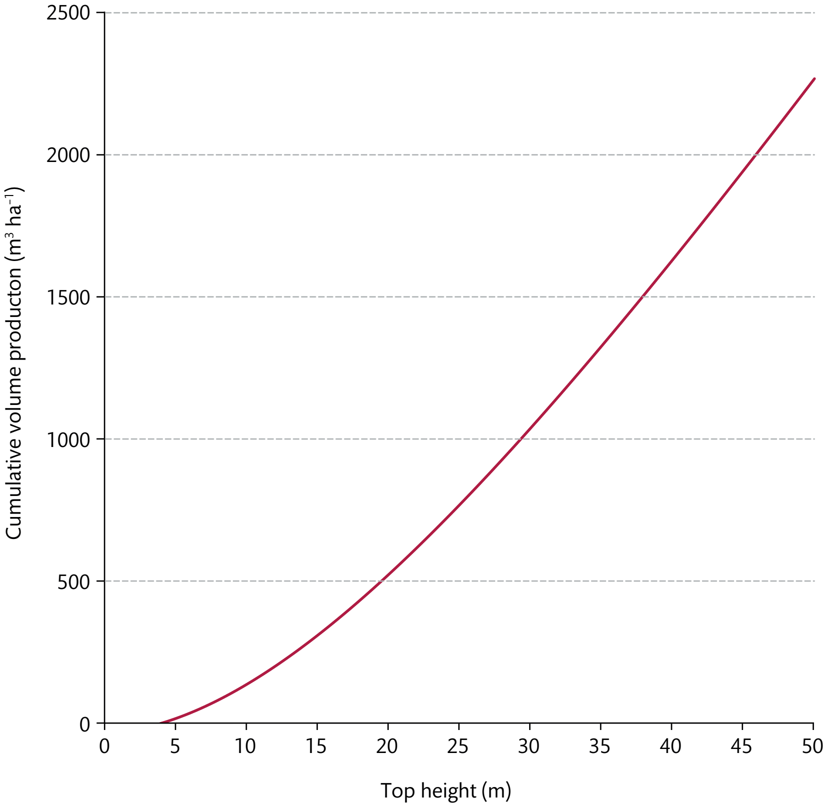
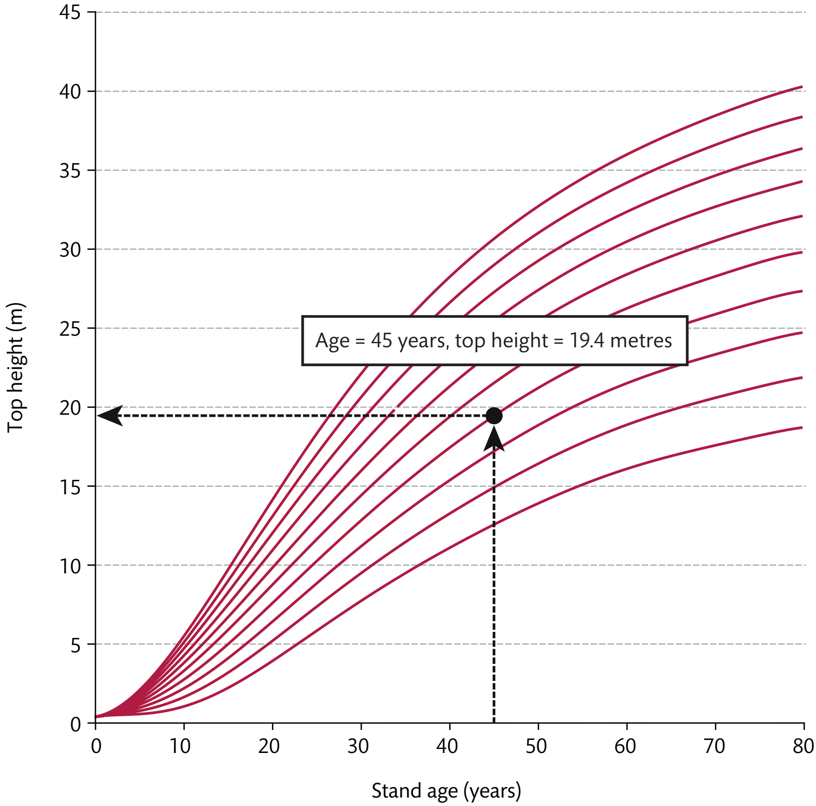
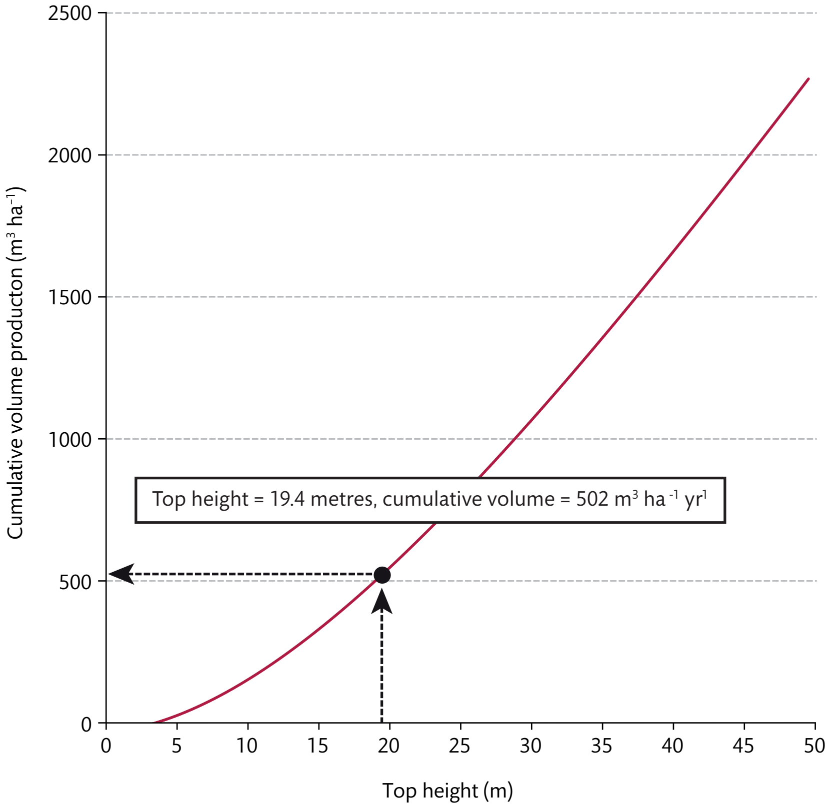


Figure 5a–c Illustrations of the method used to construct a family of curves for cumulative volume production with respect to age for different yield classes using the master table method.

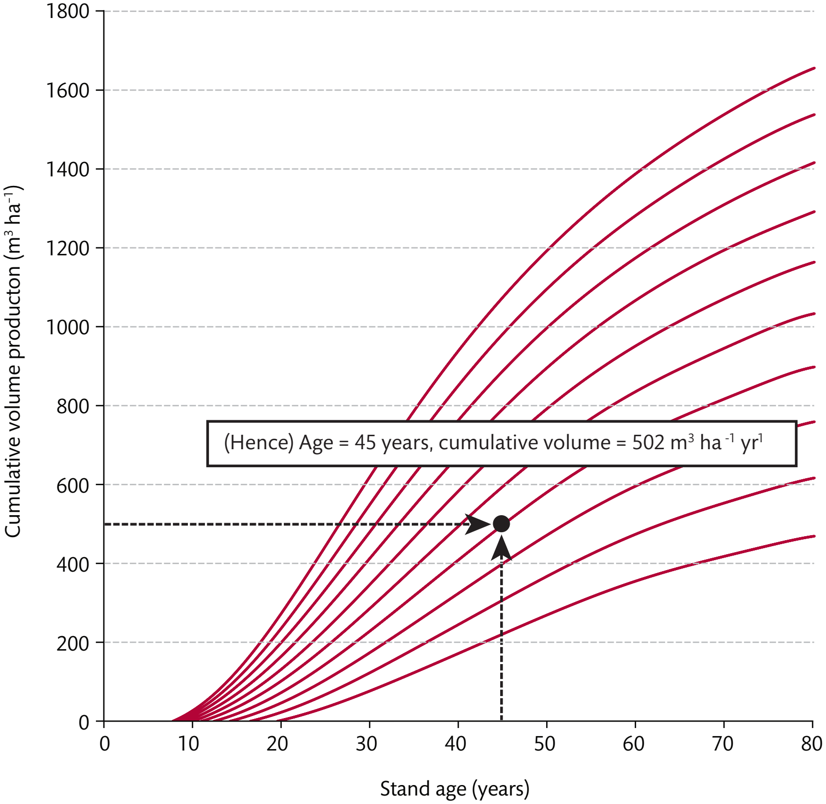
a) A family of curves is constructed by hand to describe development of stand top height with age. The curve representing a particular productivity class is selected and estimates of top height can be read off for a sequence of stand ages.



b) The estimates of top height for successive stand ages can be used as input to the master table for cumulative volume production so as to find equivalent estimates of cumulative volume for each stand age.



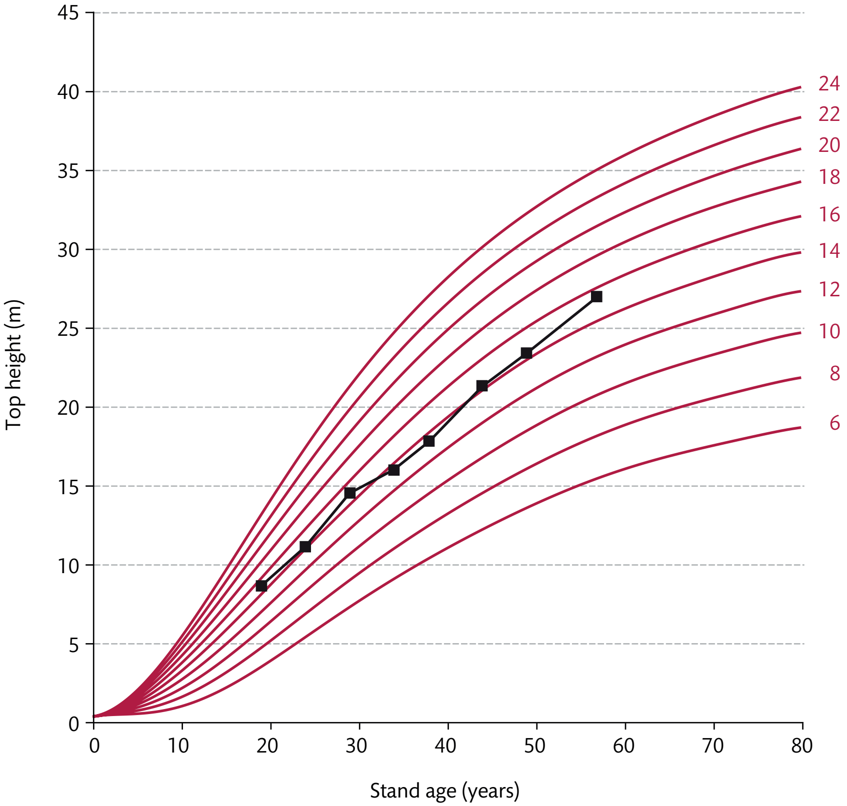
c) The cumulative volume production estimates can be plotted directly against stand age to provide the relevant curve for the particular productivity class of interest. The same approach may be adopted to construct curves for other productivity classes.



The existence of the master table relationship between cumulative volume and top height makes it possible for yield class to be estimated from an assessment of stand top height and the stand age. The top height assessment is compared with a standard set of top height on age curves as illustrated in Figure 6 This type of estimate is known as 'General Yield Class' (GYC). These are the General Yield Class curves in Forest Yield.

In Figure 6, top height measurements for the sample plot referred to in Table 5 are plotted to allow comparison with the model curves. Six out of nine assessments lie close

Figure 6 Illustration of a set of growth curves for describing development of top height with respect to stand age, showing ten distinct productivity classes (yield classes). The curves shown are based on the Forest Yield tables for Sitka spruce. The black points illustrate top height as measured in an actual stand (the same one as in Table 5), which can be compared with the model curves.



to the curve for yield class 14, while just three are closer to the curve for yield class 16 or mid-way between the yield class 14 and 16 curves. Overall this suggests a GYC estimate of 14, one class down from the LYC estimate of 16 obtained earlier (Figure 3). This illustrates how GYC is not an exact estimate of LYC. The application of GYC in forestry practice relies on the assumption that it will be an unbiased estimate of LYC on average over many stands. However, the possibility exists that GYC may systematically overestimate or underestimate LYC in certain situations, for example due to the particular growth characteristics of stands of a certain species growing in a certain region or managed in a certain way.

General Yield Class curves

The Forestry Commission convention is to estimate and report GYC (which has units of cubic metres per hectare per year) as even numbers only, e.g. 4, 6, 8, etc. A graphical example of the 'banded' GYC curves for Sitka spruce, similar to that implemented in Forest Yield is shown in Figure 7.

The two cubic metre per hectare per year 'band' or interval was selected because the yield tables were constructed from data collected across the whole of Great Britain and, as described earlier, GYC is not an exact estimate of local growth rates. The boundaries between the bands are in fact determined from the GYC curves for odd-numbered yield classes, for example the band for GYC 14 is bounded by the GYC curves equivalent to 13 m^3 per hectare per year and 15 m^3 per hectare per year. As an example of the rounding of GYC, a top height and age assessment landing exactly on the boundary between the bands for GYC 12 and GYC 14 is rounded down to a GYC of 12, and so on.

Production class

When situations arise in which a forest manager has reason to believe that the LYC of a significant collection of stands deviates systematically from the GYC, it is possible to compensate for this by making an assessment of production class in the stands. Production class is an index of the difference between the LYC and GYC of stands of trees. For example, if the measured LYC and GYC are 16 and 14 respectively (i.e. LYC is 2 m^3 per hectare per year higher than GYC), then a production class of A may be assigned. If both the LYC and GYC are the same (say, both 14) then this suggests a production class of B, while if the LYC is 2 m^3 per hectare per year lower than the GYC (say 12 and 14 respectively) then a production class of C is implied. Table 6 summarises the values assigned to production class depending on the difference between LYC and GYC.

When a production class other than B has been ascribed to a stand, decisions about management and estimation of forecast volumes may be affected. For example, suppose a stand with a GYC of 12 has been identified as having a production class of C. Typically, the appropriate yield table based on yield class 12 would still be used to estimate future top height development. However, for all other variables (numbers of trees, basal area,

Figure 7 The 'banded' GYC curves for Sitka spruce (original models), from yield class 6 (m^3 per hectare per year) to yield class 24 (m^3 per hectare per year) in increments of 2 m^3 per hectare per year.

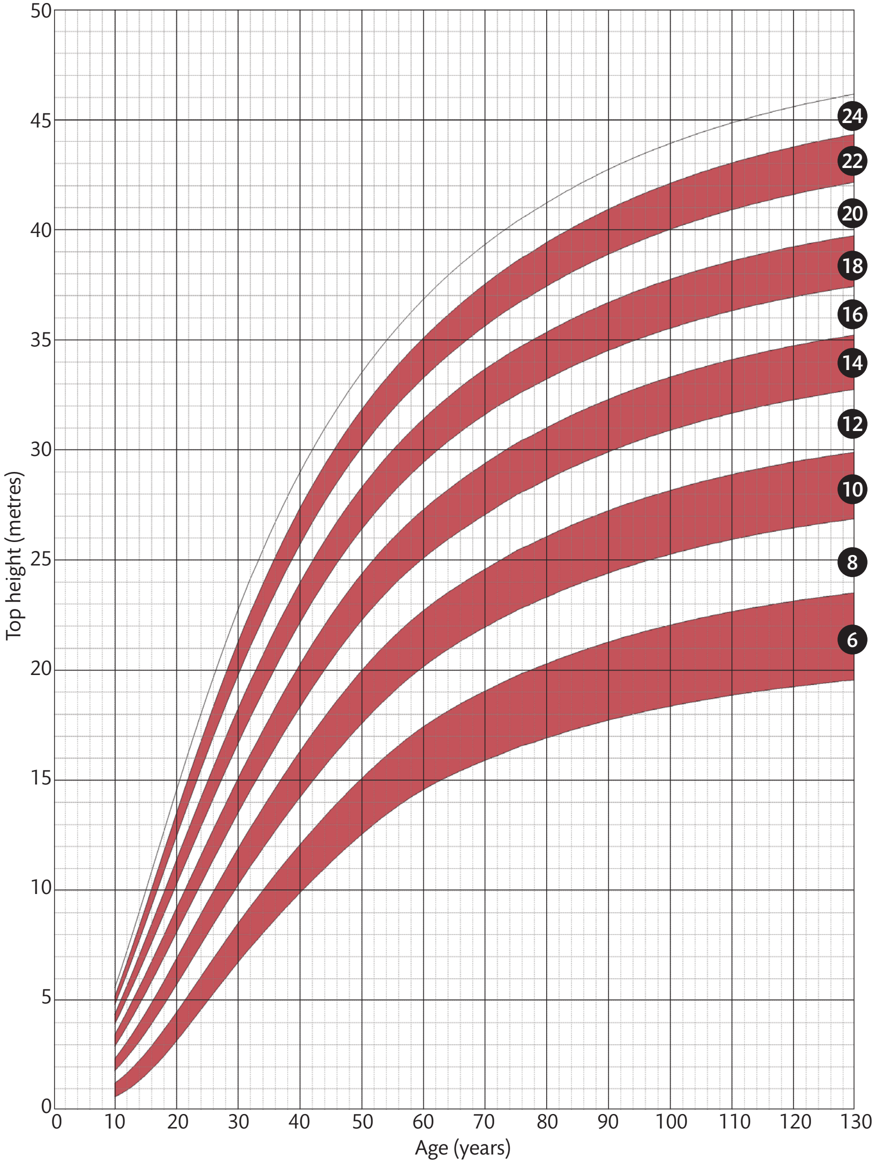


Table 6 Values taken by production class.

Difference between LYC and GYC (m^3 ha^{-1} yr^{-1})	Production class
6	A++
4	A+
2	A
0	B
–2	C
–4	C–
–6	C––

mean dbh, volume), the equivalent table for yield class 10 would be referred to. Key decisions about management (e.g. time of first thinning where relevant and felling age) would also be based on the yield table for yield class 10. For this example, this would mean that thinning would start later, thinning and felling volumes would be smaller and (generally speaking) felling age would be later than suggested by the GYC assigned to the stand.

Production class would not normally be assessed and assigned separately for individual stands because an assessment for one stand is very susceptible to uncertainty in the measurements, and to the particular growth conditions (height and volume) extant in the stand at the time of assessment – which may not necessarily reflect the longer term trend in growth. Furthermore, if production class were to be assessed for every individual stand, then assessments of LYC would be directly available for all stands and production class would not be needed. More appropriately, an assessment of production class is made for a defined selection or geographical area of stands by:

- making an assessment of GYC in all the selected stands;
- making an assessment of LYC in a statistical sample of the stands;
- comparing the LYC and GYC of the stands where both have been assessed;
- working out the 'mean' production class for the selected stands based on the mean difference between LYC and GYC for the sample.

The sample assessment of LYC as part of a production class survey would still be expensive and difficult in practice. Realistically, cumulative volume production is always expensive to assess because of the cost of accurate stem volume measurements. For this reason, cumulative basal area production has been considered as a surrogate for cumulative volume production in the estimation of production class. However, there is limited evidence to support the assumption that the development of cumulative basal area in stands is a reliable indicator of cumulative volume production.

Cumulative volume or basal area production are also difficult to assess in stands beyond the time of second thinning because records of previous removals of volume or basal area in thinnings will often not be available.

The consequence of these issues is that, in practice, assessments of production class will tend to be limited to stands during the earlier stages of development (first or second thinning at the latest), which may not necessarily reflect longer term productive potential, and will often rely on assessments of patterns in basal area growth, which may not be a reliable indicator of the patterns in volume growth. Thus, on the one hand, production class is potentially very useful in refining the management of stands and forecasting production from them, taking account of local conditions. On the other hand, the problems associated with the reliable assessment of production class may limit its usefulness. Decisions about the application of production class as part of forest management therefore need to be taken with care.

Dependence of yield class on management prescription

As highlighted earlier, a common misunderstanding is that yield class represents the maximum potential volume productivity that a tree species can achieve on a given site, i.e. irrespective of how the stand is managed. In fact, the values of yield class referred to in Forest Yield often do not represent maximum potential productivity. In many cases, yield class may be close to maximum potential productivity on a given site, but in some cases yield class is defined very differently, depending on how stands of a particular tree species are typically managed.

More correctly, yield class is based on the maximum mean annual increment (MAI) that can be achieved by a stand of trees of a given tree species, growing on a given site and, crucially, managed according to a specified prescription. This is particularly the case for GYC. Furthermore, predictions of maximum MAI in yield tables will not always match the quoted yield class, depending on the management prescription that has been specified.

These points are well illustrated by the yield tables for poplar included in Forest Yield. For example, Figure 8 shows the development of MAI with age as given in three yield tables for poplar, all with a quoted yield class of 10 and based on a no-thinning regime. The thinning regime is the same for the three yield tables, but the assumed initial spacings are different, taking values of 2.7 m, 4.6 m and 7.3 m. (See ‘Initial spacing’, page 42, and ‘Range of initial spacings in Forest Yield’, page 43, for more information about the initial spacings represented in the yield tables in Forest Yield.) It is clear from Figure 8 that the maximum MAI for the three initial spacings is different. Maximum MAI is highest for the narrowest spacing (2.7 m), at 23.2 m^3 per hectare per year, and lowest at the widest spacing (7.3 m), at 10 m^3 per hectare per year. The timing of maximum MAI also varies, from 29 years for 2.7 m spacing to 39 years for 7.3 m spacing.

For the example poplar yield curves in Figure 8, maximum MAI is only equal to the quoted yield class of 10 for an initial spacing of 7.3 m and is significantly higher than the quoted yield class for the narrower spacings. This illustrates how maximum MAI can vary in yield tables for the same tree species grown on the same site when managed according to different prescriptions (in this example, different initial spacings). It is also evident that the quoted yield class for these example yield tables (yield class 10) does not represent the absolute maximum volume productivity for the tree species on a given site. In this example based on the poplar yield tables, this is because the GYC curves were constructed based on an assumed standard management prescription of 7.3 m initial spacing with no thinning. One interpretation of yield class for the narrower spacings is that the GYC (based on top height) is always 10, but LYC takes a different value; for example, LYC could be taken as 24 (rounded from 23.2 m^3 per hectare per year) for the initial spacing of 2.7 m illustrated in

Figure 8 The development of mean annual increment (MAI) with age in yield tables for poplar, yield class 10, based on a no-thinning regime and initial spacings of 2.7 m, 4.6 m and 7.3 m.

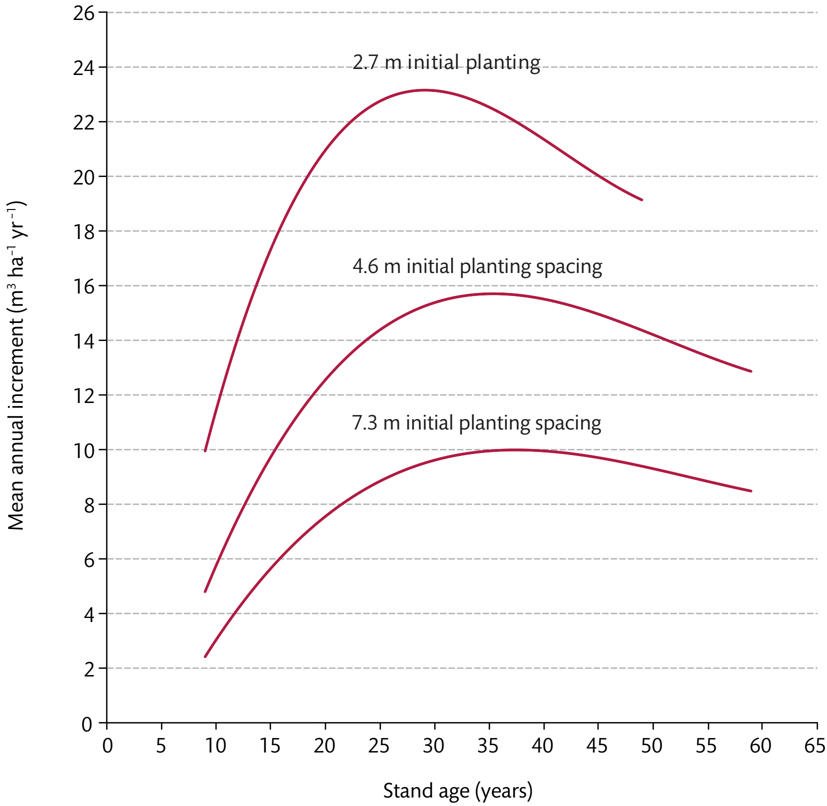


Figure 8. (See 'Standard management prescriptions in Forest Yield', page 61, for an explanation of the selection of initial spacing and thinning treatments in standard management prescriptions for tree species.)

The example given above for poplar represents an extreme case. However, variations in maximum MAI with management prescription can be found generally in yield tables for other tree species. An example is given in Table 7 for Sitka spruce. The table gives values for maximum MAI as reported in Sitka spruce yield tables for a quoted yield class of 12, and for various management prescriptions. For Sitka spruce, the 'standard' management prescription is based on an initial spacing of 1.7 m and intermediate thinning starting at the recommended age for first thinning (see 'Thinning treatment', page 47 and 'Standard management prescriptions in Forest Yield', page 61, for a detailed description). Maximum MAI varies between 10.6 and 12.4 m^3 per hectare per year and the age of maximum MAI varies between 54 and 61 years. Typically, maximum MAI decreases as the initial spacing is increased. Variations with thinning treatment are more complex but the inclusion of a delay to the start of thinning or an initial line thinning generally involves a modest reduction in maximum MAI compared with standard thinning. For narrow initial spacings, treatments based on no thinning generally have lower maximum MAI compared with standard thinning treatments.

Table 7 Examples of maximum MAI and timing as given in yield tables for General Yield Class 12 Sitka spruce.

Management prescription	Maximum MAI (m^3 ha^{-1} yr^{-1})	Age of maximum MAI (years)
Standard thinning, 1.7 m initial spacing	12.0	59
Standard thinning, 0.9 m initial spacing	12.4	57
Standard thinning, 2.0 m initial spacing	11.7	60
Standard thinning, 3.0 m initial spacing	10.6	61
No thinning, 1.7 m initial spacing	11.0	54
10 year delay to standard thinning, 1.7 m initial spacing	11.9	59
Standard thinning but with initial line thinning (1 row in 3), 1.7 m initial spacing	11.9	60

Allowing for changes in growth rate

Changes in growth rate may be accounted for by combining the current growth rate with an 'adjusted age'. An estimate of the 'adjusted age' of a stand of trees can be obtained through the use of annual top height increment tables, which are available for a limited range of conifer species (Tables A2.1 to A2.7, Appendix 2), in combination with standard GYC curves.

In order to use annual top height increment tables, both the current stand height growth rate (height increment) and the current stand top height must be known. The current height increment may be derived from successive top height assessments made a few years apart. However, a height increment estimated in this way could be subject to a large error due to the relatively low precision of top height assessments when based on small sample sizes. A more reliable measure of height increment may be obtained by estimating the average representative internodal length for the immediately preceding years.

The estimates of current stand top height and height increment are used to obtain an estimate, from the appropriate top height increment table, of the current GYC of the stand, adjusted for recent growth rate. The 'adjusted age' is then derived from the top height/age curves, using the estimate of GYC generated from the top height increment table and the measured top height.

For example, assume that a 39-year-old stand of Scots pine has a top height of 15.0 m, and that the average height increment of the stand has been in the region of 37 cm per year for each of the past 4 years. Simply using top height and age, the GYC of the stand is estimated as 10 m^3 ha^{-1} yr^{-1}. However, reference to Table A2.1 in Appendix 2 indicates that the GYC of a stand of Scots pine with a top height of 15.0 m and a current height increment of 37 cm per year is 12 m^3 per hectare per year. Referring to the GYC curves for Scots pine, an average stand of trees of yield class 12 would be expected to achieve a top height of 15.0 m at age 33 years. This is the 'adjusted age' of the stand.

Further examples of the use of top height increment tables are given in Examples 3 and 4 of the 'Manipulating yield table results' section of the Forest Yield user manual.