Forestry Commission

Forest Yield

A handbook on forest growth and yield tables for British forestry

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Introduction

Yield models are one of the foundations of forest management. They provide essential information about the patterns of tree growth and potential productivity that can be expected in forest stands of different tree species, with varying growth rates, when managed in different ways. Yield models are essential for demonstrating that ongoing and intended management is consistent with the principles of sustainable forestry. The outputs of yield models support many other calculations and models relevant to the evaluation of forests and forestry. These include analyses of the development of forest structure at the stand and landscape scales, the modelling of timber and wood properties, the estimation of forest biomass and carbon stocks, the modelling of forest greenhouse gas balances and the economic evaluation of forest policies and forest management options.

This handbook is a companion to the computer software 'Forest Yield: a PC-based yield model for forest management in Britain'. It provides an introduction to the essential theory of forest growth and yield, with emphasis on the implications for their practical application and the interpretation of outputs. It also includes a comprehensive description of the specific yield tables included in Forest Yield in terms of tree species, growth rate and management prescriptions represented. Many of the Forest Yield tables were developed some decades ago but they are still highly relevant to forest planning and management in Britain. They are in daily use by forest managers and practitioners when making decisions about the future management of a forest, whether it is an individual stand of trees or a whole estate. They are also applied when forecasting future levels of production and making commitments to supply timber markets, and when planning and scheduling forest operations.

Overview of the Forest Yield tables

The Forest Yield tables have been developed for use in British forestry. They present estimates of stand growth and yield, based on data collected by the Forestry Commission

'Forest Yield: a PC-based yield model for forest management in Britain' provides easy and flexible digital access to yield tables for British forestry, based on those originally published in the Forestry Commission Booklet *Yield models for forest management*. For more information, go to: www.forestry.gov.uk/forestyield

since the 1920s. Yield tables have been constructed for all the major forest species in Britain using data gathered from a network of permanent sample plots and thinning and spacing experiments for a wide variety of management prescriptions.

The yield tables are designed mainly for application to even-aged silvicultural systems. They have limited application to forest stands with more complex structure and silvicultural practice, for example uneven-aged stands of trees – this is a subject of ongoing research and development. Individual yield tables are specified by a combination of: tree species, yield class and management prescription.

Tree species

The Forest Yield tables can be applied to around 150 tree species currently growing in the British Isles (see Appendix 1 of the Forest Yield user manual for more information). Species that were historically considered to be 'commercial' generally have their own set of yield tables. Other species listed in Appendix 1 of the user manual, for which models have not been developed, are mapped to these more 'commercial' species on the basis of growth and silvicultural characteristics.

Forest Yield also includes new yield tables for Sitka spruce, which can be used as an alternative to the originals. These are based on the preliminary outputs of a dynamic growth and yield model which is being developed by the Forestry Commission and is currently in use as a research tool. The new tables may be particularly useful for application to Sitka spruce stands managed according to prescriptions not covered in the original yield tables, and in providing improved predictions for unthinned stands.

Yield class

Yield class is an index used in Britain of the potential productivity of even-aged stands of trees. It is based on the maximum mean annual increment of cumulative timber volume achieved by a given tree species growing on a given site and managed according to a standard management prescription. It is measured in units of cubic metres per hectare per year (m^3 ha^{-1} yr^{-1}). This handbook includes a thorough explanation of the concept of yield class and its application (see 'Productivity and yield class', page 21).

Management prescription

In general, the Forest Yield tables represent one silvicultural system: even-aged, single species stand management. Within this system, a range of management prescriptions is considered. The prescriptions are defined in terms of a combination of assumed initial tree spacing and a programme of thinnings. This is used to represent stands planted or established at different densities and thinned in various ways, including initial line thinnings, as well as stands that are left unthinned. Details of the different management prescriptions described in Forest Yield are given in 'Management regimes' (page 41).

Interpreting yield tables

The Forest Yield software is used to display yield tables based on information entered for tree species, yield class and management prescription. The results are displayed as yield tables, with content laid out as illustrated in Tables 1 and 2.

Information on the tree species, yield class and management prescription used to select the yield table are summarised in the yield table header.

The yield tables contain values for all the main growth and yield variables for a sequence of stand ages. There are two table formats. The first format is for displaying yield tables involving thinning as part of the management prescription (e.g. Table 1). The format is designed to show results for both standing trees and thinnings. The second format is for displaying yield tables for unthinned stands (e.g. Table 2), and only shows values for standing trees and a summary for volume lost to mortality.

Yield tables for thinned and unthinned stands display values for:

- stand age
- top height
- number of trees per hectare
- mean diameter at breast height (dbh)
- basal area per hectare
- mean volume per tree
- volume per hectare
- per cent mortality (applies to unthinned stands only)
- mean annual increment (MAI).

Yield tables for thinned stands display values for standing trees and thinnings separately and also show cumulative production of basal area and volume. For unthinned stands, values for cumulative volume production are not displayed and values for mean annual increment are based on standing volume rather than cumulative volume, i.e. not including volume effectively lost due to mortality.

The yield tables display values for different stand attributes in a series of columns, with values for different ages forming the rows. The values shown in the columns of the yield tables are described in Box 1 and full explanations of the different attributes are given in later sections of this handbook.

When displaying a yield table, the values for number of trees, basal area and volume are normally expressed for a stand area of one hectare so that they represent per-hectare results. However, a different stand area can be specified in Forest Yield if required, in which case, values will be displayed that relate to the specified area.

Table 1 The yield table for yield class 10 Scots pine planted at 1.4 m spacing and subject to an intermediate thinning regime.

1st thin delay	1st thin type	1st thin age	2nd thin age	Max MAI age	Sub thin type	Late thin age	Late thin cycle
0 years	Intermediate	25 years	30 years	70 years	Intermediate	N/A	N/A

Stand age (years)	Top height (m)	Maincrop after thinning					Yield from thinnings					Cumulative production		MAI
		Trees per ha	Mean dbh cm	BA $m^2\ ha^{-1}$	Mean vol m^3	Vol $m^3\ ha^{-1}$	Trees per ha	Mean dbh cm	BA $m^2\ ha^{-1}$	Mean vol m^3	Vol $m^3\ ha^{-1}$	BA $m^2\ ha^{-1}$	Vol $m^3\ ha^{-1}$	Vol $m^3\ ha^{-1}\ yr^{-1}$
20	8.1	4186	9	25	0.02	64	0	0	0	0.00	0	25	64	3.2
25	10.2	2187	11	20	0.04	77	1481	10	13	0.02	35	33	112	4.5
30	12.1	1433	13	20	0.07	101	753	11	8	0.05	35	40	171	5.7
35	13.9	1056	16	22	0.13	132	377	14	6	0.09	35	48	237	6.8
40	15.6	831	19	25	0.20	167	225	16	5	0.16	35	55	307	7.7
45	17.1	681	23	27	0.30	204	150	19	4	0.23	35	63	379	8.4
50	18.5	575	26	30	0.42	240	106	22	4	0.33	35	69	450	9.0
55	19.8	497	29	32	0.55	273	79	25	4	0.45	35	75	518	9.4
60	20.9	436	31	34	0.70	304	60	28	4	0.58	35	80	584	9.7
65	22.0	391	34	35	0.85	331	46	31	3	0.73	33	85	644	9.9

Table 2 The yield table for unthinned yield class 10 Scots pine planted at 1.4 m spacing.

Stand age (years)	Top height (m)	Maincrop after thinning					Yield from thinnings	
		Trees per ha	Mean dbh cm	BA $m^2\ ha^{-1}$	Mean vol m^3	Vol $m^3\ ha^{-1}$	Per cent mortality	MAI vol $m^3\ ha^{-1}$
20	8.1	4186	9	25	0.02	64	0	3.2
25	10.2	3667	11	33	0.03	112	0	4.5
30	12.1	3125	12	37	0.05	170	1	5.7
35	13.9	2713	14	42	0.09	231	3	6.6
40	15.6	2345	16	46	0.12	293	5	7.3
45	17.1	2030	18	50	0.17	352	7	7.8
50	18.5	1771	20	53	0.23	408	9	8.2
55	19.8	1560	21	56	0.29	459	12	8.3
60	20.9	1392	23	59	0.36	505	14	8.4
65	22.0	1259	25	62	0.43	546	15	8.4
70	22.9	1143	27	63	0.51	582	17	8.3
75	23.7	1056	28	65	0.58	613	18	8.2
80	24.5	985	29	67	0.65	640	19	8.0
85	25.1	927	31	68	0.71	663	20	7.8
90	25.6	881	32	69	0.77	683	21	7.6

Note: definitions of the column headings in Tables 1 and 2 are given in Box 1.

Box 1 Definitions of the attributes used in standard yield tables.

Age Stand age in years. Typically, a yield table presents values at 5-year intervals, starting 5 years before the age of first thinning. However, this format may vary in individual tables, depending on the timing of thinnings. Forest Yield can also be set to display annual values.

Top height Top height is the mean height, in metres, of the 100 trees of largest dbh per hectare. (See also 'Height', page 16.)

Trees per ha Number of measurable trees per hectare, i.e. only those with a dbh of at least 7 cm overbark. In yield tables for thinned stands, the numbers of trees per hectare are presented separately for trees comprising the main crop and for trees assumed to be removed in thinning operations. (See also 'Number of trees', page 16.)

Mean dbh Quadratic mean dbh (diameter at breast height), in centimetres, of the measurable trees. In yield tables for thinned stands, mean diameters are presented separately for trees comprising the main crop and for trees assumed to be removed in thinning operations. (See also 'Diameter', page 17.)

BA Basal area (BA) per hectare is the sum of the basal areas, in square metres, of the individual measurable trees, expressed on a per-hectare basis. (The basal area of an individual tree is the cross-sectional area of the tree at its breast height point.) In yield tables for thinned stands, values of basal area per hectare are presented separately for trees comprising the main crop and for trees assumed to be removed in thinning operations. In all yield tables, values are also given for cumulative basal area. (See also 'Basal area', page 18.)

Mean vol Mean volume per tree is the volume per hectare, in cubic metres, divided by the number of trees per hectare. In yield tables for thinned stands, values of mean volume per tree are presented separately for the trees comprising the main crop and for trees assumed to be removed in thinning operations. (See also 'Volume', page 18.)

Vol Volume per hectare is the sum of stem volumes, in cubic metres, for individual measurable trees to a top diameter of 7 cm overbark, expressed on a per-hectare basis. In yield tables for thinned stands, values of volume per hectare are presented separately for trees comprising the main crop and for trees assumed to be removed in thinning operations. In all yield tables, values are also given for cumulative volume. (See also the sections on 'Volume' and 'Measuring volume productivity', starting on pages 18 and 22 respectively.)

Per cent mortality Only applicable to yield tables for unthinned stands. Per cent mortality is defined as the cumulative volume lost due to mortality expressed as a percentage of the sum of stand cumulative volume production and cumulative volume lost due to mortality.

MAI Mean annual increment (MAI) is the cumulative per hectare volume production divided by the stand age. It is the average rate of volume production achieved from time of planting up to a given stand age. (See 'Measuring volume productivity', page 22.) However, for unthinned stands values for mean annual increment are based on standing volume rather than cumulative volume, i.e. they do not include volume effectively lost due to mortality.

Note: volume is assessed to a minimum top diameter of 7 cm overbark, or the point at which no main stem is distinguishable – whichever comes first. The minimum timber length to 7 cm top diameter considered to have measurable volume is 1.3 m. The minimum dbh of a tree considered to have measureable volume is 7 cm.

Limitations of the yield tables

A characteristic stand growth pattern and a particular management prescription have been assumed in the construction of each yield table. Any deviation from the assumed growth pattern or management prescription will result in different stand characteristics compared with predictions. Direct comparisons of the results for an actual stand with predictions from a yield table may not be meaningful because it is inevitable that the growth of an individual stand will vary in some way from the patterns assumed in a yield table. However, the trends of growth which are given in a yield table can be used to estimate the probable development of any particular stand. This is explained in more detail in the section on 'Manipulating yield table results' in the Forest Yield user manual and 'Productivity and yield class' in this handbook.

Applications of yield tables

Forest managers need information on current and future rates of growth for two main reasons:

1. It affects the way their stands may be treated.
2. It is an essential requirement for planning purposes. Yield tables are models of stand growth and yield and they are the basis for forest planning, often by means of economic analysis.

Yield tables are available for a wide range of thinning treatments and initial plant spacings. A forest manager can use the yield tables to compare the results of alternative treatments, before deciding how to manage a particular stand or group of stands. The final choice of regime will be influenced by several external factors, such as the availability of markets for particular roundwood sizes and labour, and possible methods of extraction, along with wider management objectives.

A forest manager may also need to forecast the timber production from the forest, so suitable markets can be arranged and harvesting work planned. In this case, the forest manager first chooses the most appropriate yield table. This is then used to forecast the production from the stand by referring to the stand volume assortment tables (see Appendix 1, Tables A1.1 to A1.3) as a guide to the likely produce assortment. The Forest Yield software provides an easy and flexible way to estimate volume assortments directly from yield table information, as explained in the 'Displaying volume assortments' section of the Forest Yield user manual.

Comparing management prescriptions

When establishing new stands of trees, a forest manager needs to decide the initial tree spacing, or number of trees per hectare. Once the stand is growing, the forest manager needs to decide whether or not to thin it. If the stand is to be thinned it is necessary to decide when thinnings are to be carried out, how frequently, how heavily and in what way. Finally, the forest manager needs to decide when to fell the stand. Yield tables help in making all these decisions.

For example, consider a forest manager who is planning to plant a site with Sitka spruce at 2 m spacing or 3 m spacing. The forest manager expects the stand to grow at yield class 12 for at least 40 years, if it is left unthinned. Comparison of the yield tables for Sitka spruce, yield class 12, unthinned, at 2 m and 3 m spacing (see Tables 3 and 4) shows an expected difference in total volume production at age 40 of about 62 m^3, while the mean diameter of the trees increases from about 20 cm to about 26 cm. This information can assist in making a decision about which spacing best suits the particular situation.

Table 3 The yield table for Sitka spruce, yield class 12, unthinned, at 2 m spacing.

Species	Yield class	Thinning treatment	Max MAI age	Initial spacing	Stand area
Sitka spruce	12	No Thinning	55	2.0	1.00

Age yrs	Top ht m	Maincrop after thinning					Yield from thinnings	
		Trees/ha	Mean dbh cm	BA m^2/ha	Mean vol m^3	Vol m^3/ha	Percentage mortality	MAI vol m^3/ha
35	14.9	1911	18	49	0.16	301	2	8.6
36	15.4	1871	18	50	0.17	318	2	8.8
37	15.8	1832	19	51	0.18	335	2	9.0
38	16.3	1792	19	52	0.20	352	3	9.3
39	16.7	1753	20	53	0.21	369	3	9.5
40	17.2	1714	20	54	0.23	386	3	9.7
41	17.6	1680	20	55	0.24	402	4	9.8
42	18.0	1647	21	55	0.25	418	4	9.9
43	18.4	1613	21	56	0.27	433	4	10.1
44	18.8	1580	21	57	0.28	449	4	10.2
45	19.2	1547	22	58	0.30	465	5	10.3
46	19.5	1518	22	58	0.32	479	5	10.4
47	19.9	1490	22	59	0.33	493	5	10.5
48	20.3	1461	23	59	0.35	506	6	10.6
49	20.6	1433	23	60	0.36	520	6	10.6

Table 4 The yield table for Sitka spruce, yield class 12, unthinned, at 3 m spacing.

Species	Yield class	Thinning treatment	Max MAI age	Initial spacing	Stand area
Sitka spruce	12	No Thinning	61	3.0	1.00

Age yrs		Maincrop after thinning					Yield from thinnings	
	Top ht m	Trees/ha	Mean dbh cm	BA m^2/ha	Mean vol m^3	Vol m^3/ha	Percentage mortality	MAI vol m^3/ha
35	14.2	993	23	41	0.24	239	2	6.8
36	14.7	985	24	43	0.26	256	2	7.1
37	15.1	972	24	44	0.28	273	3	7.4
38	15.6	960	25	46	0.30	290	3	7.6
39	16.0	947	25	47	0.32	307	3	7.9
40	16.4	935	26	48	0.35	324	3	8.1
41	16.9	922	26	50	0.37	341	3	8.3
42	17.3	910	27	51	0.39	357	4	8.5
43	17.7	898	27	52	0.41	372	4	8.7
44	18.1	886	28	53	0.44	388	4	8.8
45	18.4	874	28	54	0.46	404	4	9.0
46	18.8	862	28	55	0.49	420	4	9.1
47	19.2	851	29	55	0.51	434	4	9.2
48	19.5	840	29	56	0.53	449	5	9.3
49	19.9	829	30	57	0.56	463	5	9.4

The choice of treatment will generally need to take account of the economics of the alternatives. For example, the forest manager could compare the likely relative economic value of different treatment options. The first step would be to construct a price–size curve giving the value per cubic metre of standing timber for a range of mean diameters or mean volumes. The yield tables show the mean size of the trees, so by using the price–size curve, the standing value of each thinning and the final felling can be calculated. The calculations must take account of possible changes in the price–size curve with treatment (e.g. using wider spacing may produce knotty, wide-ringed timber which is of lower value), and consider differences in costs (e.g. an unthinned stand may not need any roads before it is felled).

In addition, the forest manager may have specific markets for timber in different top diameter classes. In such situations, the manager may wish to estimate the likely volumes of roundwood in one or more of these discrete top diameter classes. Forest yield can provide this information. (See the section on 'Displaying volume assortments' in the Forest Yield user manual.)

Yield tables do not always reflect the precise growth of individual stands, but they do accurately describe the differences between different treatments, and consequently are very suitable for the comparison of treatments.

Application to mixed-species and multi-storeyed stands

When using Forest Yield as a management tool for mixed-species stands, or for stands with two or more storeys, these situations are most conveniently dealt with by separating the component species or storeys and deriving an effective net area of each, based either on the proportion of the canopy occupied or on the proportion of total basal area for each component. See Example 5 in the 'Manipulating yield table results' section of the Forest Yield user manual.

Estimating volume assortments

Predicted thinning and felling volumes from yield tables can be subdivided into volume in large-diameter roundwood and smaller roundwood, as defined by selecting appropriate top diameters. Forest Yield enables the estimation of such volume assortments (see the 'Displaying volume assortments' section of the Forest Yield user manual).

Volume assortments can also be calculated by referring to an appropriate stand volume assortment table (see Appendix 1, Tables A1.1 to A1.3). Based on mean diameter as an input (which is given in the yield tables), the assortment tables give the percentage of the volume which is likely to be composed of roundwood of more than the stated minimum top diameter. The use of volume assortment tables is discussed in more detail in *Forest* *mensuration: a handbook for practitioners.* The tables given in Forest mensuration are based on stands planted at spacings of about 1.4 m to 1.8 m, and thinned at the marginal thinning intensity (see 'Volume removed in thinnings (thinning yield)', page 54). If the stand has been treated differently, e.g. planted at 3 m, or not thinned, then the volume assortments may be slightly different. It is obviously not practical to produce assortment tables for all treatments, but three stand volume assortment tables covering the range of likely treatments are given in Appendix 1, Tables A1.1 to A1.3. Table A1.1 is recommended for application to most thinned stands, and also for fellings of unthinned stands planted at (or respaced to) spacings of about 3 m; Table A1.2 is recommended for unthinned stands planted at spacings of about 2 m or less; while Table A1.3 is recommended for thinned stands planted at (or respaced to) spacings of about 3 m. Table A1.2 is also likely to be most suitable for estimating the assortments:

- from a line thinning;
- from stands which have received a single line thinning and no subsequent thinning;
- from stands which have had repeated crown thinnings.

Forest Yield automatically selects an appropriate assortment table to apply in conjunction with the predictions of a selected yield table.

In all three assortment tables, a minimum 3 m log length is assumed for any roundwood with a top diameter greater than 7 cm.

It is important to note that the assortment tables in Forest Yield do not distinguish between tree species. Rather, they have been designed for general application to even-aged stands of coniferous tree species grown in Britain. Application of these assortment tables to stands with a more complex structure (e.g. uneven-aged stands), or to stands of broadleaved tree species, should therefore be undertaken with caution.

Production forecasting

Forecasts of production from a forest can be calculated by totalling the forecasts of production from each individual stand within a forest. For each stand, the following information is needed: species, age, yield class, area, past treatment including initial tree spacing, and proposed future management. The species and age are generally relatively easy to ascertain, and the assessment of yield class is discussed in 'Productivity and yield class' on page 21, with more detailed information given later in this handbook. Accurate maps are required to determine the area, and it is most important that this is the area 'fully stocked' with trees, i.e. excluding roads, rides, and any other unproductive areas in terms of timber (e.g. ponds). This fully stocked area is sometimes called the net area, to distinguish it from the gross (or total) area. When only gross areas are available (and there is no other relevant information), a notional deduction of 15% is recommended to allow for roads, rides and other unproductive areas that are not mapped. Finally, for an accurate forecast, details of past management must be recorded, and the proposed future management must be decided. This information is needed to select the most appropriate yield table to represent each stand in the forecast.

The expected volume and other stand characteristics at each thinning can be read directly from the yield table. The values for the main crop represent the standing trees after thinning. If information is required about volume and other stand characteristics for a clearfelling at a specified stand age, the results for the main crop should be referred to. If a yield table also includes a thinning at the stand age for the intended clearfelling, the results for the thinning should be combined with those for the main crop. Alternatively, the Forest Yield software includes an option to display results for the main crop before thinning (see the 'Preferences' section in the Forest Yield user manual).

The forecast is likely to differ from the actual production for two reasons:

1. No stand grows exactly as predicted.
2. The actual management of stands is unlikely to be the same as that planned.

It is very difficult to estimate the effect of these variations, but they can easily alter the forecast for an individual stand by 20% or more. Take the case where there is an error in an estimate of the yield class of a stand. This might occur for a number of reasons, for example because height measurements used in the estimation of yield class were not taken accurately, or because the estimated yield class was assessed accurately but the actual yield class of the stand is different. Suppose the estimated yield class of the stand is 10 but the true yield class is 12, then its volume production will be 20% more than expected. If this additional volume is not taken out in the thinnings, then the final felling volume could be more than 40% above the expected value (i.e. from the yield table). The volume (product) assortments may also be very different. However, errors in individual stands may cancel out over whole forests.

Measures of forest growth

The growth and development of forest stands can be characterised by various quantitative values, including number of trees per hectare, measures of tree height, mean diameter, basal area per hectare, volume per hectare, and various other derived quantities. The main descriptive values are defined below and further information can be found in *Forest mensuration: a handbook for practitioners*. Some additional information can also be found in the Glossary.

Number of trees

The number of living trees in an area of woodland is usually expressed on a per hectare basis. As a stand of trees grows the number of trees per hectare generally reduces. This is influenced by several factors including competition-induced mortality as individual trees grow at different rates, mortality due to pests and diseases, windthrow and wind snap, and thinning and harvesting operations.

Number of trees is usually assessed using a series of sample plots of known area and counting the number of living trees in each plot. The number of trees per hectare can then be calculated by dividing the total number of trees counted in all of the sample plots by the total area (in hectares) of those same plots. Further details on assessing number of trees are given in Section 4.3 of *Forest mensuration: a handbook for practitioners*.

Height

Tree and stand height are expressed in metres. The precision of height assessments of individual trees depends on the precision of the measurement instrument used. By convention, assessments are rounded down to the nearest 0.1 m. Calculated values of stand height (e.g. top height) are usually rounded to the nearest 0.1 m up or down as appropriate.

The total height of a standing tree is the vertical distance from the base of the tree to the uppermost point (tip). The total length of a felled tree is the straight line distance from the base to the tip. The total length of felled trees should be measured with a tape. Note that the total height of a tree may be different from the actual length of the tree from its base to its tip, because of the different conventions used in their measurement. This is very likely to occur when a tree is leaning. The total height of young standing trees can be measured with graduated poles. The total height of other standing trees should be measured with a manual or electronic hypsometer or clinometer, and the instructions supplied with the instrument should be followed. Each tree should ideally be measured from two opposite sides, and the measurements averaged. The distance of the observation points from the tree should be in the region of 1 to 1.5 times the height of the tree. When measuring the heights of trees it is important to remember that accurate use of hypsometers or clinometers requires training, checking, and, most of all, practice. The assessment of total height can sometimes be difficult, especially in larger broadleaves. Further details on height measurement are given in Section 3.3 of *Forest mensuration: a handbook for practitioners*.

The timber height of a tree (or the timber length) is the distance from the base of the tree to the lowest point on the main stem where the diameter is 7 cm overbark. In hardwoods and occasionally in conifers this point may alternatively be the 'spring of the crown', i.e. the lowest point at which no main stem is distinguishable. It should be measured in exactly the same way as total height.

The top height of a stand is the average total height of the 100 trees of largest diameter at breast height per hectare. Usually, top height is assessed by measuring the total heights of a sample of these trees. A top height sample tree can be identified as the tree of largest diameter at breast height in a 0.01 ha sample plot. This is not necessarily the tallest tree in the plot.

Diameter

The dbh is the diameter, in centimetres, at the breast height point on a tree. Trees with a dbh of less than 7 cm are assumed to have no volume and are conventionally classified as 'unmeasurable'.

The breast height point is the point on the tree which is 1.3 m above ground level. On sloping ground, this is the ground level on the upper side of the tree, while on leaning trees on level ground, this is the ground level on the underside of the tree. Further details on the conventions for measuring dbh are given in Section 3.1 of *Forest mensuration: a handbook for practitioners*.

The mean dbh of a stand or of a group of trees is the diameter at breast height related to a tree of mean basal area. Mean dbh is therefore calculated as a quadratic mean (or root mean square) of dbh values rather than as an arithmetic mean. (If the arithmetic mean was used, the mean dbh would not be consistent with the mean basal area.) Unmeasurable trees are normally excluded from this calculation, but if they are included this should be clearly stated. The mean diameter can be calculated as follows, using a calculator or computer:

1. Square each dbh.
2. Add all the squared values together.
3. Divide by the number of trees, to give the mean squared dbh.
4. Calculate the square root of this value, to give the mean dbh.

Basal area

The basal area of an individual tree is the cross-sectional area of the stem of the tree at its breast height point:

$$ba = \frac{\pi \times dbh^2}{40000}$$

where ba = basal area in m^2 and dbh = diameter at breast height in cm.

The basal area of a stand is the sum of the basal areas of all the trees in the stand. All basal areas should be recorded in square metres, or square metres per hectare.

The basal area of a stand can be estimated using one of two methods:

1. using a relascope.
2. assessing basal area based on measurements of dbh for all, or a sample of, individual trees.

Further details on the assessment of basal area are given in Section 3.2 of *Forest mensuration: a handbook for practitioners*.

Volume

The volumes presented in Forest Yield are stem timber volumes overbark. The conventional top diameter limit for timber volume is 7 cm overbark, or the point at which no main stem is distinguishable, whichever comes first. As a consequence trees with a dbh of less than 7 cm are normally ignored when estimating volume.

In general volumes are recorded in cubic metres to two or three significant figures, as required.

Further details on the estimation of volume are given in Section 3.5 of *Forest mensuration: a handbook for practitioners*.

Volume assortment

Total stem volumes can be separated into volumes of larger timber, to stated top diameters, and volumes of smaller timber. This is done using stand volume assortment tables, which use mean diameter (from yield tables) as an input to give the percentage of the total volume which is likely to be in timber of more than a given stated minimum top diameter. Their use is discussed in more detail with supporting examples in the ‘Displaying volume assortments’ section of the Forest Yield user manual, and in Appendix

1 of this handbook. Further information is given in Section 3.7 and Appendix 1 of *Forest mensuration: a handbook for practitioners*.

Biomass

Estimates of timber biomass can be obtained for tree stems, either individually or at the stand level (see Example 7 in the 'Manipulating yield table results' section of the Forest Yield user manual). Multiplying the stem volume, obtained from Forest Yield, by an estimate of the nominal specific gravity (basic density) for the species in question gives a value for stem biomass. Useful sources for estimates of basic density are *The strength properties of timber*[1] and Section 5 of the Forestry Commission *Woodland Carbon Code: carbon assessment protocol* (www.forestry.gov.uk/carboncode/monitoring).

Estimates of the biomass contained in other parts of the tree (i.e. branches, stem tip, twigs, foliage and roots) can be obtained by applying various equations, examples of which are presented in Section 5 of the Forestry Commission *Woodland Carbon Code: carbon assessment protocol*.

The units for estimates of biomass, as obtained above, are oven-dry tonnes.

Carbon

Having obtained a biomass estimate, the carbon content (in tonnes) can be estimated simply by dividing by 2 (or multiplying by 0.5) (see Forestry Commission Technical Paper 4, *The carbon content of trees*). Examples of the estimation of the carbon content of trees are presented in Example 7 of 'Manipulating yield table results' in the Forest Yield user manual and in Section 6 of the *FC Woodland Carbon Code: carbon assessment protocol*.

[1]Lavers, G.M. (1983) *The strength properties of timber.* Building Research Establishment Report. Third edition, revised by G.L. Moore. HMSO, London.

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.

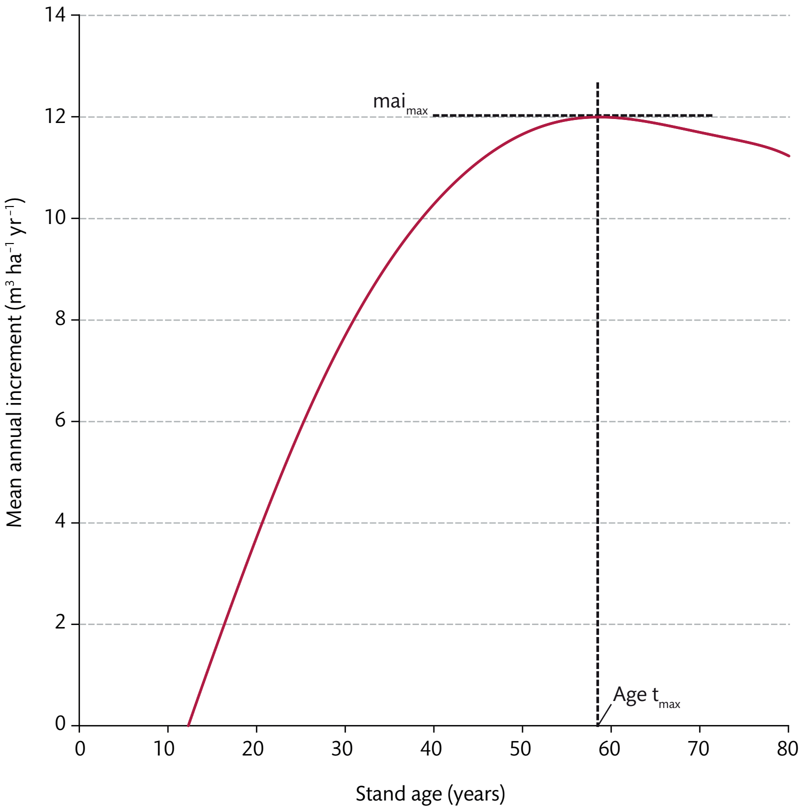
Mean annual increment (MAI) is the average rate of cumulative volume production up to a given year. In even-aged stands MAI is calculated by dividing cumulative volume production by age. For example, for the Sitka spruce stand in Table 5, the mean annual increment up to age 44 years is $658 \div 44 =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

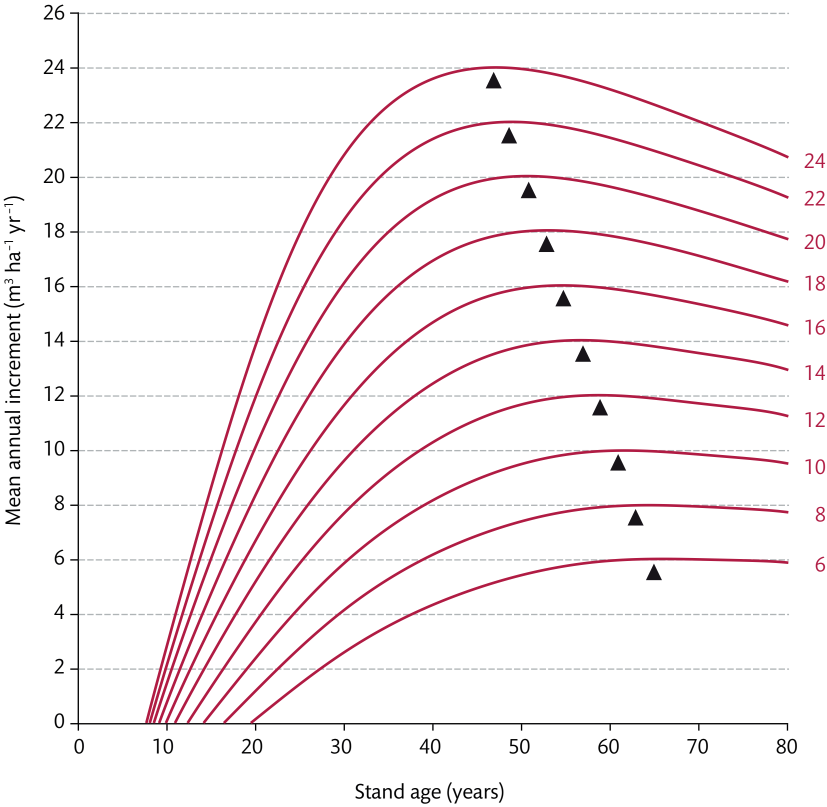


Yield class

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.

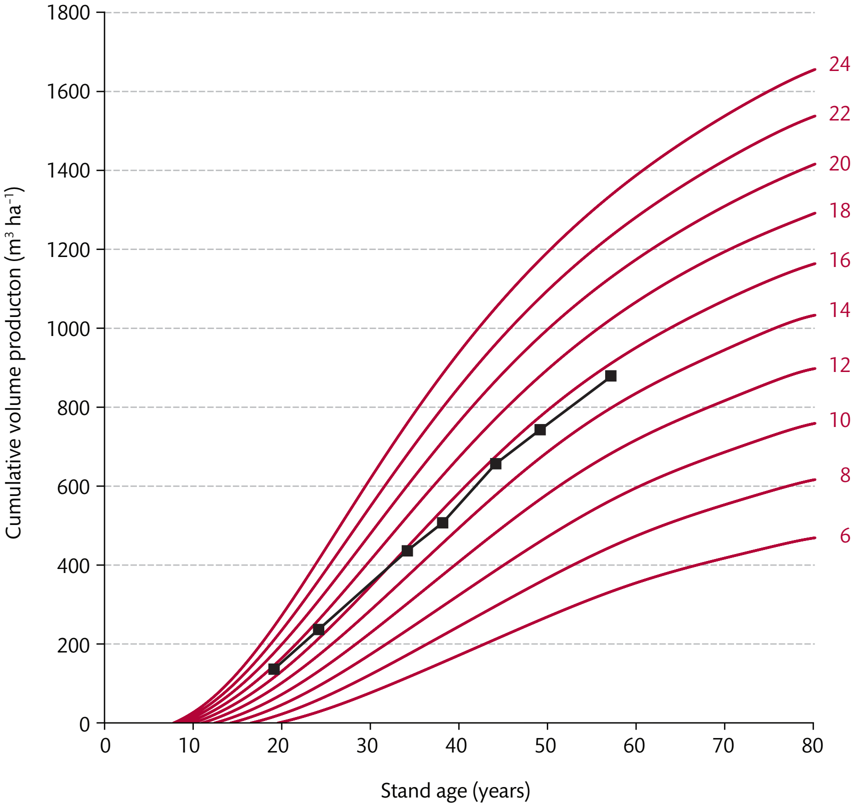
General Yield Class

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).

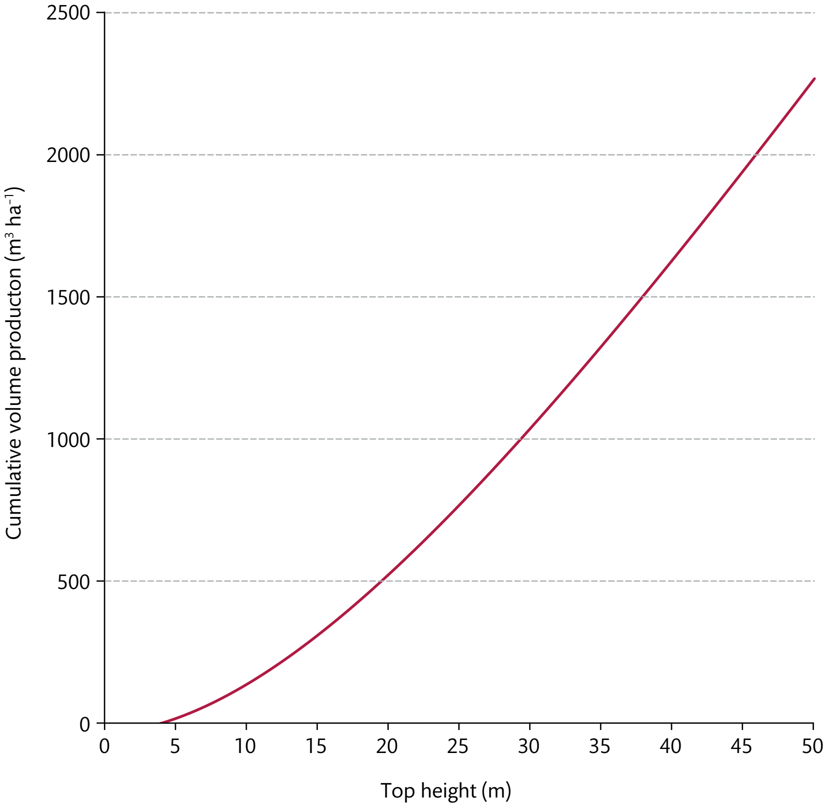
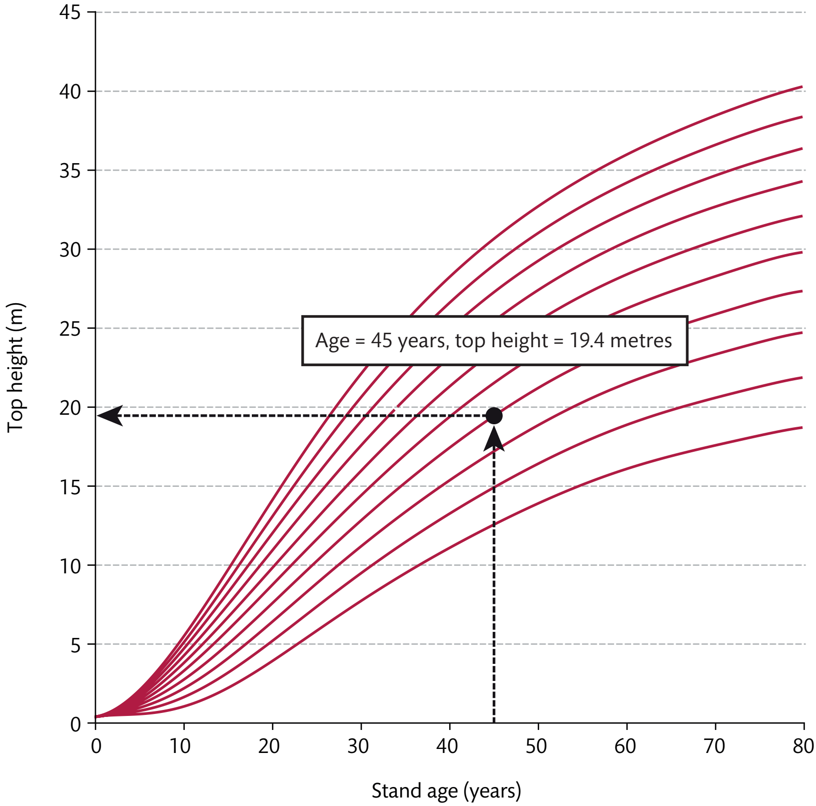
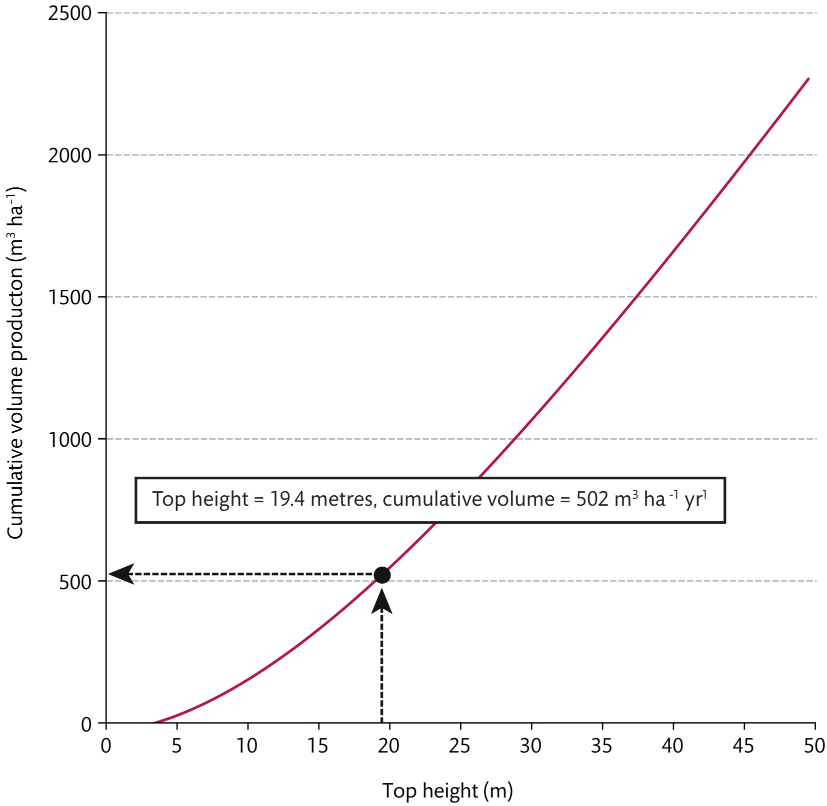


Figure 5a–c Illustrations of the method used to construct a family of curves for cumulative volume production with respect to age for different yield classes using the master table method.

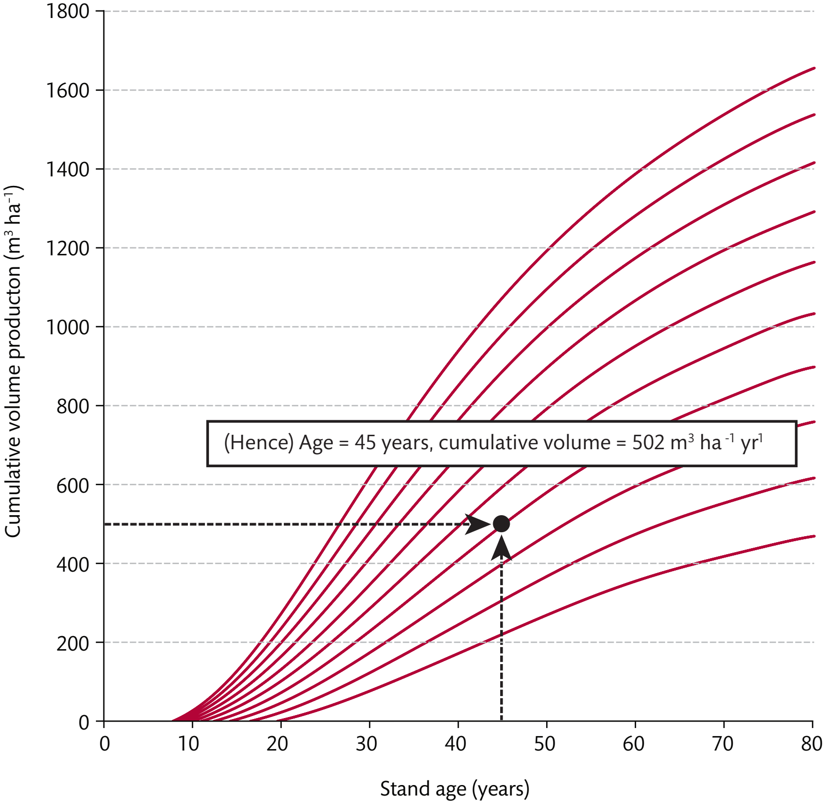
a) A family of curves is constructed by hand to describe development of stand top height with age. The curve representing a particular productivity class is selected and estimates of top height can be read off for a sequence of stand ages.



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.



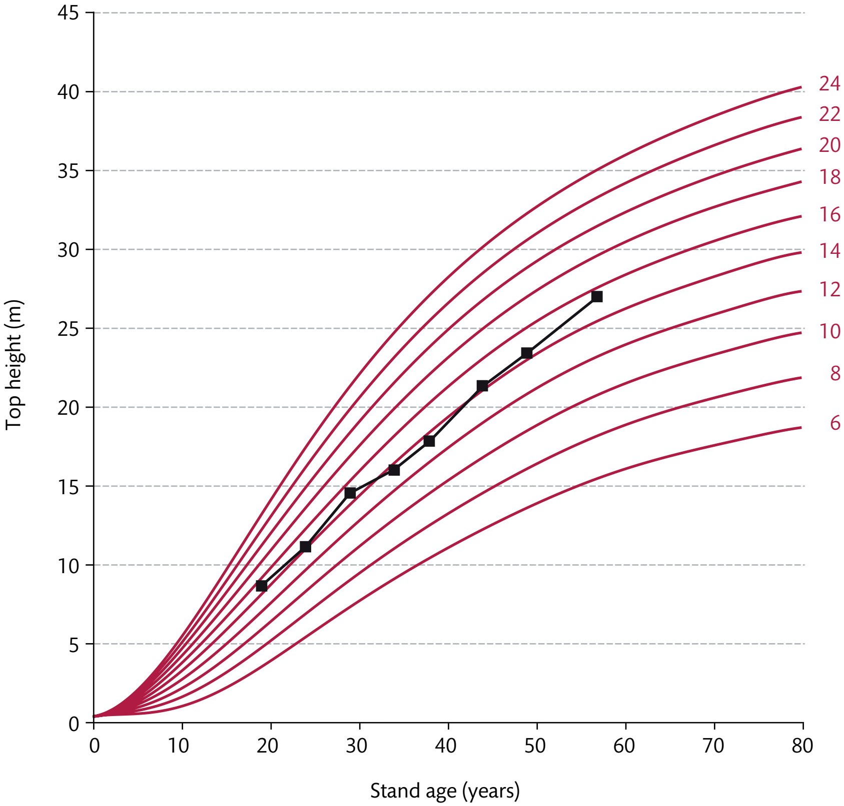
c) The cumulative volume production estimates can be plotted directly against stand age to provide the relevant curve for the particular productivity class of interest. The same approach may be adopted to construct curves for other productivity classes.



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.

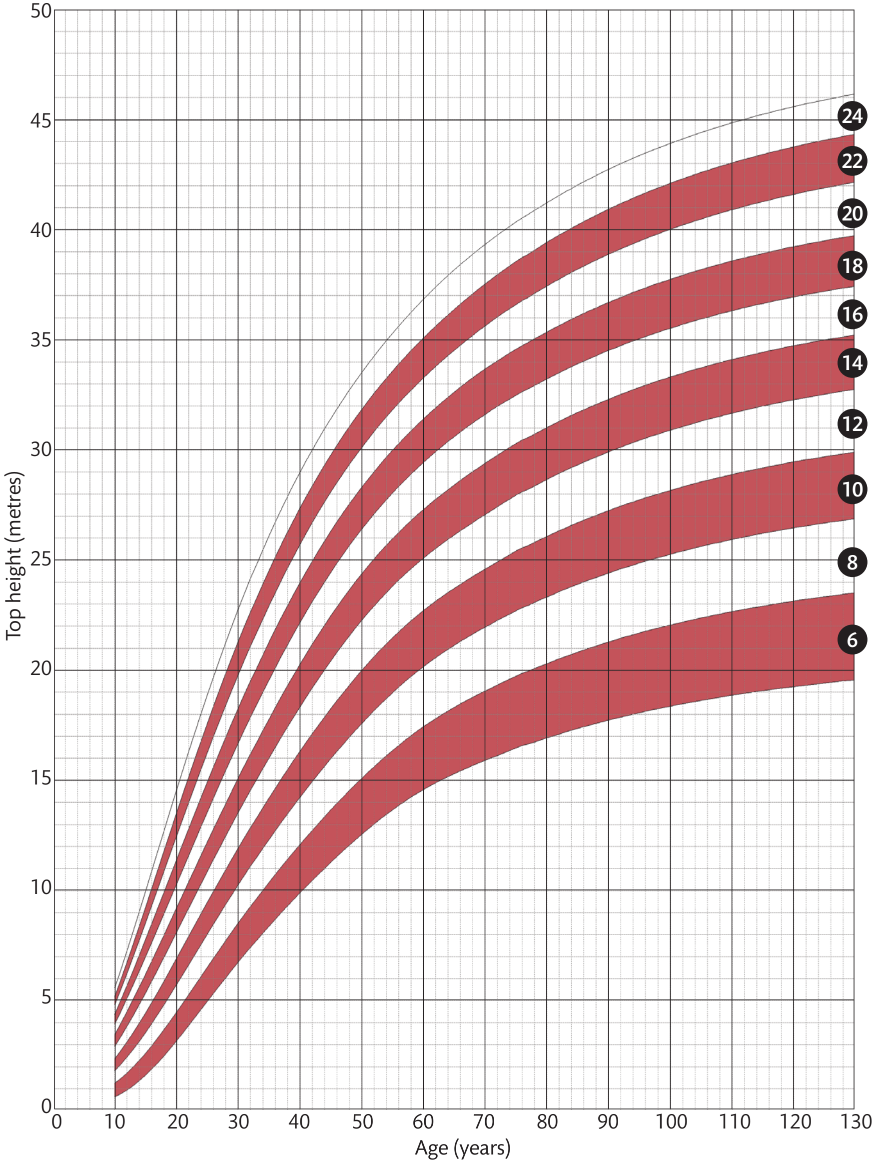


Table 6 Values taken by production class.

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.

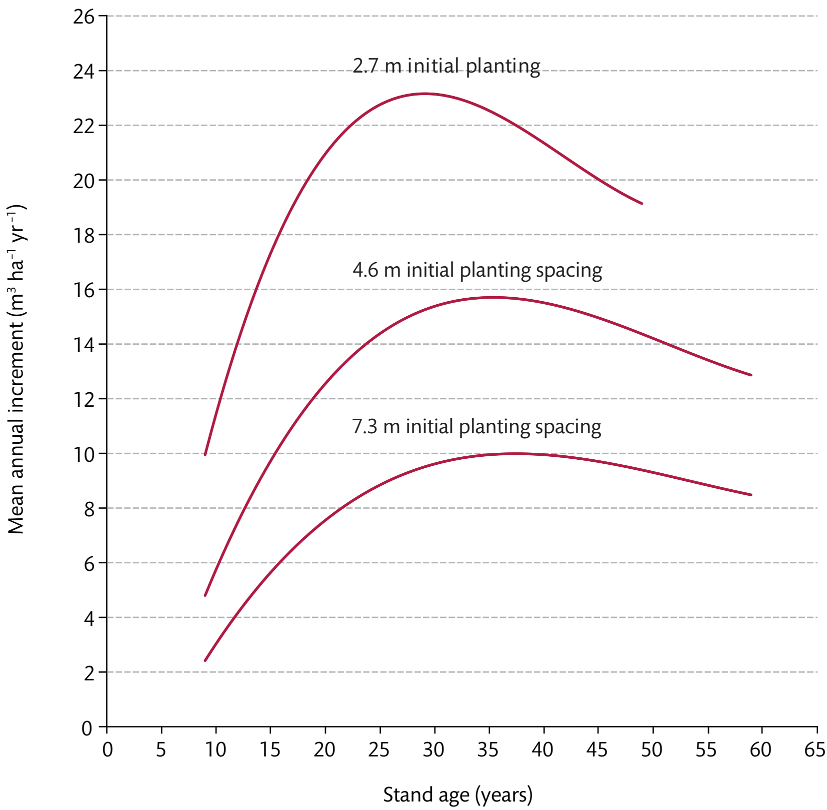


Figure 8. (See 'Standard management prescriptions in Forest Yield', page 61, for an explanation of the selection of initial spacing and thinning treatments in standard management prescriptions for tree species.)

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.

Management regimes

As explained in the previous section, the reliable application of yield models as part of forest management requires the stands of trees being managed to be assessed in terms of their productive potential, usually expressed as yield class. However, this is only the first step in the process. It is also necessary to consider how stands have been managed in the past and/or what options may be considered for future management of stands. Decisions about management will have a strong bearing on the quantities and dimensions of timber produced and the timescales involved, but they also depend on silvicultural policies and practices applying to the forest areas under consideration.

In general, the Forest Yield tables represent one silvicultural system: even-aged, single-species stand management. Within this system, a wide range of management prescriptions can be considered. The management prescriptions in Forest Yield are defined in terms of an assumed initial tree spacing and a programme of thinnings. This section describes in detail how different management prescriptions have been constructed in terms of combinations of initial spacing and thinning treatment. First the assumptions about initial planting spacing of trees (or density of regeneration) are explained, then the various patterns of thinning represented in the yield tables are described. Finally, full details are given of the different management prescriptions covered by the yield tables.

Initial spacing

Strictly, the Forest Yield tables are for stands formed by planting trees rather than arising from natural regeneration. The vast majority of yield tables also involve an assumption of square planting spacing, so that the spacing between rows of trees is the same as the spacing between trees in each row, forming a perfectly square matrix. In practice, the yield tables can also be applied in situations involving rectangular planting spacing and even natural regeneration, provided that an appropriate equivalent square spacing is selected.

Rectangular planting spacings

An equivalent square spacing can be used to select the most appropriate yield table for a stand which has been planted according to a rectangular planting pattern. If a yield table is to be applied to a stand with rectangular planting spacing, it is possible to estimate an equivalent square spacing using the equation:

$$\text{Equivalent square spacing} = \sqrt{\text{spacing between rows} \times \text{spacing between trees}}$$

This is known as a geometric mean, and the result is the length of the side of a square with the same area as the original rectangle.

For example, if the spacing between rows is 2 m and the spacing between trees in a row is 3 m then the equivalent square spacing is:

$\sqrt{2 \times 3} = \sqrt{6}$ = 2.4495 to four decimal places, or 2.4 m to one decimal place.

Regenerated stands

When a stand has arisen from natural regeneration, an assessment can be made of the initial stocking of the trees. A square spacing equivalent to an initial stocking of trees can be found using the equation

$$\text{Equivalent square spacing} = \sqrt{\frac{10\,000}{N}}$$

where N is the initial stocking of the trees expressed as the number of trees per hectare.

For example, if the initial stocking is 7210 trees per hectare, then the equivalent square spacing is

$$\sqrt{\frac{10\,000}{7120}}$$

$= \sqrt{1.38696} = 1.1777\text{m}$ to four decimal places, or 1.2 m to one decimal place.

Strictly, the application of an equivalent square spacing involves assuming that the regeneration is evenly spread, rather than composed of 'gaps and clumps'. Sometimes dense or clumpy regeneration may be 'respaced'. This involves thinning out some of the regeneration at an early stage in the stand's development (say after 5 years) to give an even distribution of trees. If respacing has been carried out, the stocking of the respaced trees should be used in the calculation of an equivalent square spacing.

Range of initial spacings in Forest Yield

Initial spacings based on imperial measurements

The Forest Yield tables have been developed over many decades and many of them date from the time when measurements were made in imperial units, and trees were planted at spacings measured in feet and inches. A large number of the yield tables are thus based on initial spacings expressed in imperial units, although these are quoted in Forest Yield as the nearest metric spacing in metres to one decimal place. This means that, for a number of yield tables, the quoted 'metric spacing' is in reality the nearest 'imperial spacing' (to the nearest 6 inches). For example, in most cases the yield tables with an assumed initial spacing displayed as 1.7 m are in fact based on a spacing of 5 feet 6 inches (1.6764 m to four decimal places).

Table 8 lists the range of imperial spacings used in the Forest Yield tables along with the metric spacing quoted in the software. Also shown are the initial stocking densities implied by these spacings, which are based on the original imperial spacing. These are the initial densities used in the construction of the yield tables, rather than the metric conversion. This means that the initial number of trees per hectare assumed in a yield table can be slightly different to that suggested by the metric spacing. For example, basing the initial stocking directly on a quoted metric spacing of 1.8 m would give 3086 trees per hectare, while referring to the original imperial spacing (6 feet, 1.8288 m to four decimal places) gives 2990 trees per hectare.

Initial spacings based on metric measurements

From the mid-1970s onwards, yield tables were constructed based on assumed initial spacings based on true metric measurements. Table 9 lists the range of metric spacings used in the Forest Yield tables along with the initial stocking densities implied by these spacings.

Initial spacings in new Sitka spruce yield tables

The most recent yield tables to have been constructed are the new alternative set for Sitka spruce based on outputs from a computer-based dynamic growth model. The range of initial spacings represented in these yield tables is very similar to those listed in Tables 8 and 9, except that all the spacings are true metric (e.g. for these yield tables, a quoted spacing of 1.7 m really does mean an initial spacing of 1.7 m, not 5 feet 6 inches).

Table 8 Initial spacings and stocking based on imperial measurements.

Original imperial spacing in feet (′) and inches (″)	Quoted metric spacing (m)	Initial stocking (Number of stems per hectare)
3′ 0″	0.9	11 960
4′ 0″	1.2	6 727
4′ 6″	1.4	5 316
5′ 0″	1.5	4 306
5′ 6″	1.7	3 558
6′ 0″	1.8	2 990
8′ 0″	2.4	1 682
9′ 0″	2.7	1 329
15′ 0″	4.6	478
24′ 0″	7.3	187

Table 9 Initial spacings and stocking based on metric measurements.

Initial spacing (m)	Initial stocking (Number per hectare)
2.0	2 500
2.1	2 268
2.2	2 066
2.5	1 600
2.6	1 479
3.0	1 111
4.5	494

Table 10 lists the range of initial spacings used in the new Sitka spruce yield tables in Forest Yield along with the initial stocking densities implied by these spacings. The assumed standard spacing is 1.7 m, for compatibility with the original yield tables.

Table 10 Initial spacings and stocking used in new yield tables for Sitka spruce.

Initial spacing (m)	Initial stocking (Number per hectare)
0.9	12 346
1.2	6 944
1.4	5 102
1.5	4 444
1.7	3 460
1.8	3 086
2.0	2 500
2.1	2 268
2.2	2 066
2.4	1 736
2.5	1 600
2.6	1 479
2.7	1 372
3.0	1 111
4.5	494
4.6	473
7.3	188

Unusual spacings in Forest Yield

Forest Yield includes a small number of yield tables that are not based on the usual assumption of an initial square planting spacing. These are:

- yield tables for Corsican pine, yield classes 14 and 16, involving rectangular spacing and windrows;
- yield tables for Douglas fir, yield classes 14 and 16, planted at 1.7 m initial spacing but with assumptions about understocking due to poor establishment.

The additional yield tables for Corsican pine, of yield class 14 and 16, are based on an assumed rectangular planting spacing of 2 m between rows and 3 m between trees in each row, which has been practised in some parts of East Anglia. These yield tables also allow for the presence of 'windrows' (lines formed of heaps of tree stumps which were dug up at the end of the previous rotation in order to limit risk of fungal infection of the new stand). The windrows are assumed to occur at regular intervals in place of a planted row of trees. Yield tables were constructed to represent the presence of windrows every 30, 40, 50 or 60 m.

The yield tables for Douglas fir are based on an assumed square planting spacing of 1.7 m, but also involve assumptions about understocking due to exceptionally high losses of trees during establishment. The motivation for constructing these yield tables was not documented at the time but was probably an attempt to represent the growth and yield of Douglas fir stands in the Forest of Dean, in which these conditions had occurred.

Table 11 lists the planting spacings and associated initial stocking densities for these unusual yield tables. The initial stocking for the Douglas fir case reflects the understocking issue. The extent of the understocking represented in these yield tables appears to be moderate – about 90% of the stocking that would be expected in a fully stocked stand of 1.7 m before thinning.

Table 11 Initial spacings used in unusual yield tables.

Species	Initial spacing (m)	Initial stocking
Corsican pine	2 m × 3 m with windrows every 30 m	1 556 (allowing for windrows)
	2 m × 3 m with windrows every 40 m	1 583 (allowing for windrows)
	2 m × 3 m with windrows every 50 m	1 600 (allowing for windrows)
	2 m × 3 m with windrows every 60 m	1 611 (allowing for windrows)
Douglas fir	1.7 m (understocked)	2 500 (at time of first thinning)

Thinning treatment

The thinning treatments represented in Forest Yield fall into four broad classes:

1. No thinning.
2. A single line thinning during the rotation.
3. A single ‘neutral’ thinning during the rotation.
4. A sequence of thinnings over the rotation.

While this list includes a wide range of possible thinning prescriptions, it is not comprehensive. It should be stressed that Forest Yield is designed mainly for application to even-aged stands of trees in the UK. It has limited applications to forest stands with more complex structure and silvicultural practice, for example uneven-aged stands. This is a subject for ongoing research and development.

Yield tables involving no thinning

This type of yield table is based on the assumption that no thinning operations are carried out during the lifetime of the stand. For most initial spacings, leaving stands unthinned will result in the loss of trees due to mortality caused by competition, primarily for light. The yield tables take account of this, with the numbers of trees per hectare generally becoming fewer with stand age. Losses of basal area per hectare and volume per hectare due to mortality are also taken into account. Only at the widest initial spacing (7.3 m) do some of the yield tables show no reduction in numbers of trees.

The new yield tables for Sitka spruce involve significantly revised assumptions about levels of tree survival in unthinned stands, based on data collected since the original yield tables were constructed.

Yield tables involving a single line thinning

This type of yield table is based on the assumption that a single line thinning operation is carried out during the rotation, after which no further thinning interventions are made in the stand. (This sort of thinning is sometimes referred to as a ‘solitary line thinning’.)

Yield tables involving a solitary line thinning were originally constructed for lodgepole pine, Norway spruce and Sitka spruce at 2 m initial spacing only and only for selected yield classes. When referring to the new Sitka spruce yield tables (see the ‘Preferences’ section in the Forest Yield user manual), the full range of square spacings (see Table 10) and yield classes is represented.

Pattern of line thinning

Only one pattern of line thinning is represented in Forest Yield involving the removal of 1 row in every 3 standing originally. Figure 9 illustrates two examples of simple line thinnings, based on removal of 1 row in every 3 standing, and 2 rows in every 8 standing.

Line thinning based on removal of 1 row in every 3 was of great interest at the time most of the yield tables were constructed but is not particularly representative of contemporary thinning practice involving line thinning. This is worth bearing in mind when choosing a yield table with a management prescription that most closely represents what is actually being planned or practised (see 'Selecting a yield table', page 63).

More complicated patterns of line thinning are possible. One example is known as 'line and chevron' thinning, which entails removing rows of trees as in a line thinning, and also removing lines of trees across the removed rows according to an arrowhead (or chevron) pattern as illustrated in Figure 10. Such extreme systematic thinning types are distinctly out of fashion in present times. However, they were very important as an approach for initiating thinning and beginning to break up and diversify the structure of the large areas of uniform conifer stands that had been established in the UK during the twentieth century. A more contemporary thinning treatment involves a combination of line thinning and selective thinning in the matrix (i.e. the blocks of trees left standing between removed rows). However, types of line thinning other than the removal of 1 row in 3 are not represented in the yield tables included in Forest Yield.

Figure 9 An illustration of two possible patterns of line thinning: a) 1:3 – i.e. one row removed in every three, and b) 2:8 – i.e. two adjacent rows removed in every eight. (Only the first of these thinning patterns is included in the yield tables available in Forest Yield.)

a b

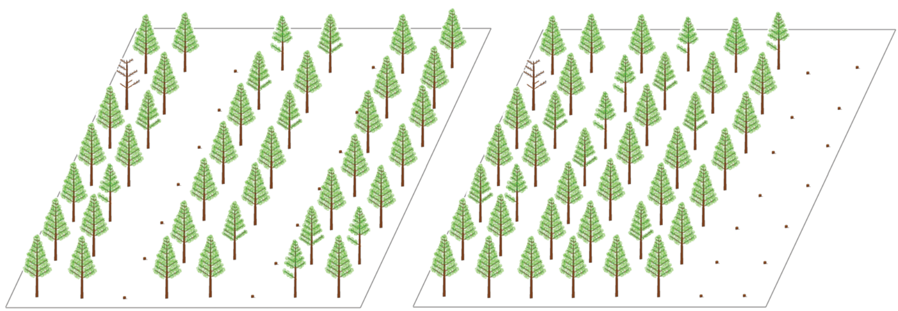
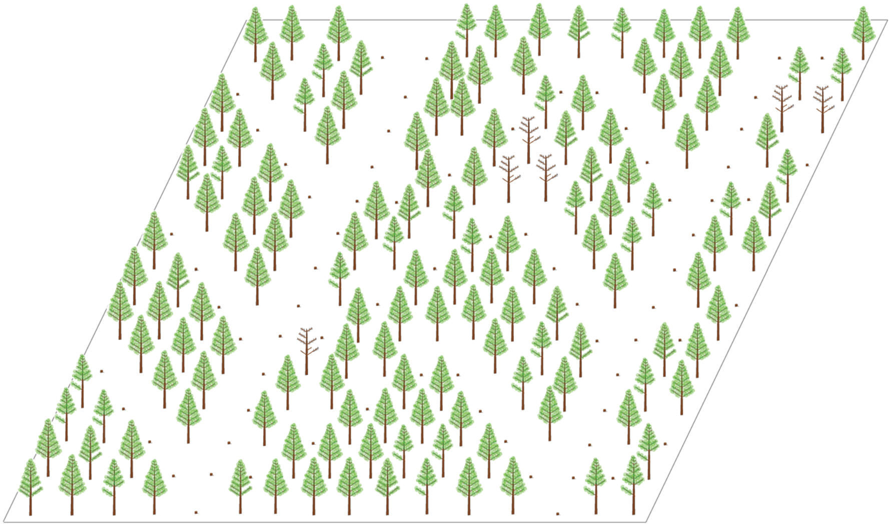


Figure 10 An illustration of a 'line and chevron' thinning pattern.



Timing of line thinning

Two types of yield table for solitary line thinning treatments are included in Forest Yield, based on different assumptions about the time at which the thinning takes place:

- Thinning takes place at 'management table thinning age'.
- Thinning takes place 5 years after 'management table thinning age'.

The definition of management table age is explained fully in the section on 'Yield tables involving a sequence of thinnings' (see page 51). In essence it involves selecting a stand age for an initial thinning which results in a desired level of standing volume per hectare being left after thinning. To achieve this, the value of management table thinning age changes depending on the tree species, yield class and initial spacing.

Yield tables involving a single neutral thinning (poplar only)

This type of yield table is based on the assumption that a single 'neutral' thinning operation is carried out during the rotation, after which no further thinning interventions are made in the stand. (This sort of thinning can be referred to as a 'solitary neutral thinning'.)

Yield tables involving a solitary neutral thinning were constructed for poplar only, at initial spacings of 2.7 m and 4.6 m. (There are also yield table for poplar planted at 7.3 m spacing, but these are based on a no-thinning prescription.)

Pattern of neutral thinning in models for poplar

A neutral thinning involves selecting trees as thinnings such that their size/diameter at breast height (dbh) distribution is the same as that of the trees left after thinning. (At the stand level, this means that the mean dbh of the thinnings is the same as the mean dbh of the trees left after thinning). There are several ways in which this might be achieved – one method involves line thinning (or some other spatially systematic pattern of thinning) while another method relies on selecting the trees for thinning completely at random. The neutral thinning pattern assumed in the construction of the yield tables for poplar was not documented at the time; however, the predictions are unlikely to be sensitive to these details due to the initial spacings involved.

It was assumed that 50% of the live standing trees are removed in the single neutral thinning.

Timing of neutral thinning in models for poplar

The yield tables for solitary neutral thinning treatments included in Forest Yield are based on the assumption that the thinning takes place when the stand attains a top height of 18 m. The reason for selecting this target top height for determining the time of first thinning was not documented when the models were developed. However, in his 1994 publication, Forestry Commission Technical Paper 6, *Provisional yield tables for poplar in Britain*, John Christie wrote:

> *Poplars require free growth to attain their maximum rates of growth, as they are more sensitive to competition than other species* (Forestry Commission Bulletin 62 Silviculture of Broadleaved woodlands). *During field work undertaken for this project it was noticed that their crowns do not intermingle, as is the case with other species of broadleaved trees. ... To ensure both unrestricted diameter growth in the closer-spacing models and an early return from thinnings, the [close-spacing] models were assumed to receive a systematic thinning when the percentage crown occupancy was estimated to be about 90 per cent*.

It is not possible to establish for certain whether a similar rationale was adopted for the poplar yield tables in *Yield models for forest management*. However, inspection of the provisional yield tables involving thinning in Forestry Commission Technical Paper 6, *Provisional yield tables for poplar in Britain*, reveals that the first thinning in the yield tables for 3 m spacing takes place around a stand top height of about 16 m, while in the yield tables for 4 m thinning takes place around a top height of about 12 m. If these values are used to crudely estimate what top height might be expected at 2.7 m spacing (the narrowest spacing included for poplar in the Forest Yield tables), a value just over 17 m is obtained. This suggests that the target top height of 18 m might have been selected to ensure that thinning is scheduled to take place around the time that poplar trees close canopy when planted at 2.7 m spacing. Note that the use of this constant target top height will mean that thinning takes place before canopy closure in poplar stands planted at spacings wider than 2.7 m.

Yield tables involving a sequence of thinnings

The majority of the Forest Yield tables are of this type and they involve either a sequence of 'selective' thinnings, or an initial line thinning followed by a sequence of 'selective' thinnings. The detailed thinning prescriptions are defined by:

- the type of selective thinning carried out;
- the stem volume per hectare removed in thinnings ('thinning yield');
- the timing of the first thinning;
- the time between thinnings ('thinning cycle').

Types of selective thinning

'Selective' thinning types all involve selecting certain sorts of tree for removal as thinnings, while favouring other sorts of tree for retention, allowing them to grow on. Selective thinning methods therefore require a way of classifying the different sorts of trees forming a stand, which is then used to make decisions about which trees to choose as thinnings and which to keep in the stand. Silviculturists have developed many such tree classification systems; for over 50 years the Forestry Commission has referred to a relatively simple system as illustrated in Figure 11. This identifies seven classes of tree in terms of their competitive status (or 'dominance class') and/or their broad stem quality characteristics (see Table 12).

Different types of selective thinning treatment can be defined, depending on how these different classes of trees are emphasised for thinning or retention. The management prescriptions in the yield tables in Forest Yield involve two types of selective thinning:

1. Crown thinning.
2. Intermediate thinning.

Intermediate thinning combines ideas from the crown thinning type with those for another type, called low thinning. All three types are described in Table 13. Yield tables representing a sequence of intermediate thinnings are the most common variety to be found in Forest Yield.

Table 12 A simple way of categorising trees in a stand (see Figure 11)

Number	Tree class	Description
1	Dominant	The tallest trees in the stand but not necessarily the straightest
2	Co-dominant	Trees in the upper canopy but slightly below the level of the dominant trees
3	Sub-dominant	Trees which do not hold a place in the upper layer of the canopy but which still retain access to light
4	Suppressed	Trees which have their leading shoots directly under some portion of the crown of another tree and as a consequence are denied access to light
5	Wolf	Mis-shapen trees with large crowns which both outgrow and damage their neighbours
6	Whips	Slender stems without stability which damage neighbouring trees when they sway
7	Dead and dying	Suppressed or diseased trees that have died or are dying, including leaning and blown trees

Figure 11 Illustration of the seven classes of tree forming a stand.

Table 13 Descriptions of different selective thinning types.

Thinning type	Description
Low	Trees are removed primarily from the lower canopy, i.e. suppressed and sub-dominant trees, and from among the smaller diameter trees. The aim of low thinning is to concentrate potential for growth onto the larger diameter trees by removing competing smaller trees. Low thinning tends to result in relatively dense stands of evenly distributed trees, although clumps of dominant trees can develop. Wolf trees, which are usually of relatively large diameter, are not usually removed in a strict low thinning. Small-diameter whips will often be included in low thinnings. Normally the mean diameter of early thinnings will be quite small compared to that of the stand before thinning – in extreme cases the mean dbh of thinnings might be only one half that of the remaining standing trees. As the number of trees removed in a low thinning is increased, trees are removed from among progressively larger diameter classes so that the mean dbh of thinnings gets bigger.
Crown	Trees are removed primarily from the upper canopy, i.e. containing a mix of dominants and co-dominants, together with some trees from other classes. The aim of a crown thinning is to give selected dominant trees freedom to grow more rapidly by gradual removal of competing trees. Some trees may also be removed from the lower canopy if they are in the proximity of selected dominants. The choice of the selected dominants is not fixed but judged subjectively at successive thinnings. Poorly formed wolf trees will be identified for removal in early thinnings. Whips will be removed if they interfere with the crowns of selected dominants. A true crown thinning regime cannot be maintained throughout the rotation of a stand of trees because repeated crown thinnings tend to result in too few dominants remaining to select from, while smaller trees get left in dense groups and growth becomes suppressed. As a result, later crown thinnings are often closer to intermediate thinnings. The mean dbh of early crown thinnings will be very similar to the mean dbh of the remaining standing trees, and sometimes greater.
Intermediate	This involves a combination of the ideas behind low and crown thinning (hence the name intermediate). As in low thinning, suppressed and sub-dominant trees are removed to favour the growth of the larger trees; at the same time, as in crown thinning, the canopy is opened up and a uniform stand structure is maintained by breaking up groups of competing dominants and co-dominant trees. Poorly formed wolf trees will be identified for removal in early thinnings. Small-diameter whips will often be included in thinnings. The mean dbh of early thinnings will usually be somewhat smaller than that of the remaining standing trees, but bigger than observed in low thinnings. Intermediate thinning is generally preferred among the selective thinning types, and is the most commonly used, because a pragmatic view of thinning is taken, encouraging the development of better

Thinning type	Description
Intermediate (contd.)	trees in the stand while maintaining diameter growth and developing a fairly open and stable stand structure. At later ages, stands which have been subjected to intermediate thinning will tend to develop into a characteristically grand overstorey of well-spaced, large trees, sometimes referred to as a 'cathedral of trees'.

Volume removed in thinnings (thinning yield)

The volume removed in most selective thinning operations as represented in a particular yield table is fixed at a constant quantity, which is calculated from the yield class for the yield table. The method used to calculate this thinning volume from yield class is based on the assumed existence of a 'marginal thinning intensity', as explained below.

A thinning operation can be described as 'light' or 'heavy', depending on how much basal area or stem volume is removed in the thinning, or how many trees are thinned. 'Thinning intensity' is a measure of the 'lightness' or 'heaviness' of a thinning, usually (but not always) expressed in terms of the proportion of volume per hectare removed when compared with the theoretical marginal thinning intensity.

A very light thinning is likely to result in standing trees remaining densely packed, with the consequence that diameter growth will become reduced and trees may die due to competition. Heavier thinning will release the trees left standing from competition and their diameter increment should increase (or at least not decrease due to competition). However, very heavy thinning is likely to leave only a few trees behind, with the result that the overall increment of the remaining stand (in terms of volume per hectare) will be reduced compared to lighter thinnings. Somewhere between the extremes of very light and very heavy thinning, there should be an 'optimum' intensity of thinning which releases the standing trees from competition and increases their diameter increment, while retaining sufficient growing stock to capture the available light resource and maintain overall stand volume growth.

From the earliest days of the Forestry Commission, trials and experiments formed of groups of permanent mensuration sample plots were established in stands of different tree species to permit the impacts of thinning treatments at different intensities to be investigated. In the 1960s the results of these experiments were analysed to see whether an 'optimum thinning intensity' of the sort discussed above could be identified. The analysis was difficult because the trials and experiments did not conform to a coherent statistical design (in fact they were very diverse), while the main method of analysis at the time involved hand-drawing graphs of stand growth over time and then inspecting them to look for common trends or other consistent features. Despite these difficulties, as reported in Forestry Commission Booklet 16, *Forest management tables*, it was possible to ascertain that total volume production seemed to remain reasonably constant across a fairly wide range of thinning intensities (and indeed thinning types). A broad-brush (and momentous) conclusion was reached, which involved defining an optimum thinning intensity, regardless of tree species, in terms of the yield class of stands. This intensity is frequently referred to as the 'marginal thinning intensity', because it is supposed to be the heaviest intensity of thinning that can be carried out in a stand without compromising the continued growth of the remaining growing stock. The adoption of the marginal thinning intensity as the standard for thinning should also have the effect of maximising diameter increment while maintaining volume production. The results of more recent thinning experiments based on permanent mensuration sample plots broadly support the original definition of marginal thinning intensity.

For a particular stand, the volume removed in a selective thinning at marginal intensity, as generally represented in the yield tables in Forest Yield, can be calculated very simply as:

Volume removed in thinning = 0.7 × GYC × time to next thinning (or 'thinning cycle', years).

For example, if the GYC of the stand is 12 and the thinning cycle is 5 years, then the volume removed in the thinning is:

$0.7 \times 12 \times 5 = 42$ m^3 per hectare

The value of 0.7 times (or 70% of) the yield class is sometimes referred to as the 'annual thinning yield', as it represents the volume that would be removed if thinnings were carried out every year. (For the example this is 0.7 x 12 = 8.4 m^3 per hectare per year.) When thinnings are carried out every 5 years, the volume to be removed is five times the annual thinning yield (sometimes called a 5-year cut); if thinnings were to be carried out every 7 years then the volume to be removed would be seven times the annual thinning yield (a 7-year cut), i.e. for the example:

$0.7 \times 12 \times 7$ or $8.4 \times 7 = 58.8$ m^3 per hectare every 7 years.

Because the marginal thinning intensity is the standard intensity assumed for selective thinnings in the majority of Forest Yield tables (which were once called 'management tables'), it is sometimes referred to as 'management table intensity', or 'MTI'.

Light and heavy thinnings can be expressed as multiples or percentages of MTI; for example a light thinning might be 0.8 MTI or 80% MTI while a heavy thinning might be 1.2 or 120% MTI. For the example above and assuming 5 years between thinnings, these give thinning yields of:

$0.8 \times 0.7 \times 12 \times 5$ or $0.8 \times 8.4 \times 5 = 33.6$ m^3 per hectare for the light thinning; and

$1.2 \times 0.7 \times 12 \times 5$ or $1.2 \times 8.4 \times 5 = 50.4$ m^3 per hectare for the heavy thinning.

Timing of first thinning

In general forestry practice, decisions about when to start thinning (or indeed whether to thin) are often driven by a range of silvicultural and economic considerations. The yield tables in Forest Yield representing a sequence of thinnings cannot cover all possibilities for timing of first thinning, but cover three options:

1. Thinning starts at 'MT thinning age'.
2. Thinning starts 5 years after 'MT thinning age' (MT thinning age + 5 years).
3. Thinning starts 10 years after 'MT thinning age' (MT thinning age + 10 years).

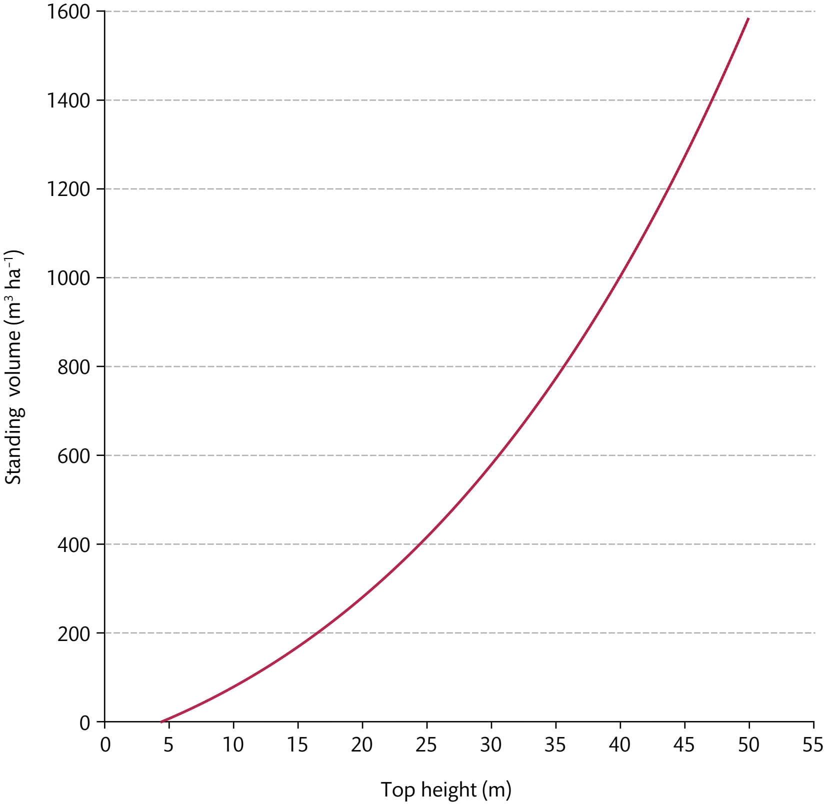
MT (management table) thinning age is effectively a recommended time to start thinning. The value of MT thinning age is selected to result in a desired level of standing volume per hectare being left after thinning, to maintain the growing stock and increment. Additionally, information about general operational policy towards the timing of first thinning was taken into account when constructing the yield tables. Forestry practitioners considered that thinning needed to achieve a minimum mean tree volume and/or dbh, in combination with a minimum target for total per-hectare thinning volume yield. It follows that the timing of the recommended age of first thinning in most yield tables was derived by optimising with respect to three criteria:

1. A target thinning yield, equivalent to Management Table Intensity, see 'Volume removed in thinnings (thinning yield)', on page 54.
2. A target minimum mean tree volume or a target minimum mean tree dbh.
3. The retention of sufficient growing stock to maintain stand volume increment.

In order to establish the target level of growing stock to retain after thinning, for the vast majority of yield tables, a relationship was characterised between the desired level of standing volume per hectare and stand top height, as illustrated in Figure 12. These relationships were developed by graphical analysis of observations of standing volume and top height made in mensuration sample plots. For the most part, decisions about when to thin and how much volume to remove in these plots were down to the silvicultural judgements of the foresters managing the sample plots. The levels of standing volume were therefore the outcome of a process in which foresters aimed to develop a growing stock over time according to a pattern which met forest management objectives. The application of a characteristic relationship between standing volume and top height in determining the time to start thinning is therefore a quantitative method for achieving a defined outcome for forest management. The standard relationship between standing volume and top height varies slightly with initial spacing, and for a few tree species, specific relationships were characterised for individual yield classes.

The method used to determine MT thinning age in the new Sitka spruce yield tables was similar to the approach described above, but also took account of other factors, such as the space occupied by tree crowns at time of first thinning.

Figure 12 Standing volume per hectare after thinning plotted against top height, based on entries in yield tables for Scots pine, initial spacing 1.4 m and involving a sequence of intermediate thinnings at management table intensity. The existence of an assumed underlying relationship between standing volume and top height is evident.



Time between thinnings (thinning cycle)

For ease of management, the time between thinnings is usually constant and is commonly referred to as the thinning cycle. The faster the rate of growth in a stand of trees, the more frequently it is possible to thin the stand while retaining sufficient growing stock. Thinning cycles of relevance to growing conditions in Britain are in the range 3 to 7 years (sometimes with cycles of 10 years – appropriate when stands have grown well beyond the time of maximum mean annual increment).

The Forest Yield tables involving a sequence of thinnings adopt a thinning cycle of 5 years as a standard treatment. For the most part, this means the schedule of thinnings represented in a yield table starts at MT thinning age, with further thinnings every 5 years. However, in many yield tables, the period between the first thinning and second thinning may be varied from 5 years – in some cases it may be as low as 4 years (Sitka spruce, original models, GYC 24, 1.7 m, 1 in 3 line thinning) or more than 15 years (Scots pine, GYC 4, 1.4 m, 1 in 3 line thinning). This variable period between the first and second thinning is sometimes referred to as the 'recovery period'.

Range of thinning treatments in Forest Yield

Table 14 (see page 66) gives a full list of the thinning treatments included in Forest Yield. The details of yield tables involving no thinning or a solitary line or neutral thinning have been described earlier. The Forest Yield tables involving a sequence of thinnings cover three options:

1. A sequence of intermediate thinnings.
2. A sequence of crown thinnings.
3. An initial line thinning followed by a sequence of intermediate thinnings.

Detailed patterns in thinning sequences

Intermediate and crown thinning starting at management table age

In yield tables involving a sequence of intermediate or crown thinnings starting at MT thinning age, a simple pattern is usually followed in which the thinnings take place on a strict 5-year cycle at an intensity of 1.0 MTI roughly up to the time when mean annual increment maximises. In some of these yield tables (generally at very narrow or very wide initial spacings), the recovery period may be varied from 5 years to ensure that maximum mean annual increment is as consistent as possible with the quoted GYC and that a sufficient level of standing volume per hectare is maintained (see 'Time between thinnings', above).

In the period of stand development after mean annual increment has maximised, the maintenance of thinnings at management table intensity cannot be sustained without causing significant reductions in the growth and level of standing volume of the stand. As a result, in the yield tables, the volume suggested for removal in thinnings is progressively reduced from around the age of maximum mean annual increment. According to Forestry Commission Booklet 16, *Forest management tables*:

> *The annual thinning yield remains constant until a few years before age of maximum mean annual increment, at which point the values begin to decline ... they are of lesser importance and are likely to be used only when stands are being retained beyond the normal rotation age for reasons of amenity, etc.*

These later, albeit lighter thinnings, may be of greater relevance in contemporary forestry where long-term retention of stands is more commonplace.

In yield tables for stands involving very long rotations (greater than 100 years, i.e. for beech and oak), the reduced intensity of thinning for later ages still ultimately results in a decrease in the standing volume later in the rotation.

A small number of Forest Yield tables were constructed at a time when entries in yield tables were always displayed on a rigid 5-year time step, i.e. stand ages of 10, 15, 20, 25 years and so on. Examples are the yield tables for beech and oak involving intermediate thinning. As a consequence, the first thinning always occurs on one of these 5-year time steps, which in many cases does not coincide exactly with the estimated MT thinning age. To allow for this, the volume removed at the first thinning may be less than the marginal thinning intensity.

For yield tables involving a sequence of intermediate thinnings, it is very important to note that the first thinning in the sequence is generally not strictly an intermediate thinning type but instead is closer to a crown or neutral thinning (see 'Timing of first thinning' page 56). This is because the Forest Yield tables typically involved an assumption that the first thinning would need to fulfil a certain combination of objectives. There was a particular emphasis on meeting target tree sizes for thinnings, as well as those elements of intermediate thinning concerned with breaking up dense groups of dominant trees and removing large, badly formed 'wolf' trees, to ensure uniformity of tree cover in the subsequent development of the stand. In addition, 'racks' of trees are often removed to allow access to the stand and there is also less emphasis placed on low thinning principles. The result is that, for the first thinning in these yield tables, the mean diameter at breast height and mean volume of thinnings can be very close to, and sometimes even slightly greater than, the equivalent values for the standing trees after thinning.

For yield tables involving a sequence of crown thinnings, the first thinning conforms most clearly to the crown thinning type. Subsequent thinnings migrate towards the intermediate thinning type. This pattern was included in the original yield tables because silvicultural practice suggested that it was not feasible to continue a sequence of crown thinning treatments in the long term. This was because the population of trees competing with favoured dominants would be removed in the initial thinnings, leaving no further trees to remove, or leading to a very irregular stand structure. In contemporary silviculture, achieving an irregular stand structure may be an explicit objective.

Intermediate thinning starting after management table age

There are further sets of yield tables involving a sequence of intermediate thinnings which start 5 or 10 years after MT thinning age. These were constructed in recognition that it will not always be possible to start thinning at the recommended time because of policy, business or operational constraints. (It is important to note that these yield tables do not reflect conditions in which a stand may not be ready for thinning at MT age, for example due to unexpectedly low basal area and volume growth.) In these types of yield tables, the volume removed in early thinnings is usually boosted above marginal thinning intensity in order to bring the standing volume (viewed as 'overstocked') back towards the characteristic level. The boost to thinning intensity is capped at 1.4 times the marginal thinning intensity (effectively a 7-year cut on a 5-year cycle), which the developers of the original yield tables believed was the greatest thinning intensity an overstocked stand could sustain without compromising increment.

Initial line thinning at management table age followed by intermediate thinning

For yield tables involving an initial line thinning, patterns of line thinning can be defined in terms of the numbers of rows of trees removed relative to the number of rows originally existing in the stand. Examples of patterns of line thinning were discussed earlier (see 'Yield tables involving a single line thinning', page 47, and in particular 'Pattern of line thinning', page 48). The yield tables involving line thinning included in Forest Yield all involve the removal of 1 row in every 3 standing originally.

The intermediate thinnings following the initial line thinning have a pattern similar to that already described for a sequence of just intermediate thinnings. However, with an initial line thinning, it is common for the recovery period (see 'Time between thinnings (thinning cycle)', page 57) to be varied from 5 years in order to ensure that maximum mean annual increment is as consistent as possible with the quoted GYC and that the desired level of standing volume per hectare is maintained. In addition, the intensity of the first and sometimes second intermediate thinning may be varied from 1.0 MTI as a further refinement to the development of standing volume. These variations in intensity range from 0.85 MTI to 1.4 MTI.

Initial line thinning after management table age followed by intermediate thinning

There are further sets of yield tables involving initial line thinning and a sequence of intermediate thinnings which start 5 or 10 years after MT thinning age. These were constructed in recognition that it will not always be possible to start thinning at the recommended time because of policy, business or operational constraints. In these types of yield tables, the recovery period may be varied from 5 years (e.g. down to 4 years) and the volume removed in early thinnings is usually boosted above marginal thinning intensity in order to bring the standing volume (viewed as 'overstocked') back towards the characteristic level. The boost to thinning intensity is capped at 1.4 times the marginal thinning intensity (effectively a 7-year cut on a 5-year cycle), which the developers of the original yield tables assessed as being the greatest thinning intensity an overstocked stand could sustain without compromising increment.

Unusual thinning treatments in Forest Yield

Forest Yield includes a few yield tables that are not based on the general patterns for sequences of thinnings described above. These yield tables are for Douglas fir and involve intermediate thinnings with intensities greater than 1.0 times the marginal thinning intensity before the time of maximum mean annual increment, and sustained at 1.0 times the marginal thinning intensity after the time of maximum mean annual increment.

These yield tables have already been referred to earlier in this handbook (see page 46), and represent the growth and yield of Douglas fir stands in the Forest of Dean which were slightly below normal stocking at MT thinning age and were subsequently subjected to several heavy thinnings, resulting in what was described as 'understocking' (conceivably as part of conversion to continuous cover management). In these yield tables, the heavy thinning was represented by boosting the intensity of the second, third, fourth and fifth thinnings to 1.2 times the marginal thinning intensity, and also maintaining the full intensity of 1.0 times the marginal thinning intensity in the period after maximisation of mean annual increment. In a variant to this regime, alternative yield tables for 'understocked' Douglas fir were constructed, with the further assumption that thinning shifted to a 10-year cycle (at 1.0 times the marginal thinning intensity) at later stand ages.

Thinning treatments in new yield tables for Sitka spruce

In general, the patterns of thinnings in the new yield tables for Sitka spruce are similar to the original yield tables. Many yield tables involve adjustments to the standard recovery period of 5 years between the first and second thinnings (see 'Time between thinnings (thinning cycle)', page 57). In yield tables involving a delay to the start of thinning, thinning intensities may be varied over a greater range than observed in the original yield tables, with intensities as small as 0.5 times the marginal thinning intensity or as great as 2.0 times the marginal thinning intensity being employed in some yield tables. The variations in thinning pattern in the new Sitka spruce yield tables are thus consistent with those observed in the original yield tables (see preceding discussion of thinning patterns in original yield tables), but these occur more commonly in the new tables.

The new yield tables for Sitka spruce involving a sequence of crown thinning treatments follow a similar pattern to that adopted in the original yield tables (see 'Intermediate and crown thinning starting at management table age', page 58). However, there is more emphasis on representation of strict crown thinning treatments in the new models.

Standard management prescriptions in Forest Yield

Yield tables have been constructed for a wide range of different initial spacings and thinning treatments. However, an important feature of the yield tables is that, for each species, one management prescription involving a particular combination of initial spacing and thinning treatment is taken as a standard prescription. This is necessary as part of the identification of distinct yield classes and in the subsequent calculation of management table thinning intensity in each published yield table. Table 15 (see page 68) lists the standard management prescriptions assumed for each tree species.

The selection of the standard initial spacings shown in Table 15 has been described in Forestry Commission Booklet 16, *Forest management tables*:

> *The ... value is based on an assumed (square) planting distance ... The assumed spacing is an estimate of the average for existing crops, based on a survey of current practice in the Forestry Commission and on the evidence of sample plots on Commission and private woodlands.*

The authors were referring to 'current practice' in 1966. Contemporary practice involves somewhat wider initial spacings on establishment.

The basis for adoption of either intermediate or crown thinning (and in one case no thinning) as the standard thinning treatment was not documented at the time but would appear to be consistent with the approach for selection of initial spacing, i.e. reflecting common practice at the time.

Range of management prescriptions in Forest Yield

Tables 16a to 16i list the complete range of yield tables for different management regimes (initial spacing × thinning treatment) available for tree species covered by Forest Yield. Each of Tables 16a to 16i describes the yield tables available for a specified thinning treatment, in combination with different initial spacings and yield classes. The thinning treatment is indicated in the title of each table and is based on the summary descriptions for thinning treatments given in the last column of Table 14.

Generally, only certain management regimes are covered for each tree species. Moreover, for some species, yield tables for certain management regimes have only been constructed for a restricted set of yield classes. Colour coding is used in Tables 16a to 16i to show where yield tables for a particular management regime are available for all yield classes represented for the species or for just a restricted set of yield classes.

The yield class ranges represented for Sitka spruce in the original and newly developed yield tables are different (6–24 and 6–34 respectively). The colour coding in Tables 16a to 16i indicates where management regimes are covered by the original yield tables. However, whenever new Sitka spruce yield tables have been constructed for a given management regime, this has always been done for the full (new) yield class range.

Selecting a yield table

Choosing a yield table that is most appropriate to apply to a particular forest stand or situation is not always straightforward. As stressed earlier, the yield tables cover a wide range of possible management prescriptions, but they are not comprehensive; Forest Yield is designed mainly for application to even-aged stands of trees in the UK. It has limited applications to forest stands with more complex structure and silvicultural practice, for example uneven-aged stands. This is a subject for ongoing research and development. Moreover, the range of yield tables available in Forest Yield for some tree species is quite limited. In some cases, the range is so limited it makes the choice easy; for example, there is only one management prescription represented for oak, consisting of 1.2 m initial spacing and intermediate thinning starting at management table age.

In general, the 'best available' yield table to represent a particular stand or situation can be identified by following a sequence of steps:

1. The first step involves indentifying the tree species and yield class. The yield class may be derived from an assessment on an actual stand, or may be hypothetical, depending on the details of the situation to which the yield table is to be applied. Compare the required yield class with the range available for the tree species. If the required yield class is above the range represented, select the highest available yield class. If the required yield class is below the range represented, select the lowest yield class. Note that if yield class is estimated using the Forest Yield software by comparing top height and age with the GYC curves for the tree species, then the software automatically applies the highest or lowest available yield class to values outside the range.

2. Identify the initial spacing available for the tree species that is closest to the initial spacing of interest. If the required initial spacing falls exactly between two yield tables for narrower and wider initial spacings, then choose the wider initial spacing. (This choice is likely to give conservative estimates of total volume production and a later age of first thinning, but may give a moderate overestimate of mean diameter at breast height and assortment volumes.)

3. Identify the thinning prescription from among available yield tables for the tree species, yield class and initial spacing which represents the 'best fit' to the required thinning prescription. Table 17 provides some guidance on selecting the nearest appropriate yield table for some example management prescriptions. The choices suggested in the table have been informed by knowledge of the various combinations of yield tables for different tree species available in the Forest Yield software. It must be stressed that some of the thinning prescriptions recommended in Table 17 will be a very rough approximation of the required thinning prescription in some cases.

4. Repeat step 3 for other values of available initial spacing either side of the value selected in step 2. In some instances, a 'better fitting' thinning prescription may be identified than for the initial spacing that was first selected. For example, suppose a yield table is required to represent a stand of yield class 8 Scots pine with an initial

spacing of 1.8 m and subject to regular thinning, where the first thinning takes place at the recommended age and is a line thinning without trees being removed in the matrix. The Forest Yield software includes some yield tables for an initial spacing of 1.8 m but the nearest management prescription relevant to this example is the second choice suggested in Table 17 of ‘Intermediate (MT age)’. However, a yield table for the management prescription ‘Line (1:3)’ is available if the nearest narrower initial spacing of 1.4 m is selected.

For certain tree species, notably Corsican pine, Douglas fir and poplar, it should be recalled that yield tables are available for some unusual initial spacings and thinning treatments. Further information can be found in the sections on ‘Unusual spacings in Forest Yield’, page 46, and ‘Yield tables involving a single neutral thinning (poplar only)’, page 49.

Table 14 Range of thinning treatments included in Forest Yield.

First thinning			
Type	**Time**	**Intensity**	**Type**
Intermediate	MT thinning age	MTI	Intermediate
Intermediate	MT thinning age + 5 years	MTI	Intermediate
Intermediate	MT thinning age + 10 years	MTI	Intermediate
Intermediate	MT thinning age	MTI	Intermediate
Intermediate	MT thinning age	MTI	Intermediate
Crown	MT thinning age	MTI	Crown
Line	MT thinning age	1 in 3	Intermediate
Line	MT thinning age + 5 years	1 in 3	Intermediate
Line	MT thinning age + 10 years	1 in 3	Intermediate
Line	MT thinning age	1 in 3	None
Line	MT thinning age + 5 years	1 in 3	None
Neutral	18 m top height	50%	None
No thinning	–	–	–

Notes:
See 'Timing of first thinning', page 56 for an explanation of MT thinning age.
See 'Volume removed in thinnings (thinning yield)', page 54, for an explanation of MTI thinning intensity.
See 'Pattern of line thinning', page 48, for an explanation of line thinning and 1 in 3 thinning intensity.
See 'Pattern of neutral thinning in models for poplar', page 50, for an explanation of neutral thinning and 50% intensity.
See 'Types of selective thinning', page 51, for an explanation of Intermediate and crown thinning.
See 'Measuring volume productivity', page 22, for an explanation of maximum MAI.

	Later thinnings	Summary description
	Intensity	
	MTI, thinning yield reduced after time of maximum MAI	Intermediate (MT age)
	1.4 MTI (7-year cut on 5-year cycle), reducing to MTI, reduced again after time of maximum MAI	Intermediate (5-year delay)
	1.4 MTI (7-year cut on 5-year cycle), reduced after time of maximum MAI	Intermediate (10-year delay)
	MTI (1.2 MTI at 2nd–5th thinnings)	Intermediate, 2nd–5th at 1.2 MTI
	MTI (1.2 MTI at 2nd–5th thinnings), 10-year cycle after 5th thinning	Intermediate, 2nd–5th at 1.2 MTI (10-year cycle later)
	MTI, thinning yield reduced after time of maximum MAI	Crown (MT age)
	MTI, thinning yield reduced after time of maximum MAI	Line 1:3 (MT age)
	1.4 MTI (7-year cut on 5-year cycle), reducing to MTI, reduced again after time of maximum MAI	Line 1:3 (5-year delay)
	1.4 MTI (7-year cut on 5-year cycle), reduced after time of maximum MAI	Line 1:3 (10-year delay)
	–	Solitary line 1:3 (MT age)
	–	Solitary line 1:3 (5-year delay)
	–	Neutral 50% (18 m top height)
	–	No thinning

Table 15 Standard management prescriptions adopted in yield tables.

Species	Initial spacing (m)	Thinning treatment
Conifers		
Norway spruce	1.5	Intermediate (MT age)
Sitka spruce	1.7	Intermediate (MT age)
Corsican pine	1.4	Intermediate (MT age)
Scots pine	1.4	Intermediate (MT age)
Lodgepole pine	1.5	Intermediate (MT age)
European larch	1.7	Intermediate (MT age)
Japanese/hybrid larch	1.7	Intermediate (MT age)
Douglas fir	1.7	Crown (MT age)
Grand fir	1.8	Crown (MT age)
Noble fir	1.5	Crown (MT age)
Western red cedar/Leyland cypress	1.5	Crown (MT age)
Western hemlock	1.5	Crown (MT age)
Broadleaves		
Oak	1.2	Intermediate (MT age)
Beech	1.2	Intermediate (MT age)
Sycamore, ash and birch	1.5	Intermediate (MT age)
Nothofagus	1.7	Intermediate (MT age)
Poplar	7.3	No thinning

Tables 16a to 16i Complete list of yield tables for different management regimes (thinning prescription × initial spacing) for the tree species covered by Forest Yield. (For tree species mappings, see Tables A1.1 and A1.2 in Appendix 1 of the Forest Yield user manual.)

Species abbreviations: NS, Norway spruce; SS, Sitka spruce; CP, Corsican pine; SP, Scots pine; LP, lodgepole pine; EL, European larch; JL/HL, Japanese larch/hybrid larch; DF, Douglas fir; PO, poplar; OK, oak; BE, beech; SAB, sycamore, ash and birch; NO, Nothofagus (note that in the Forest Yield software *Nothofagus* appears under the common names rauli and roble); GF, grand fir; NF, noble fir; RC, western red cedar; LC, Lawson cypress; WH, western hemlock

Key to Tables 16a to 16i

- No yield tables of this type available for this species
- Yield tables of this type available for selected yield classes of this species
- Yield tables of this type available for the full range of yield classes for this species

Note: if yield tables of a particular type are available for Sitka spruce for a given thinning prescription and any initial spacing, then new Sitka spruce yield tables based on the dynamic growth model are available for the full range of yield classes and all initial spacings listed in the table.

Table 16a Available yield tables for thinning treatment: No thinning.

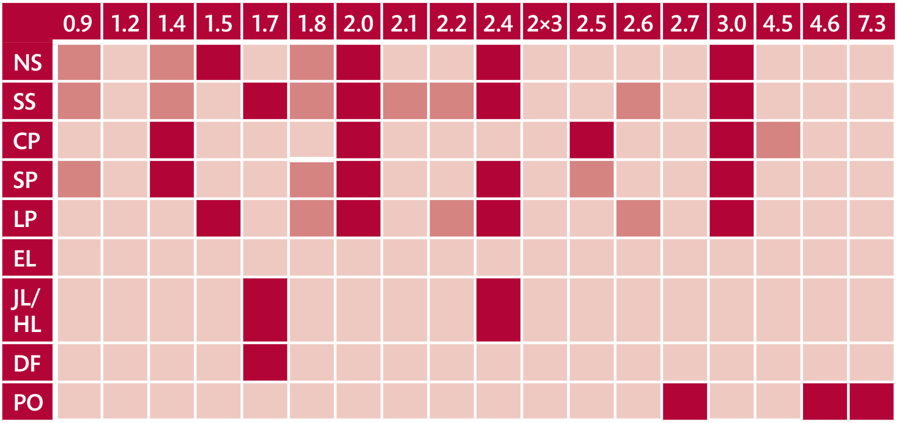


Table 16b Available yield tables for thinning treatment: Solitary line 1:3 (MT age) and Solitary line 1:3 (5-year delay).

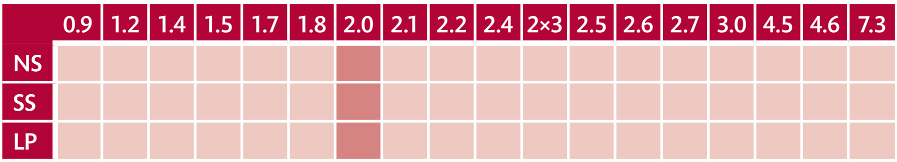


Table 16c Available yield tables for thinning treatment: Neutral 50% (18 m top height).

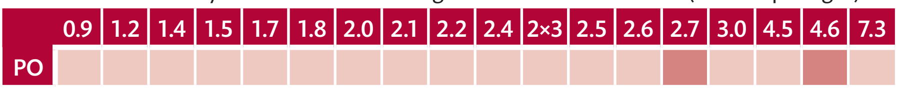


Table 16d Available yield tables for thinning treatment: Intermediate (MT age).

	0.9	1.2	1.4	1.5	1.7	1.8	2.0	2.1	2.2	2.4	2×3	2.5	2.6	2.7	3.0	4.5	4.6	7.3
NS																		
SS																		
CP																		
SP																		
LP																		
EL																		
JL/HL																		
OK																		
BE																		
SAB																		
NO																		

Table 16e Available yield tables for thinning treatment: Intermediate (5-year delay) and Intermediate (10-year delay).

	0.9	1.2	1.4	1.5	1.7	1.8	2.0	2.1	2.2	2.4	2×3	2.5	2.6	2.7	3.0	4.5	4.6	7.3
NS																		
SS																		
CP																		
SP																		
LP																		

Table 16f Available yield tables for thinning treatment: Intermediate, 2nd–5th at 1.2 MTI and Intermediate, 2nd–5th at 1.2 MTI (10-year cycle later).

	0.9	1.2	1.4	1.5	1.7	1.8	2.0	2.1	2.2	2.4	2×3	2.5	2.6	2.7	3.0	4.5	4.6	7.3
DF																		

Table 16g Available yield tables for thinning treatment: Crown (MT age).

	0.9	1.2	1.4	1.5	1.7	1.8	2.0	2.1	2.2	2.4	2×3	2.5	2.6	2.7	3.0	4.5	4.6	7.3
NS				■														
SS					■													
DF					■													
GF						■												
NF				■														
RC				■														
LC				■														
WH				■														

Table 16h Available yield tables for thinning treatment: Line 1:3 (MT age).

	0.9	1.2	1.4	1.5	1.7	1.8	2.0	2.1	2.2	2.4	2×3	2.5	2.6	2.7	3.0	4.5	4.6	7.3
NS										■								
SS					■		■			■								
CP			■				■					■						
SP			■				■			■								
LP				■			■			■								
EL																		
JL/HL					■													
DF					■													

Table 16i Available yield tables for thinning treatment: Line 1:3 (5-year delay) and Line 1:3 (10-year delay).

	0.9	1.2	1.4	1.5	1.7	1.8	2.0	2.1	2.2	2.4	2×3	2.5	2.6	2.7	3.0	4.5	4.6	7.3
NS				■														
SS					■													
CP			■															
SP			■															
LP				■														
JL/HL					■													
DF					■													

Table 17 Guide to selecting 'best-fit' thinning prescription.

Broad thinning prescription required
Regular thinning (intermediate), with the first thinning near to MT age
Regular thinning (including crown thinnings), with the first thinning near to MT age
Regular thinning (intermediate), with the first thinning near to MT age involving line thinning and no selective thinning in the matrix
Regular thinning (intermediate), with the first thinning near to MT age involving line thinning and also selective thinning in the matrix
Regular thinning (intermediate), with the first thinning around 5 years after MT age
Regular thinning (including crown thinnings), with the first thinning around 5 years after MT age
Regular thinning (intermediate), with the first thinning around 5 years after MT age involving line thinning and no selective thinning in the matrix
Regular thinning (intermediate), with the first thinning around 5 years after MT age involving line thinning and also selective thinning in the matrix
Regular thinning (intermediate), with the first thinning around 10 years after MT age
Regular thinning (including crown thinnings), with the first thinning around 10 years after MT age
Regular thinning (intermediate), with the first thinning around 10 years after MT age involving line thinning and no selective thinning in the matrix
Regular thinning (intermediate), with the first thinning around 10 years after MT age involving line thinning and also selective thinning in the matrix
Just one or two thinnings, with the first thinning near to MT age
Just one or two thinnings, with the first thinning around 5 years after MT age
Just one or two thinnings, with the first thinning around 10 years after MT age
No thinning

Note:
See Table 14, pages 66–67 for an explanation of summary descriptions of thinning prescriptions.

	First choice (best fit)	Second choice (if best fit not available)	Third choice	Fourth choice
	Intermediate (MT age)	Crown (MT age)		
	Crown (MT age)	Intermediate (MT age)		
	Line 1:3 (MT age)	Intermediate (MT age)		
	Intermediate (MT age)	Crown (MT age)		
	Intermediate (5-year delay)	Intermediate (MT age)	Crown (MT age)	
	Intermediate (5-year delay)	Crown (MT age)	Intermediate (MT age)	
	Line 1:3 (5-year delay)	Intermediate (5-year delay)	Intermediate (MT age)	Crown (MT age)
	Intermediate (5-year delay)	Intermediate (MT age)	Crown (MT age)	
	Intermediate (10-year delay)	Intermediate (MT age)	Crown (MT age)	
	Intermediate (10-year delay)	Crown (MT age)	Intermediate (MT age)	
	Line 1:3 (10-year delay)	Intermediate (10-year delay)	Intermediate (MT age)	Crown (MT age)
	Intermediate (10-year delay)	Intermediate (MT age)	Crown (MT age)	
	Solitary line 1:3 (MT age)	No thinning	Intermediate (MT age)	
	Solitary line 1:3 (5-year delay)	No thinning	Intermediate (MT age)	
	No thinning	Intermediate (MT age)		
	Intermediate (MT age)			

Appendices

Appendix 1 – Stand volume assortment tables

Forestry Commission Booklet 48, *Yield models for forest management*, included three generic stand (volume) assortment tables covering the range of likely management treatments. Updated versions of these tables, based on mathematical functions derived from the Booklet 48 originals, are presented on the following pages as Tables A1.1 to A1.3.

Table A1.1 is recommended for:

- most thinned stands, i.e. stands planted at (or respaced to) spacings of about 2 m or less;
- fellings of 'wide-spaced' unthinned stands, i.e. planted at (or respaced to) spacings of about 3 m.

Table A1.2 is recommended for unthinned stands planted at spacings of about 2 m or less. This table is also likely to be the most suitable one for estimating the assortments from a line thinning or from stands which have received a single line thinning and no subsequent thinning.

Table A1.3 is recommended for 'wide-spaced' thinned stands, i.e. planted at (or respaced to) spacings of about 3 m.

In all three assortment tables, a minimum 3 m log length is assumed for any roundwood specified with a top diameter greater than 7 cm. The log volume is expressed as a percentage of the total volume to 7 cm top diameter, assuming the conventional minimum length of 1.3 m for this volume. The assortment tables also include estimates of percentage volume 'to tip' (See 'Volume to tip', page 84). No minimum length is assumed in calculating the 'to tip' percentages.

The original assortment tables have been expressed as a set of equations for several reasons. Firstly, this makes it easier to include predictions of assortments as part of the Forest Yield software. Secondly, the equations can be used to extrapolate predictions outside the ranges of the original tables, in particular for large values of mean diameter at breast height and top diameter. The need for such estimates is becoming more important as silviculture in British forests develops, e.g. involving long-term retention of some stands and greater emphasis on management for 'continuous cover'. Finally, requests are occasionally received from practitioners and researchers who would like to have access to assortment predictions in the form of equations rather than tables.

The equations (Equations A1.1 to A1.4), and their associated parameters, are presented on pages 80 to 84 of this handbook while the use of stand volume assortment tables is discussed in more detail in Appendix 2 of *Forest mensuration: a handbook for practitioners*. The discussion in *Forest mensuration* also considers some of the limitations and assumptions relating to the assortment equations used in Forest Yield.

Table A1.1 Stand volume assortment table for **thinned stands** giving volumes to specified top diameters for logs of minimum length 3 m as a percentage of overbark volume.

Mean dbh cm	To tip	Overbark top diameter in centimetres																	
		7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
7	176	100	24	9	2														
8	154	100	43	23	11	3													
9	139	100	58	37	23	12													
10	129	100	70	50	36	22	7	1											
11	122	100	79	62	48	33	16	7	3										
12	117	100	85	71	59	44	26	16	9	3									
13	113	100	90	79	69	54	37	25	17	10	4								
14	110	100	93	84	76	63	48	35	26	18	11	4	1						
15	108	100	95	89	82	71	58	45	35	26	19	12	7	1					
16	107	100	97	92	87	77	66	54	44	35	27	19	13	6	1				
17	106	100	98	94	90	82	73	63	53	43	35	27	20	12	5	1			
18	105	100	98	96	93	86	79	70	61	51	43	34	27	18	11	6	1		
19	104	100	99	97	95	89	84	76	67	58	50	42	34	24	16	11	6	1	
20	103	100	99	98	96	92	87	81	73	65	57	49	41	31	22	16	11	6	2
21	103	100	100	98	97	94	90	85	78	71	64	55	47	37	29	22	17	11	7
22	102	100	100	99	98	95	93	88	82	75	69	61	54	44	35	28	22	16	12
23	102	100	100	99	99	96	94	91	86	80	74	66	59	50	41	34	28	22	17
24	102	100	100	99	99	97	96	93	89	83	78	71	65	56	47	40	33	27	22
25	102	100	100	100	99	98	97	94	91	86	82	75	69	61	53	45	39	32	27
26	101	100	100	100	99	98	97	96	93	89	85	79	73	66	58	50	44	38	32
27	101	100	100	100	100	99	98	97	94	91	87	82	77	70	63	55	49	43	37
28	101	100	100	100	100	99	99	97	95	93	89	84	80	74	67	60	54	47	42
29	101	100	100	100	100	99	99	98	96	94	91	87	83	77	71	64	58	52	46
30	101	100	100	100	100	99	99	98	97	95	93	89	86	80	75	68	62	56	50
31	101	100	100	100	100	100	99	99	98	96	94	90	88	83	78	72	66	60	55
32	101	100	100	100	100	100	100	99	98	97	95	92	90	85	81	75	70	64	58
33	101	100	100	100	100	100	100	99	99	97	96	93	91	87	83	78	73	67	62
34	101	100	100	100	100	100	100	99	99	98	97	94	92	89	85	80	76	70	65
35	101	100	100	100	100	100	100	100	99	98	97	95	94	91	87	83	78	73	69
36	101	100	100	100	100	100	100	100	99	99	98	96	95	92	89	85	81	76	71
37	100	100	100	100	100	100	100	100	99	99	98	97	95	93	90	87	83	78	74
38	100	100	100	100	100	100	100	100	100	99	98	97	96	94	92	88	85	81	76
39	100	100	100	100	100	100	100	100	100	99	99	98	97	95	93	90	86	83	79
40	100	100	100	100	100	100	100	100	100	99	99	98	97	96	94	91	88	84	81
41	100	100	100	100	100	100	100	100	100	100	99	98	98	96	95	92	89	86	83
42	100	100	100	100	100	100	100	100	100	100	99	99	98	97	95	93	91	88	84
43	100	100	100	100	100	100	100	100	100	100	99	99	98	97	96	94	92	89	86
44	100	100	100	100	100	100	100	100	100	100	100	99	99	98	97	95	93	90	87
45	100	100	100	100	100	100	100	100	100	100	100	99	99	98	97	95	94	91	89
46	100	100	100	100	100	100	100	100	100	100	100	99	99	98	97	96	94	92	90
47	100	100	100	100	100	100	100	100	100	100	100	99	99	99	98	97	95	93	91
48	100	100	100	100	100	100	100	100	100	100	100	99	99	99	98	97	96	94	92
49	100	100	100	100	100	100	100	100	100	100	100	100	99	99	98	97	96	94	93
50	100	100	100	100	100	100	100	100	100	100	100	100	99	99	99	98	97	95	93

Notes on the application of this table are given at the start of this appendix (page 76).

Table A1.2 Stand volume assortment table for **unthinned stands** giving volumes to specified top diameters for logs of minimum length 3 m as a percentage of overbark volume.

Mean dbh cm	To tip	Overbark top diameter in centimetres																	
		7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
7	191	100	20	14	5														
8	165	100	40	29	16	5													
9	147	100	55	43	27	13	4												
10	135	100	67	55	39	23	11	6											
11	126	100	76	64	50	33	20	13	6	3									
12	120	100	83	73	59	43	29	22	14	10	3								
13	116	100	87	79	68	52	39	30	22	17	10	5	2						
14	112	100	91	84	75	61	48	39	30	24	17	11	7	3					
15	110	100	93	88	80	68	57	47	38	31	24	18	13	8	2				
16	108	100	95	91	85	74	64	54	46	39	31	25	20	14	7	3	1		
17	107	100	97	93	88	79	71	61	53	45	38	32	26	19	12	8	5	2	1
18	105	100	98	95	91	84	76	67	59	52	44	38	32	25	17	13	9	6	4
19	105	100	98	96	93	87	81	73	65	58	51	44	38	30	23	18	14	11	8
20	104	100	99	97	95	90	85	77	70	63	56	49	43	36	28	23	18	15	11
21	103	100	99	98	96	92	88	81	75	68	61	55	49	41	33	28	23	19	15
22	103	100	99	98	97	94	90	84	79	72	66	59	54	46	38	33	27	24	19
23	102	100	100	99	98	95	92	87	82	76	70	64	58	50	43	38	32	28	23
24	102	100	100	99	98	96	94	89	85	79	74	68	63	55	47	42	36	32	27
25	102	100	100	99	99	97	95	91	87	82	77	72	66	59	52	46	41	36	31
26	102	100	100	99	99	98	96	93	89	85	80	75	70	63	56	51	45	40	35
27	101	100	100	100	99	98	97	94	91	87	83	78	73	66	60	54	49	44	39
28	101	100	100	100	99	99	98	95	93	89	85	80	76	70	63	58	53	48	43
29	101	100	100	100	100	99	98	96	94	91	87	83	79	73	67	62	56	52	46
30	101	100	100	100	100	99	99	97	95	92	89	85	81	75	70	65	60	55	50
31	101	100	100	100	100	99	99	97	96	93	91	87	84	78	73	68	63	58	53
32	101	100	100	100	100	99	99	98	96	94	92	88	85	80	75	71	66	61	57
33	101	100	100	100	100	100	99	98	97	95	93	90	87	82	78	73	69	64	60
34	101	100	100	100	100	100	99	99	98	96	94	91	89	84	80	76	71	67	62
35	101	100	100	100	100	100	100	99	98	96	95	92	90	86	82	78	74	70	65
36	101	100	100	100	100	100	100	99	98	97	96	93	91	87	84	80	76	72	68
37	101	100	100	100	100	100	100	99	99	97	96	94	92	89	85	82	78	74	70
38	100	100	100	100	100	100	100	99	99	98	97	95	93	90	87	83	80	76	73
39	100	100	100	100	100	100	100	100	99	98	97	95	94	91	88	85	82	78	75
40	100	100	100	100	100	100	100	100	99	98	98	96	95	92	89	86	83	80	77

Notes on the application of this table are given at the start of this appendix (page 76).

Table A1.3 Stand volume assortment table for **wide-spaced stands** giving volumes to specified top diameters for logs of minimum length 3 m as a percentage of overbark volume.

Mean dbh cm	To tip	Overbark top diameter in centimetres																	
		7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
7	171	100	15	5															
8	148	100	34	19	9														
9	134	100	51	34	20	4													
10	125	100	65	48	33	16	2												
11	119	100	75	61	46	29	12	3											
12	115	100	83	71	58	41	23	13	3										
13	112	100	88	79	68	52	35	24	13	6									
14	109	100	92	85	76	62	46	35	23	14	6								
15	108	100	95	89	82	70	57	45	34	24	14	7							
16	106	100	96	92	87	76	66	54	44	33	23	15	6						
17	105	100	98	95	90	82	73	63	53	42	32	24	14	5					
18	104	100	98	96	93	86	79	70	61	51	41	32	23	13	3				
19	104	100	99	97	95	89	84	76	68	58	49	41	32	20	10	3			
20	103	100	99	98	96	92	88	80	74	65	57	48	40	28	17	10	3		
21	103	100	99	99	97	94	91	84	79	71	64	55	47	36	25	17	10	5	
22	102	100	100	99	98	95	93	88	83	76	70	62	54	43	32	24	17	11	4
23	102	100	100	99	99	96	95	90	86	81	75	67	61	50	39	31	24	17	10
24	102	100	100	100	99	97	96	92	89	84	79	72	66	56	46	38	31	24	16
25	102	100	100	100	99	98	97	94	91	87	83	76	71	62	53	45	37	30	23
26	101	100	100	100	100	98	98	95	93	90	86	80	76	67	59	51	44	36	29
27	101	100	100	100	100	99	98	96	95	92	89	83	80	71	64	56	50	42	35
28	101	100	100	100	100	99	99	97	96	93	91	86	83	75	69	62	55	47	40
29	101	100	100	100	100	99	99	98	97	94	92	88	85	79	73	66	60	53	46
30	101	100	100	100	100	99	99	98	97	96	94	90	88	82	77	70	65	58	51
31	101	100	100	100	100	100	99	99	98	96	95	92	90	85	80	74	69	62	56
32	101	100	100	100	100	100	100	99	98	97	96	93	91	87	83	77	72	66	60
33	101	100	100	100	100	100	100	99	99	98	97	94	93	89	86	80	76	70	64
34	101	100	100	100	100	100	100	99	99	98	97	95	94	91	88	83	79	73	68
35	101	100	100	100	100	100	100	99	99	99	98	96	95	92	90	85	81	76	71
36	101	100	100	100	100	100	100	100	99	99	98	97	96	93	91	87	84	79	74
37	101	100	100	100	100	100	100	100	99	99	99	97	97	94	92	89	86	82	77
38	100	100	100	100	100	100	100	100	100	99	99	98	97	95	94	90	88	84	80
39	100	100	100	100	100	100	100	100	100	99	99	98	98	96	95	92	89	86	82
40	100	100	100	100	100	100	100	100	100	100	99	98	98	97	95	93	91	87	84
41	100	100	100	100	100	100	100	100	100	100	99	99	98	97	96	94	92	89	86
42	100	100	100	100	100	100	100	100	100	100	100	99	99	98	97	95	93	90	87
43	100	100	100	100	100	100	100	100	100	100	100	99	99	98	97	95	94	91	89
44	100	100	100	100	100	100	100	100	100	100	100	99	99	98	98	96	95	93	90
45	100	100	100	100	100	100	100	100	100	100	100	99	99	98	98	97	95	93	91
46	100	100	100	100	100	100	100	100	100	100	100	99	99	99	98	97	96	94	92
47	100	100	100	100	100	100	100	100	100	100	100	100	99	99	99	98	96	95	93
48	100	100	100	100	100	100	100	100	100	100	100	100	100	99	99	98	97	96	94
49	100	100	100	100	100	100	100	100	100	100	100	100	100	99	99	98	97	96	95
50	100	100	100	100	100	100	100	100	100	100	100	100	100	99	99	98	98	97	95

Notes on the application of this table are given at the start of this appendix (page 76).

To describe the predictions in the original assortment tables published in the Forestry Commission Booklet *Yield models for forest management*, a Gompertz equation was used which has the form:

$$P_{TD} = a_{TD} + ((100 - a_{TD}) \times \exp(-\exp(-b_{TD} \times (DBH - m_{TD})))) \qquad \text{(Equation A1.1)}$$

where P_{TD} = percentage of total overbark stem volume to a specified top diameter (TD) in cm overbark
DBH = quadratic mean dbh of standing trees or thinnings (cm)
and a_{TD}, b_{TD} and m_{TD} are parameters of the equation which vary with top diameter.

Note that the form of the Gompertz equation as given above has been constrained to ensure that P_{TD} cannot exceed 100%. For certain values of DBH and TD, the equation can return negative values for P_{TD}, in which case P_{TD} should be taken to be zero.

Unfortunately, it is not possible to determine simple continuous functions for a_{TD}, b_{TD} and m_{TD} with respect to TD within the range of values of TD covered by the original Booklet 48 assortment tables. This is because the predictions include a number of discontinuities in predicted values of P_{TD} with respect to TD, generally reflecting points at which trees in stands with a certain mean dbh are 'just big enough' to contain some volume for the specified top diameter. It is also a reflection of the methods used to construct the original assortment tables in the Forestry Commission Booklet *Yield models for forest mamagement*, which were based on hand-drawn curves and manual calculations, rather than continuous mathematical relationships. However, it has been possible to find reasonable estimates of the parameters a_{TD}, b_{TD} and m_{TD} for whole-number values of TD within the ranges of the originally published assortment tables. To estimate P_{TD} for values of TD within these ranges other than for whole-number values of TD, it is necessary to interpolate between the predictions of P_{TD} for nearby whole-number values of TD.

Estimates for parameters a_{TD}, b_{TD} and m_{TD} giving the predictions in Tables A1.1, A1.2 and A1.3 are listed in Tables A1.4, A1.5 and A1.6 respectively. However, it should be stressed that the predictions given for percentage assortment volumes in Tables A1.1 to A1.3, based on Equation A1.1 and using the parameter values in Tables A1.4 to A1.6, do not exactly reproduce the predictions given in the original assortment tables published in Booklet 48. It is only possible for the equations to approximate the original values and there are small but noticeable deviations for a small number of table entries, as is revealed by detailed comparison of predictions in Tables A1.1 to A1.3 with the original Tables 3 to 5 in the Forestry Commission Booklet *Yield models for forest mamagement*.

Limitations to the application of the assortment tables are discussed in more detail in Appendix 2 of *Forest mensuration: a handbook for practitioners*.

Table A1.4 Estimates for parameters a_{TD}, b_{TD} and m_{TD} which give the stand volume assortment predictions in Table A1.1 (volume assortment for thinned stands).

Top diameter (m)	a_{TD}	b_{TD}	m_{TD}
8	-54.20	0.38320	6.2870
9	-15.25	0.33610	8.2924
10	-8.63	0.32110	9.6490
11	-8.27	0.27839	10.8840
12	-7.47	0.27710	12.5210
13	-7.24	0.25600	13.6830
14	-6.88	0.23565	14.6960
15	-9.58	0.21304	15.5520
16	-13.54	0.19595	16.1650
17	-20.63	0.17346	16.6040
18	-13.64	0.16961	18.1820
19	-12.22	0.16028	19.7320
20	-12.60	0.15196	21.0200
21	-15.70	0.13843	21.8150
22	-19.28	0.12781	22.4190
23	-23.04	0.11829	23.0910
24	-24.97	0.11052	23.8120

Table A1.5 Estimates for parameters a_{TD}, b_{TD} and m_{TD} which give the stand volume assortment predictions in Table A1.2 (volume assortment for unthinned stands).

Top diameter (m)	a_{TD}	b_{TD}	m_{TD}
8	-153.00	0.33500	4.1200
9	-43.40	0.29140	6.6887
10	-14.07	0.27870	9.0610
11	-8.67	0.25427	10.8490
12	-7.58	0.24156	12.2760
13	-12.73	0.20764	12.8350
14	-19.02	0.18785	13.3370
15	-19.12	0.16793	14.0920
16	-24.32	0.15510	14.6140
17	-34.30	0.13731	14.5400
18	-26.38	0.13207	16.0880
19	-25.94	0.11944	17.2200
20	-26.62	0.11302	18.4810
21	-31.96	0.10346	18.7000
22	-22.69	0.10101	20.8960
23	-28.08	0.09287	20.9600
24	-18.37	0.09183	23.4920

Table A1.6 Estimates for parameters a_{TD}, b_{TD} and m_{TD} which give the stand volume assortment predictions in Table A1.3 (volume assortment for wide-spaced stands).

Top diameter (m)	a_{TD}	b_{TD}	m_{TD}
8	-37.10	0.39720	6.922
9	-12.77	0.36460	8.667
10	-6.64	0.33730	9.974
11	-25.10	0.27880	10.370
12	-12.12	0.28900	12.509
13	-21.43	0.24720	12.957
14	-20.20	0.23810	14.073
15	-14.54	0.22189	15.434
16	-15.26	0.21409	16.446
17	-26.30	0.18696	16.578
18	-26.80	0.18530	17.626
19	-23.93	0.17047	19.151
20	-20.02	0.17030	20.923
21	-28.20	0.15260	21.250
22	-32.70	0.14407	21.870
23	-27.58	0.13580	23.340
24	-34.00	0.12787	23.840

To extrapolate predictions of percentage assortment volume for values of TD beyond the range of the original yield tables, it is possible to use Equation A1.1 and estimated values for parameters a_{TD}, b_{TD} and m_{TD} obtained from Equations A1.2 to A1.4 given below:

$$a_{TD} = p + (q / ((1 + r \times TD))) \quad \text{(Equation A1.2)}$$

$$b_{TD} = s / (1 + (w \times TD)) \quad \text{(Equation A1.3)}$$

$$m_{TD} = k \times TD \quad \text{(Equation A1.4)}$$

where p, q, r, s, w and k are parameters. Estimates for these parameters suitable for use in extrapolation of predictions of P_{TD} using Equation A1.1 for values of TD outside the range given in Tables A1.1 to A1.3 are given in Table A1.7.

Table A1.7 Estimates for parameters suitable for use in equations A1.2 to A1.4 to generate estimated values of the parameters a_{TD}, b_{TD} and m_{TD} for inclusion in Equation A1.1.

	Thinned stands	Unthinned stands	Wide-spread stands
p	-35.53	-34.73	-59.1
q	199	-550	109.2
r	0.53	-3.1	0.122
s	-1.174	-0.6413	-2.561
w	-0.4513	-0.3299	-0.854
k	1.0138	0.9204	1.0032

It must be stressed that:

- Equation A1.1 should be used in conjunction with the parameter values given in Tables A1.4 to A1.6 when estimating percentage assortment volumes for top diameters within the ranges covered by Tables A1.1 to A1.3 respectively. As already noted, to estimate P_{TD} for values of top diameter within table ranges other than for whole number values of top diameter, it is necessary to interpolate between the predictions for P_{TD} for nearby whole-number values for top diameter.
- The above approach should also be taken when extrapolating predictions of P_{TD} for top diameters within the ranges covered by Tables A1.1 to A1.3, but for values of mean dbh outside the ranges of these tables.
- When estimating percentage assortment volumes for top diameter outside the ranges covered by Tables A1.1 to A1.3, Equations A1.2 to A1.4 should be used in conjunction with Equation A3.1. Use of Equations A1.2 to A1.4 in conjunction with Equation A1.1 for values of top diameter within the ranges covered by Tables A1.1 to A1.3 is not recommended.

Volume 'to tip'

The stand volume assortment tables published in Forestry Commission Booklet 48 (*Yield models for forest management*) have two additional columns for volume assortments with respect to overbark top diameter, representing volume 'to tip' and volume to 7 cm. These columns are included in Tables A1.1 to A1.3, above.

Values to 7 cm represent an obvious case and are by definition always 100% of the stem volume, irrespective of mean dbh.

Values to tip exceed 100% and are largest for small values of mean dbh, declining progressively towards 100% as mean dbh increases.

An equation of the form given below (Equation A1.5) was used to describe the predictions of percentage volume to tip with respect to stand mean dbh, as reported in the original assortment tables in Booklet 48.

$$P_{tip} = 100 + c \,/\, (1 + \exp(-b \times (\log_e(DBH) - m))) \qquad \text{(Equation A1.5)}$$

where P_{tip} = percentage of total overbark stem volume to tip.
DBH = quadratic mean dbh of standing trees or thinnings (cm)
and *c*, *b* and *m* are parameters of the equation.

Estimates of parameters *c*, *b* and *m* giving the values for percentage volume to tip shown in Tables A1.1 to A1.3 are given in Table A1.8.

Table A1.8 Estimates for parameters suitable for use in equation A1.5 for estimating stand volume assortments 'to tip'.

	Thinned stands	Unthinned stands	Wide-spread or heavily thinned stands
c	315.2	328.6	2 228.0
b	-3.2269	-3.3061	-2.9727
m	1.5889	1.6576	0.7960

It is important to note that the assortment tables and equations described in this appendix and as built into Forest Yield, like the originals in Booklet 48, are not species specific but have been estimated generally for even-aged stands of coniferous tree species grown in Great Britain. Application of these predictions for assortments based on these tables and equations to stands with more complex structure (e.g. uneven-aged stands) or to stands of broadleaved tree species should therefore be undertaken with caution.

Appendix 2 – Annual top height increment tables

Table A2.1 Annual top height increment, in centimetres per year, for Scots pine.

Top height (m)	Yield class					
	4	6	8	10	12	14
8	27	32	37	44	51	59
9	25	31	36	42	49	57
10	23	29	35	40	47	54
11	22	28	34	39	45	51
12	20	26	32	37	43	49
13	18	24	30	36	41	46
14	16	23	29	34	39	44
15	13	21	27	33	37	41
16	10	19	26	31	36	40
17	-	17	24	29	34	38
18	-	15	22	28	33	37
19	-	12	20	26	31	35
20	-	-	18	24	30	34

Table A2.2 Annual top height increment, in centimetres per year, for Corsican pine.

Top height (m)	Yield class							
	6	8	10	12	14	16	18	20
8	29	37	44	50	54	58	62	66
9	27	36	43	49	54	58	62	66
10	26	34	41	48	53	57	62	66
11	24	32	40	46	52	57	61	65
12	23	30	38	45	51	56	60	64
13	21	29	36	43	49	55	59	63
14	20	27	34	41	47	53	58	62
15	18	25	32	39	45	52	57	61
16	15	23	30	37	43	50	55	60
17	11	21	28	35	41	48	53	59
18	-	19	26	32	39	46	52	57
19	-	16	24	30	37	44	50	55
20	-	13	22	28	35	41	47	53

Table A2.3 Annual top height increment, in centimetres per year, for lodgepole pine.

Top height (m)	Yield class					
	4	6	8	10	12	14
8	29	39	48	56	63	70
9	26	37	47	55	63	70
10	24	35	45	54	62	70
11	21	32	43	52	61	69
12	19	30	40	50	59	67
13	17	27	38	48	57	66
14	15	25	35	45	55	64
15	14	23	33	42	52	61
16	13	21	30	39	50	59
17	-	20	28	37	47	56
18	-	18	26	35	44	53
19	-	17	25	33	41	51
20	-	16	23	31	39	48

Table A2.4 Annual top height increment, in centimetres per year, for Japanese larch.

Top height (m)	Yield class					
	4	6	8	10	12	14
8	34	44	52	59	67	75
9	31	42	50	58	65	73
10	28	39	48	56	63	71
11	24	36	46	53	61	69
12	21	33	43	51	59	66
13	17	30	40	48	56	64
14	14	26	37	46	53	61
15	11	23	34	43	51	58
16	8	20	30	40	48	55
17	-	17	27	37	45	52
18	-	14	24	33	42	49
19	-	12	21	30	39	46
20	-	9	18	27	36	43

Table A2.5 Annual top height increment, in centimetres per year, for Sitka spruce.

Top height (m)	Yield class									
	6	8	10	12	14	16	18	20	22	24
8	36	43	49	54	58	63	68	74	80	86
9	34	42	48	53	58	63	69	75	81	88
10	33	40	47	53	58	63	69	75	82	88
11	31	38	46	52	57	63	69	75	82	89
12	29	37	44	51	57	62	69	75	82	89
13	27	35	42	50	56	62	68	74	81	88
14	25	33	41	48	54	61	67	73	80	87
15	22	31	39	47	53	60	66	72	79	86
16	18	29	37	45	52	58	65	71	78	85
17	14	27	35	43	50	57	63	69	76	83
18	12	24	33	41	48	55	61	68	74	81
19	-	20	31	39	46	53	59	66	72	79
20	-	16	28	36	44	51	57	64	70	76

Table A2.6 Annual top height increment, in centimetres per year, for Norway spruce.

Top height (m)	Yield class								
	6	8	10	12	14	16	18	20	22
8	30	38	45	50	54	57	60	64	67
9	29	36	44	49	53	57	61	64	67
10	28	34	42	48	53	57	61	64	67
11	27	33	40	46	52	56	60	64	67
12	25	31	38	45	50	55	60	63	67
13	23	30	36	43	49	54	59	63	66
14	21	28	34	41	47	52	57	62	65
15	19	26	32	39	45	51	56	60	64
16	18	24	30	37	43	49	54	59	63
17	15	22	29	35	41	47	52	57	62
18	13	21	27	33	39	45	50	56	61
19	-	19	26	31	37	43	48	54	59
20	-	17	23	29	35	40	46	52	57

Table A2.7 Annual top height increment, in centimetres per year, for Douglas fir.

Top height (m)	Yield class								
	8	10	12	14	16	18	20	22	24
8	55	63	68	73	78	83	88	93	99
9	54	61	67	72	78	83	88	93	98
10	51	59	66	72	77	82	87	92	98
11	49	57	64	71	76	82	86	91	97
12	46	55	62	69	75	80	86	90	96
13	43	52	60	67	73	79	85	90	94
14	41	50	58	66	72	78	84	89	93
15	38	48	56	63	70	76	82	87	92
16	36	46	53	61	68	75	81	86	90
17	35	44	51	59	66	73	79	85	89
18	33	42	49	56	64	71	77	83	87
19	31	39	46	54	61	68	75	81	85
20	29	36	44	51	59	66	73	79	83

Further reading and useful sources of information

Forestry Commission publications

Guidance

- Forest mensuration: a handbook for practitioners (FCBK039)
  An essential, practice-based handbook designed to help all those working in the timber trade and forestry understand how to measure trees and timber.
- Woodland Carbon Code: carbon assessment protocol
  The recommended procedures for undertaking a comprehensive carbon assessment of the living tree biomass within an area of woodland.

Research archive (www.forestry.gov.uk/publications)

- Forest management tables (FCBK016)
- Forest management tables (metric) (FCBK034)
- Yield models for forest management (FCBK048)
- The carbon content of trees (FCTP004)
- Provisional yield tables for poplar in Britain (FCTP006)

Other publications

- The Strength properties of timber (Building Research Establishment Report)

Glossary

Basal area The cross-sectional area of the stem of an individual tree at its breast height point (1.3 m from ground level).

Basal area per hectare The sum of the basal areas of trees in an area of woodland expressed on a per hectare basis.

Biomass (of a tree) All of the material making up a tree or one of its components such as stem or branches.

Branch The woody material of trees excluding the stem, stump and roots.

Clearfelling The periodic harvesting of trees in a woodland, involving the complete or near-complete removal of standing trees for commercial utilisation.

Crown The branches and foliage of a tree.

Cumulative volume production An important measure of volume productivity in forestry that represents the total production of timber volume from a stand up to a given year in the stand's development. It is calculated as 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.

Diameter at breast height (dbh) The diameter on the main stem of a tree at 'breast height', i.e. 1.3 m from ground level. See Section 3.1 of *Forest mensuration: a handbook for practitioners* for more details.

General Yield Class (GYC) An index used in Britain, derived from GB-level top height on age curves, for the potential productivity of even-aged stands of trees. See the section on 'Yield class', starting on page 24, for more details.

Hectare (ha) Unit of area equivalent to 100 m x 100 m = 10 000 m^2 (1 ha = 2.47 acres).

Intermediate thinning A type of selective thinning which involves the removal of most of the suppressed and sub-dominant trees, and also the opening up of the canopy by breaking up groups of competing dominant and co-dominant trees. This encourages the development of the remaining trees and leaves an open and fairly uniform stand.

Local Yield Class (LYC) An index used in Britain, derived from direct assessments of cumulative volume production, of the potential productivity of even-aged stands of trees. See 'Yield class', starting on page 24, for more details.

Management prescription The combination of initial planting spacing, thinning regime and age of felling applied to a stand of trees.

Mean annual increment (MAI) A measure of the volume productivity of forest stands (usually even-aged). Mean annual increment is the average rate of cumulative volume production up to a given year. In even-aged stands, it is calculated by dividing cumulative volume production by age.

Mean dbh The dbh relating to the mean basal area of the trees in an area of woodland (i.e. quadratic mean dbh, or root mean square dbh).

Numbers of trees per hectare The number of trees in an area of woodland expressed on a per hectare basis.

Oven-dry tonne (odt) Unit of mass. When applied to wood, it represents the mass of wood in tonnes, not including the mass due to the moisture content of the wood (which may vary considerably).

Overbark The volume or diameter of wood including the bark.

Overstocked A subjective term used to describe a stand composed of: *either* trees where continued growth is constrained by extensive competition between their crowns; *or* trees where the stocking density is greater than a specified target level, for example as obtained from a standard yield table; *or* both of the above.

Planimetric area The area of a piece of land calculated based on the vertical projection of its boundaries, i.e. as commonly displayed on a map. A planimetric area for land on sloping ground is typically smaller than the true area based on distances measured along the slope(s).

Respacing The practice of removing trees in a pre-commercial thinning in a young stand of trees to increase the spacing between trees to achieve a target number of trees per hectare. Respacing may be undertaken for a number of objectives, for example to avoid excessive competition between trees.

Stand A distinct area of woodland, generally composed of a uniform group of trees in terms of species composition, spatial distribution, age class distribution and size class distribution.

Standing volume A measure of timber volume within standing trees. Usually expressed as cubic metres overbark standing.

Stem The woody material forming the above-ground main growing shoot of a tree. By convention, in Forest Yield, the stem is taken to include all woody volume above ground with a diameter greater than 7 cm overbark. This may mean that significant 'straight' branches (i.e. more than 3 m length greater than 7 cm top diameter) are included as part of the main stem volume.

Stocking/stocking density Usually the number of trees in a given area, generally expressed on a per hectare basis. Sometimes used to refer to basal area or volume per hectare.

Thinning The periodic harvesting of trees in a woodland, involving the removal of some trees for commercial utilisation and the retention of others for future production or long-term retention. See the section on 'Thinning treatment', starting on page 47, for more details.

Top height The mean total height of the 100 trees of largest dbh in a hectare of woodland. Usually assessed on a sample of the trees of largest dbh in a series of circular plots of 0.01 ha in area.

Understocked A subjective term used to describe a stand composed of: *either* trees with significant open (and by implication 'unproductive') space between their crowns; *or* trees where stocking density is less than a specified target level, for example as obtained from a standard yield table; *or* both of the above.

Volume/volume per hectare The stem volume, expressed in cubic metres, to 7 cm top diameter overbark of an individual tree, group of trees or all the trees in a woodland. Volume can be expressed on an individual tree, per hectare or whole-group/stand basis.

Yield class An index used in Britain of the potential productivity of even-aged stands of trees. See the section on 'Yield class', starting on page 24, for more details.

Yield models are one of the foundations of forest management. They provide information about the patterns of tree growth and potential productivity that can be expected in forest stands of different tree species, with varying growth rates, when managed in different ways. Yield models are in daily use by forest managers and practitioners when making decisions about the future management of a forest – whether it is an individual stand of trees or a whole estate. They are also applied when forecasting future levels of production, when making commitments to supply timber markets, and for planning and scheduling forest operations. The outputs of yield models support many other calculations and models relevant to the evaluation of forests and forestry. These include analyses of the development of forest structure at the stand and landscape scales, the modelling of timber and wood properties, the estimation of forest biomass and carbon stocks, the modelling of forest greenhouse gas balances and the economic evaluation of forest policies and forest management options. This handbook is designed for those who would like to know more about the theory underpinning yield modelling. It will be of use to forest and woodland managers and practitioners, researchers and students.

Forest Research

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