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Continuous Cover Silviculture & Mensuration in Mixed Conifers at the Stourhead (Western) Estate, Wiltshire, UK.

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1. Introduction

The Stourhead (Western) Estate represents the western portion of the historic Hoare Estate in southwest Wiltshire and this largely wooded property remains in the family's ownership today. The Hoare family's occupation here began with the purchase of the manor of Stourton in 1717. The adjacent Greensand escarpment and its environs had been heavily wooded in the early Saxon period and formed the core of the Royal Forest of Selwood Forest. By the later medieval period, however, this area had become a mixture of woodland, farmland, deer park and heathy commons; with the piecemeal disafforestation of the legal Royal Forest, the amount of woodland cover decreased progressively to a low point that coincided with the Hoare's arrival.

The present land-use pattern was largely created from 1741 onwards by Henry Hoare II (1705-85) and his grandson, Sir Richard Colt Hoare (1758-1838). They embarked on a major afforestation programme and also created the Park and outstanding designed landscape garden to the south of Stourhead House that is now in the ownership of the National Trust. By the end of the 19th century the oldest afforestations were 150 years old and it is clear from Richard Colt Hoare's writings that some of these first planted woods were already in a second rotation. Originating as mixed plantations including oak, beech, chestnut and sycamore together with spruce and larch, most of these older stands were probably largely broadleaved by this time but continued planting through the middle of the 19th century was at a ratio of 2:1 in favour of coniferous species. These mixed maturing woodlands now served as the backdrop to the gardens.

In 1894 a new owner, Sir Henry H.A. Hoare, the 6th Baronet, inherited at the age of 29 and in 1899 he undertook a survey of the woodlands of all his estates with a view to introducing more rigorous management[1]. Each area was assessed separately for timber and underwood with brief notes on future management. At the end there are general comments as follows:

"The large Stourton Woods are as a rule devoid of underwood except in small patches and there can be no doubt, seeing that there is scarcely any market for underwood, that it will be useless to attempt to plant these woods to underwood – the best policy seems to be to clear convenient areas and plant with firs or deciduous trees to bring crops of timber poles and pitwood. In many cases it may be wise, where the underwood is ripe, but thin, to leave a large number of standards so as to secure from them in due course of a few years crops of poles and pitwood. The areas to be cleared and replanted will have to be marked out with great care – both as to the sorts of plants and closeness of planting, and as to shelter from gales and effect on the landscape."

This report represents the beginning of systematic forest management at Stourhead although clearly 150 years of plantation forestry had already been successful in creating the forest. Over the next 25 years a steady programme of felling and re-stocking using mainly Douglas fir, Sitka spruce, European and Japanese larch took place, the ratio of conifers to broadleaves was 4:1. The current stock of very large Douglas fir dates from the early 1900's and represents some of 6th Baronet's first plantings. The Working Plan of 1927 re-iterates that the primary objective of management was: " to maintain the aesthetic beauty of the estate"[2].

The emphasis on maintaining the landscape quality of the estate in general and the aspect which formed the backdrop to the Gardens in particular, lead to the avoidance of clear-felling and the adoption of the small-scale group felling system. This policy was continued after the gifting of

[1] Report on Stourhead Estate Woods, May 1899, Stourhead (Western) Estate Archive
[2] Stourhead Woods Working Plan 1927 to 1936, Stourhead (Western) Estate Archive.

the eastern portion of the Estate to the National Trust in 1946 and there was a period of accelerated re-stocking in the 1950s and 1960s.

By the 1980's over 1200 small even-aged units were identifiable across 500 ha of forest. Despite the widespread and sustained use of plantation silviculture a specific policy of encouraging coniferous species likely to be able to regenerate naturally was explicitly followed by the present owner's grandfather, Henry Peregrine Rennie Hoare and father, Henry Cadogan Hoare, and the small-scale group felling system was sustained. Making a profit from woodland management became increasingly important, however, as forestry was now the major economic activity on the estate.

Over the last 100 years this approach to forest management provided a uniquely beneficial platform from which to move away from plantation forestry and the advent of widespread natural regeneration from the early 1990's onwards has prompted a transition to Continuous Cover Forestry techniques in which permanently irregular structures are being developed. This transformation began formally in 1998.

With the acquisition of Forestry Commission leaseholds the Stourhead (Western) Woods now cover 652 hectares. Overall around 75 % is coniferous (470 ha) and contains some of the most developed mixed coniferous irregular structures in the UK.

The management of the woods at Stourhead (Western) are in the hands of David Pengelly and Andy Poore of Selectfor Ltd. The practice outlined below has developed through the application of Continuous Cover principles across a range of sites in Southern England managed by the author and David Pengelly over the last 15 years.

2. Topography & Soils

Geologically the landscape of Stourhead (Western) Estate lies on the junction between the chalk-dominated Cretaceous 'uplands' to the east and the Jurassic clays and sands which form the lowland vales to the west, the junction forming the large-scale escarpment feature which follows the north-south boundary of Somerset and Wiltshire south of Frome.

Generally in this region the Cretaceous Upper Greensand, which lies below the chalk, forms a relatively narrow escarpment with a thin layer of Gault clay marking the non-conformity below which the Jurassic strata begin. At Stourhead (Western) however, a wider outcrop of Greensand occurs and forms valley features behind the main escarpment. On the slopes and the bottoms of these valleys the junction with the Gault clay is marked by springs. At the end of the last glaciation high ground water levels lead to extensive rotational landslipping of the Greensand on both the main escarpment and the 'inland' valley slopes. This created a series of backward facing steps that formed an awkward topographic mosaic of dry areas and wet flushes that was one reason why the area retained extensive woodlands into the Saxon period. A feature of the upper slopes is the presence of large quantities of chert, a very hard crystalline mineral rather like flint.

Soils developed on the in situ Upper Greensand can be strongly acid but soil and nutrient movement downslope leads to somewhat less acid and more fertile conditions on the lower slopes producing well developed brown earths of varying degrees of moderate podsolization and stoniness. The wet flushes provide a strong contrast with their fresh, moderately base-rich soil profiles. Considering the limiting factors for tree growth, the acidity of the podsolized cherty, soil types excludes nitrate-demanding species such as ash and sycamore and might be expected to result in low phosphate availability with detrimental effects on the growth of species such as Douglas fir. This problem does not occur, however, probably due to the presence of glauconite in the rock mix. The lower slopes also receive water and solute enrichment from up-slope and these ‘water-receiving sites’ compensate for the moderate annual rainfall of 1050 millimeters.

Overall these sites have long been known as some of the most productive for tree growth in England, particularly with regard to the northwest American conifers. Yield classes for Douglas fir, Sitka spruce and western hemlock all exceed 20 cubic metres per annum. Other major coniferous species are western red cedar, Norway spruce and larch.

The moderate fertility of the surface soil layers is also beneficial to natural regeneration since ground flora competition is relatively weak, although bracken can be a problem where understories are absent on the more acid sites.

3. Silvicultural Policy at Stourhead (Western) Estate

Silvicultural policy at Stourhead (Western) is governed by the need to make a profit from the Estate’s main asset whilst maintaining landscape quality.

The aim of producing quality timber at low cost without disrupting the landscape is being achieved through the application of Continuous Cover principles designed to produce permanently irregular structures. Management focused on a 1000 small plantations has been replaced by an approach that now deals with larger compartments often containing 10 or more productive species and incorporating complex aggregations of the 20th century plantation units whose boundaries are now increasingly indistinct as new size-classes are being recruited.

The silvicultural approach has a number of key features with regard to timber production:

- A focus on the production of quality timber including large-dimension sawlogs over 80 cm dbh. Overall we are seeking to produce more large trees and fewer small trees than is produced in a comparative even-aged, plantation cycle.
- No attempt is made to impose any regular spatial arrangement of stems after an intervention; good trees are not removed because they are perceived to be in the wrong place. This holds the key to improving timber quality since it allows complete freedom to persistently remove all lower value elements of the stand.
- Optimisation takes place at the scale of the individual tree and not at compartment level. We are trying to maximize the value of each quality tree subject to the needs of the whole stand.
- Maintaining good stems until they reach their optimum size compatible with an appropriate sustainable structure is given the highest priority. Good trees are not felled to produce a pre-determined structure.
- Natural regeneration is the normal means of regeneration. It is supplemented by planting in order to introduce key species where current conditions are not suitable due to lack of seed sources, loss of control of the seedbed etc. Generally planting is restricted to Douglas fir, western red cedar, larch and oak.
- Tending is employed to adjust species composition at the seedling/ small sapling stage, and in particular to manage western hemlock regeneration, and to ensure that a reasonable number of high quality individuals are available for recruitment into the main stand of key species such as Douglas fir.

The whole 650 hectares are very prominent landscape features: to the west the stands cover the escarpment which is very prominent in the landscape of south-east Somerset and to the east they are an integral part of the Stourhead Historic Landscape. In addition to the avoidance of major disruption through concentrated fellings the working plan includes a fairly sophisticated approach to creating a more homogeneous landscape in which sharp contrasts between evergreen conifers and deciduous conifers and broadleaves are reduced and where mixtures of varying compositions, including a broadleaved element, are developed throughout.

4. Stand Development & Mensuration in Mixed Conifer Continuous Cover Stands

The general aim of this approach to silviculture is to fill the stands with vigorous stems and to develop an optimal growing stock composition by distributing the available timber increment onto the quality stems whilst creating a sustainable framework in which an appropriate distribution of size groups is combined with sufficient seedling regeneration and recruitment into the main stand**.**

In the transformation of even-aged coniferous stands we recognize three well-defined stand development stages as shown in Table 1.

Table 1. Stand Development Model for Conifers

Stage 1. Preparatory Stage: (before seeding starts)

- Achieve stand stability by early thinning and then maintaining stand volumes near to even-aged 'Management Table' (MT) levels. Towards the end of this stage basal area (after thin) should reduced to between 5 and 10% below MT levels (depending on species).
- Avoid imposing regular spatial distributions and promote clumpy spatial distribution
- Improve phenotypes by the intensive removal of stems with negative characteristics, subject to non-timber production objectives.
- Promote species diversity by ensuring that secondary and minor species are maintained within the stand.

Stage 2. Regeneration Initiation Stage

- Reduce stand volume/ basal area below the long-term target to initiate regeneration. These levels will be substantially below equivalent even-aged MT levels, some 15-30% depending on species.
- Maintain intensive removal of stems with negative characteristics.
- Maintain secondary and minor species and other differentiated stand elements.

Stage 3. Structural Development Stage

- Allow stand volume to increase towards target volume/ basal area.
- Develop full structural and species diversification. Move towards long-term targets for size-class distribution.
- Relate stand structure to increment to guide structural development.

In Stages 1 & 2 it is broadly a question of achieving a *size* of growing stock that is compatible with the species composition and the site in order to get regeneration started. In Stage 3 the emphasis switches to the development of a sustainable structure.

At Stourhead (Western) the most advanced stands are in Stage 2 or the beginning of Stage 3.

Felling Cycle will vary with productivity and the degree to which growing stock size needs to be reduced. At Stourhead (Western) a cycle of 4-5 years has generally been used up to the middle of the Regeneration Initiation Stage. As stands enter the Structural Development Stage the cycle will adapt to productivity: the more productive sites at Stourhead (Western) are on a 4-5 year cycle whilst in less productive stands the cycle is extended to a 6-7 years.

Clearly there is a need to define some targets with regard to the stand development path defined above but currently there is virtually no guidance for the UK. There is, however, relevant information from continental Europe that could be 'calibrated' for our use. It should also be borne in mind that these targets will never be definitive; in Switzerland with its long tradition of selection forestry and mensuration, it has been clear for a long time that such targets are 'local and unstable', i.e. they are site and species specific and may change over time with climatic variation (Knuchel, 1953).

The two main target parameters are *growing stock size* for a given species composition and site and the *size-class distribution* that will be maximize quality timber increment whilst allowing sufficient recruitment into and through the main stand.

Growing stock size can be defined in terms of basal area or volume per hectare. When comparing forests in different locations and countries, basal area is to be preferred since it avoids the issue of local volume tables that will vary considerably.

Size-class distribution can be described by the use of a stem/ diameter distribution curve usually using small diameter classes of 2 or 4 cm. Alternatively, broader diameter class groups, usually 3: large, medium and small, can be used and the targets derived by allocating a percentage of basal area or volume to each.

In using size-class distribution targets care should be taken to use them at the strategic level, they should be used as part of the background to decision making and should not directly determine whether a particular tree is cut. For this reason we do **not** construct a stem/ diameter distribution curve prior to marking and further, because of the uncertainty about the precise nature of the targets, we prefer to define size-class distribution targets by the percentage of volume attributable to broad diameter-group.

In the end the determining of the 'ideal growing stock' of an appropriate size and structure for a particular stand can only be achieved by an iterative process of measuring the output of the stand over a long period and relating this to its developing structure. The main output parameter used to measure this is *timber increment*. Again, timber increment can be defined using basal area or volume and should be available by species and by diameter-group. Ideally the distribution of increment across broad timber quality classes should also be recorded where quality timber production is the main focus as it is at Stourhead (Western). Further, diameter increment is a useful parameter particularly if this can be related to particular species and size-classes.

Finally, it will also probably be necessary to monitor the progress of *regeneration and recruitment* in order to determine whether the sustention of the smaller elements of the stand is compatible with a given structure.

5. Mensuration at Stourhead (Western) Estate: Objectives & Methods

The aim of the mensurational programme at Stourhead is to produce information relating to growing stock size and structure in relation to the timber increment produced by the different species and size elements of the stands. Whilst this information could be useful for developing CCF practice in other parts of Lowland UK, the primary purpose was to derive information to inform the management at Stourhead (Western).

In order to produce information about the development of the more advanced stands we have followed the approach adopted by Henri Biolley in Neufchatel at the end of the 19^{th} century when he pioneered the adoption of the selection system into what were then predominantly even-aged stands. He selected the most irregular parts of the forest and introduced periodic enumerations using the Check Method to determine increment and to relate it to stand structure and composition. In due course a large part of the forests of Neufchatel have been enumerated and some forests such as Couvet have data series covering 120 years.

At Stourhead (Western) we selected three of the most structurally developed stands with varying species composition and on different site types as local research stands. These cover 37.50 ha, or 7.5% of the coniferous dominated stands. The intention is to use this information to guide management of the other, currently less developed, areas. A description of the three local research stands is given in Table 2 and photographs of the Sample Stands area attached at Appendix 2.

The Check Method is well described in the continental literature (see for example Knuchel 1953) and was pioneered in the UK by the late Michael Reade on his estate at Ipsden in the Chilterns (Reade 1990). Our calculation protocols derive from Knuchel and the practical application of the method at Stourhead (Western) was guided by Reade's papers and personal comments.

In brief the method involves measuring the diameter at breast height of all trees above a certain minimum, in our case 16 cm, and the diameter of all trees removed. In reasonably developed structures the amount of basal area contributed by stems in the smaller size classes will be very small whilst the measurement cost will be high.

With two enumerations the periodic timber increment contributed by the initial stand is calculated using the formula:

Volume of Initial Growing Stock – Volume of Final Growing Stock + Volume of Stems Removed

Over the period between enumerations some stems will have grown over the minimum measurable size and have been 'recruited' into the measurable stand. The volume of these stems is calculated separately. Total increment is taken as the sum of the increment on the initial stand and the 'recruitment'.

Increment can be expressed in basal area. However, conversion to a volume measure is useful in relation to timber removals and the standard approach is to use a simple, single-entry volume table (in the case of Stourhead (Western) one for conifers and one for broadleaves). Given that an average height is used for each diameter class, the volumes produced may differ a little from the felled measure until a complete range of diameters are present. In order to differentiate this 'standing measure' from that used to measure felled volume the term 'silve' has been used in Europe to denote a cubic metre measured by the standing tariff. For clarity we will use the term 'standing cubic metre (st cu m)' instead.

The increment calculation can be undertaken by species, or groups of species, and by diameter-group in order to determine the fastest growing elements in the stand. These parameters provide worthwhile results as long as the disaggregated elements contain enough data; it is difficult to obtain satisfactory information for narrow diameter classes. However, using a different kind of calculation it is possible to calculate the average *time of passage* (in years) that a stem takes to pass through narrow diameter classes. The reciprocal of this gives the average annual diameter increment.

Increment can also be expressed as a percentage of the Initial Growing Stock to show the average annual timber 'return' for the period. The productivity of different elements of the stand can be examined by comparing the 'timber return' on various parts of the forest capital.

6. Results

6.1. Growing Stock

The main results for the 3 sites are shown in Table 3 and the species composition of each stand at 2006 is shown in Figure 1. The changes in species composition since 2000 were small.

At Dropping Gutter basal area in 2000 was 29.78 sq m per ha one growing season before a major intervention. Interventions took place in financial years 00/01 and in 06/07 just prior to the second enumeration. In 2006 the basal area was 28.13. The change in the distribution of volume between diameter-group is shown in Figure 2.

At Great Combe basal area in 2002 was 29.14 sq m per ha. Two interventions have occurred during the measurement period in 02/03 and in 04/05 when only large trees were removed. In 2006 the basal area had 31.1 sq m per ha just before the next intervention which will be in 07/08. The change in the distribution of basal area between diameter-group is shown in Figure 3.

At Berridge basal area in 2002 was 25.57 sq m per ha and in 2006 this had fallen to 23.3 sq m per ha. Only one intervention has occurred in 03/04 and the next intervention will be in 09/10. The change in the distribution of basal area between diameter-group is shown in Figure 4.

6.2. Increment

The increment data for each species or species group is presented in Table 4.

Species composition differs considerably between the 3 stands and in particular the proportion of broadleaves, which generate a low increment compared to their contribution to their basal area.

Overall, Great Combe has the highest increment at almost 16 standing cubic metres per ha reflecting the high proportion of conifers and the valley bottom site. Dropping Gutter and Berridge are rather similar to each other in terms of nutrient availability but both have high proportions of broadleaves and Berridge also has a lot of larch. In volume terms Dropping Gutter is currently 25% and Berridge 45% less productive than Great Combe.

In order to be able to compare the coniferous species across the site-types represented by the 3 stands, we have included a calculation of the basal area per hectare for the coniferous element alone. This shows that the area covered by conifers at Great Combe has an increment of 16.87

standing cubic metres compared to 15.48 at Dropping Gutter. If we exclude the larch element from the Dropping Gutter figure then the result for the evergreen conifers is very close to that of Great Combe at 16.59 standing cubic metres per hectare. The differences in site productivity between Great Combe and Dropping Gutter do not, therefore, appear significant.

Figure 5 shows the productivity of different elements of the stand by looking at the increment as a percentage of the initial growing stock to produce a figure showing the annual ‘timber return’ on that part of the forest capital. These data are available for the main species and for diameter-groups. The quality of these data is good for Dropping Gutter as a whole and for larch at Berridge.

Figure 5 shows that Douglas fir is sustaining a 5% return in timber volume terms for the small, medium and large diameter-group despite the fact that the larger trees have a larger capital on which to express the increment. In the very large category the initial size of the trees, i.e. their high ‘capital value’, begins to have the effect of reducing the increment percent although the return of the very large trees is still good at 3%. These returns are clearly out-performed by the other evergreen conifers, particularly Sitka spruce and western hemlock and here the large category is returning 6.5% and the very large 4.5% that are very good results. On the other hand the performance of larch is clearly much inferior to the other conifers and is generally below 2% per annum with is a somewhat higher return for the very large category of larch at Berridge. Clearly timber values for the various sizes and qualities must also be brought into the equation when evaluating these results.

Increment percents produce growth data relative to the tree’s volume. In order to measure diameter growth directly we use the ‘time of passage’ calculation and this can be applied to narrower diameter classes. However in order to produce meaningful results there must be a significant amount of data available and this is only the case here with Douglas fir and the spruce, hemlock, red cedar species group at Dropping Gutter; the more developed structure at Dropping Gutter potentially allows divergences when compared to a regular structure to be clearly seen. The results are shown in Figure 6. This shows that diameter growth continues to accelerate as the trees get larger and not only for Douglas fir but also for the spruce and hemlock dominated species group as well. The trees that are growing fastest in absolute terms are in the 72-84 cm dbh range for both species selections. Growth only declines moderately for even larger sizes and the 96 to 108 cm Douglas fir category is still growing twice as fast in diameter as the 24-36 cm dbh class!

6.3. Regeneration

Information on regeneration is only available at present from Dropping Gutter which is now well beyond the Regeneration Initiation Stage. The measurements taken as part of another research project (see page 13 below and Poore, 2006) include regeneration and an average of 2672 seedlings over 50 cm in height per ha were recorded in 2006. 50% of these were hemlock, 30% Douglas fir, 18% Sitka spruce and 2% larch. Here the before-basal area threshold is slightly higher than Great Combe at 32-33 square metres per ha reflecting a movement to a slightly higher growing stock level nearer to what might be a long-term sustainable level.

6.4. Removals

In general removals per intervention are within the range 15-20% of before-thin basal area. Removals tend to be heavier during the Preparatory and early Regeneration Initiation Phase. As the growing stocks are reduced to a lower level the removal rate declines to nearer 15%.

Information on the impact of a particular intervention is available for the recent felling at Dropping Gutter undertaken in the winter of 2006/07. This is shown in Figure 7 where Figure 7a shows removals in terms of the stem number curve and 7b in terms of basal area. The latter is more informative since it shows how the marking has influenced the elements contributing most to growing stock size. Overall basal area was reduced from 32.8 square metres per ha to 28.1, a 15% removal rate. The basal area increment data can be used to reconstruct before-felling basal area thresholds for the other stands and at Berridge it was around 27.5 and at Great Combe around 30-31 square metres per ha.

7. Discussion

7.1. Growing Stock

The growing stocks at *Great Combe and Berridge* illustrate the before-thinning basal area thresholds used for coniferous stands in Stage 2, the Regeneration Initiation Phase; around 30-31 square metres per ha for a stand dominated by moderate shade bearers on the one hand and 26-27 for one dominated by light demanders on the other. From these and other sites these thresholds appear to be appropriate to initiate and sustain the first phase of regeneration in the stands dominated by moderate shade-bearers. It may be, however, that somewhat lower growing stocks are required for those dominated by light-demanders as current experience is more restricted with these stand-types.

At Berridge the lower growing stocks have already lead to a partial loss of control over the ground vegetation under the larch and this has lead to the use of some enrichment planting to supplement natural seeding and chemical bracken and bramble control. The medium-term solution is to achieve better seedbed conditions naturally by encouraging a scattered under-storey element of evergreen conifer which could be cut to waste as necessary to produce patches of receptive seedbed.

Although the distribution of basal area across diameter-group is not given great significance at this stage, both stands are moving in the right direction. Great Combe has a good overall distribution but has a significant imbalance in the larger sizes with a preponderance of very large trees.

At *Dropping Gutter* regeneration is underway and the parts of the stand are regarded as having moved into Stage 3: the Structural Development Phase (see Table 1). Dropping Gutter has 25% broadleaves and 8% larch and if this proportion is to be maintained then locally the growing stock will have to be lower and a lower overall average basal area would be expected. The overall objective with regard to species composition, however, is to allow the proportion of broadleaves to fall to 15% and the individual marking decisions, which at the margin are favouring good quality conifers over moderate quality broadleaves, has lead to a somewhat higher growing stock.

It does appear feasible to manage light demanders and more shade tolerant species in intimate mixture; larch regeneration, for example, arises in amongst the evergreen conifers in small gaps of less than 0.05 ha given an appropriate level of growing stock. However, the need for different levels of growing stock produces more difficult selection decisions that may involve removing shade tolerant individuals before they reach their financially optimal size.

Another complication which arises here relates to the presence of western hemlock; 50% of current regeneration is of this species and if not handled properly it could out-compete more desirable species. There are two techniques being used to avoid this: one involving stand density manipulation and the other tending. Western hemlock is given a competitive advantage by maintaining moderately high growing stocks under which other species will not germinate. Conversely in much more open conditions the success of a wider range of species means that hemlock will not become dominant. So the aim has been to produce in some parts of the stand a mosaic of areas with more variable stocking levels. Some patches of hemlock are retained at a high enough density to discourage germination, and then subsequently removed to reduce the overall percentage of hemlock in the stand. Other areas are maintained at a lower density to encourage larch and spruce to come in along with the Douglas fir and hemlock. After each intervention tending is carried out across the whole compartment, the prescription differing according to height. The primary aim with stems up to about 4.0 m tall is to favour species other than hemlock by selective cutting of the latter. For larger sizes selective pruning of key individuals at low density is also undertaken.

Having said all this, western hemlock is one of the most productive species on the site and the provenance is a reasonably good one. We will learn to live with it.

7.2. Target Growing Stocks

In these developing structures the question arises of what form of stand structure we are aiming at. As has been stated above the lack of detailed research information makes it impossible at this stage to define a target stem frequency curve (or range of curves). We are, therefore, using the percentage of volume in each diameter-group as the target parameter in order to avoid spurious exactness. In the long run we should be able to relate increment to this parameter and by iteration determine how the most productive growing stock is configured.

Three factors are likely to influence the distribution of the growing stock across these diameter classes: site productivity, species composition and crucially, the largest size-class that it is appropriate to grow. Growing stocks which extend into larger size-classes can be less dynamic with larger growing stocks and larger amounts of bigger trees than those, dominated by spruce for example, with smaller maximum sizes.

At Dropping Gutter the ability to sell large Douglas fir means that trees of over 80 cm will be part of the desired stand and as we shall see later we know that in terms of diameter increment these trees are behaving like the large silver fir in central European stands. As a starting point, therefore, we might refer to the common target referred by Swiss foresters for the lowland silver fir, spruce & beech stands of the Jura and Emmental of 20% in the small diameter-group, 30% in the medium and 50% in the large (the latter covering our 'large' and 'very large' categories). The percentage of large trees that a site can accommodate also appears to be related to site type with richer, sheltered sites having a higher proportion of large trees. So, for example, Schütz (1989) states that a range of target ratios of say 21/22/57 to 21/37/42 might be expected for high producing species and sites in the Swiss Jura using similar diameter-group ranges to those used at Stourhead (Western). In Schütz (1997) the affect of maximum size-class in these stands is shown theoretically with a maximum of 120 cm in diameter generating a simulated ideal growing stock with 50% large trees over 55 cm compared with a 60 cm maximum equating to one with only 12% in the largest category.

At Stourhead (Western) the mixed stands dominated by Douglas fir, spruce and hemlock are likely to be reasonably close in silvicultural characteristics to the Swiss stands referred to above and we are suggesting a provisional target ratio of 20/35/45 based on a maximum size of around 96 cm. This is likely to be the maximum proportion of larger trees which is desirable and this target may have to be revised downwards.

The current ratio at Dropping Gutter is 8/39/53. The lack of small trees will be made up in due course now that regeneration is beginning to be recruited into the main stand. Marking in future will need to guard against a further increase in the larger trees. At Great Combe the ratio of 22/29/49 appears nearer the target but this is deceptive since there are a high proportion of very large trees and the structure is less diversified than Dropping Gutter; the current ratio is thus less meaningful. As with Dropping Gutter, however, the next interventions will have to press hard on the larger size-classes.

At Berridge, where light demanders dominate, the production of very large trees will be less appropriate from both marketing and silvicultural reasons and thus a different target ratio would be appropriate. Something closer to a ratio of 30/40/30 might be a more suitable provisional target here. This is closer to the ratio for UK coniferous stands on reasonable sites of 30/35/35 proposed by Patterson (1958).

7.3. Increment

The most significant result arising from the increment calculations is the behaviour of *diameter increment* across different size-classes at Dropping Gutter. This shows that trees growing in the more or less open conditions of the upper canopy level in a fairly developed structure increase in absolute diameter growth as they increase in size. The fastest growing Douglas firs are in the very large category and these are growing much faster than those in the small category. The profile shown in Figure 6 replicates the well-established relationship found in silver fir dominated selection stands in Central Europe. Given the ability to sell large Douglas fir at a premium, the price-size curve rises up to and beyond 80 cm dbh, this is an important result for the economics of such stands: increment is being concentrated on the fastest growing and most valuable stems. Sitka spruce and western hemlock are growing even faster in the larger size-classes but this is less advantageous financially since larger stems of these species do not attract a premium. A crude indication of how this might relate to an even-aged stand of Douglas fir is shown by including two points derived from the YC 20 Management Tables for the diameter increment of stands with a comparable average dbh (Christie & Edwards, 1981).

Volume increment expressed as a percentage of the initial growing stock provides a measure of the *timber production 'return'* for particular species or size-classes. The 5% per annum which the Douglas fir is 'earning' at Dropping Gutter across all but the largest size-classes compares very favourably with the 2.5 to 3.5% increment percentages usually achieved in Swiss silver fir selection stands (Zingg et al 1997). Even the 'very large' class is returning a respectable 3% per annum. When you add in the fact that the best quality stems are increasing substantially in price per cubic metre as they rise above 80 cm dbh, the overall annual increase in value of these stems can reach 9% per annum!

Another marked feature of Figure 5 is the much lower timber 'return' of larch. At Dropping Gutter this is partly the result of the level of the growing stock that is somewhat higher than optimal for larch. Timber increment is not that much better at Berridge, however, where stand conditions are more appropriate. Overall, these results highlight the marked sacrifice in timber production terms involved in growing larch on these sites. The very low increment of the broadleaved elements is also a feature of these results although the same provisos with regard to growing stock size apply here also.

The *actual absolute increment* produced by Douglas fir and the evergreen conifers, based on the basal area that they occupy, is 16.5-17 cubic metres per annum per ha on both Dropping Gutter and Great Combe. This compares with an average yield class for Stourhead (Western) of around 20 cubic metres per annum per ha for Douglas fir and 22 for Sitka spruce and hemlock.

It should be borne in mind that the yield class system is a site classification system and is not directly concerned with measuring the actual output of a stand; the yield class number is the maximum feasible production averaged over the life of the stand presuming that it is managed to maximize volume production and that it is felled at its optimum age. In general there is little information about ***actual*** production, except for the small FC research plots on which the Yield Class/ Management Table system is based. We do not know in practice what a reasonably stocked YC 20 Douglas fir stand actually produces over its life under 'real-world' conditions.

There are a number of reasons why actual production in a regular or irregular stand might be less than this predicted maximum. Firstly, a normal stand would have some areas that are unstocked, roads and rides loading bays etc. Normal production forecasting reduces 'Management Table' volumes by 15% to convert real stands from a gross area to net, i.e. fully stocked, basis. Secondly, management may not be directed at maximizing timber production. Somewhat lower stocking in regular stands may be justifiable if it accelerates the production of the more valuable elements. In terms of stands under transition to an irregular structure there may be periods when stocking density is sub-optimal when compared to 'management table' stocking. Thirdly, with regard to an irregular stand conditions may not yet be ideal and further development may lead to increasing yields.

In the event at Dropping Gutter and Great Combe actual production for the gross area of the stand is about 20% below the absolute maximum 'management table' prediction. This means that in net area terms the difference is probably less than 10%. It may also be that as the structure develops production may increase. In summary there is no evidence for a significant loss of production in these irregular stands by the early part of Stage 3 of the transformation process.

Compared with the classic Swiss selection stands on good sites dominated by silver fir and spruce, the conifer element at Dropping Gutter and Great Combe is more than 30% more productive; the best Swiss examples have increments of 12-13 standing cubic metres per ha (Zingg et al 1997).

7.4. Removals

The data regarding removals can be construed in different ways: the average stem removed can be related to the average tree in the stand before or after thinning and the overall removals can be seen in relation to increment. Finally, the decisions to remove individual trees can be investigated.

Table 3 shows that for coniferous species the stands vary with regard to the relationship between the *average volume of tree removed* and that of the stand as a whole. At Dropping Gutter, with its more developed irregular structure, the average tree removed over the 7 year period was 1.58 standing cubic metres. This was significantly higher than the average tree at the first enumeration and is virtually identical with that recorded in 2006. This reflects the marked shift in the distribution of the stand between the diameter-groups referred to above. The large size of the average tree removed is reflected in the assortment;; of the 1816 cubic metres of softwood removed over the period at Dropping Gutter, 88% were sawlogs.

At Berridge the average stem removed is similar to the stand average at both enumerations, showing a balance between an overall reduction in growing stock and movements between size-groups. At Great Combe the average stem removed is now significantly below the stand average, largely reflecting the fact that a major intervention is due imminently.

Table 3 shows the relation between the *overall volume removed and the overall volume increment* during the measurement periods. At Dropping Gutter removals in volume terms were in balance with the increment reflecting that growing stock size is beginning to stabilise. At Berridge removals were significantly greater than increment at 12% in volume terms reflecting that management has the aim of reducing the growing stock size to an appropriate level. At Great Combe the relationship is difficult to interpret due to the way the cycle of felling has interacted with the measurement period.

An attempt was also made to analyse the *decisions behind the selection of individual trees.* Dropping Gutter is the first GB site in an expansion of a large French continuous cover research network (Poore, 2006). Part of this methodology includes such analysis and this was trialed at Dropping Gutter for all stems over 30 cm dbh during the 0607 intervention. This showed that 43% of stems were removed because they were relatively low quality or, occasionally, were interfering with better quality elements in a lower strata, i.e. they were removed to improve the stand; 38% were larger trees which had reached their optimum economic value and 10% were removed for sanitary or extraction reasons. 6% were removed to favour biodiversity features, largely senescent or dead standing hardwoods. Only 2% were removed in order to favour natural regeneration. This emphasizes that with this silvicultural approach the tactical decisions relating to tree removals at the local scale are directed at the standing trees and are not influenced by the presence of regeneration. The progress of regeneration and recruitment is controlled by the overall size and composition of the growing stock at a wider strategic scale.

8. Conclusions

The data collected at Stourhead (Western) allows us to begin to verify the approach which we have been putting into practice over the last 15 years with respect to transforming even-aged coniferous stands.

Table 5 gives some provisional figures for the levels of growing stock appropriate for the period during and just before the initiation of the first regeneration events take place. It appears that it is Norway spruce stands which require a greater reduction in growing stock during the transition from Stage 1 to 2 than Douglas fir and larch dominated stands. These thresholds correspond to the lower end of ranges suggested in Mason & Kerr (2001). Table 5 also shows how these levels compare with the equivalent for even-aged stands managed to maximize timber production (Christie & Edwards, 1981). Again it is Norway spruce which appears to diverge to a significantly greater degree from 'Management Table levels' than the other species.

It should be stressed that although we have been applying these figures to a range of sites in Southern Britain with different species compositions over the last 10-15 years, these figures are provisional and local in their relevance. Much wider application and more time to evaluate the results of this approach is required.

The diameter increment data for Dropping Gutter shows the very important result that with Douglas fir and other evergreen conifers, increment continues to increase into the very large size-classes once a fairly developed structure is achieved with the largest trees more or less isolated in the upper canopy of the stand. This means that in irregular structures it is possible to target increment on the largest and most valuable stems.

In addition the increment data for size-class and species is key to evaluating the economic performance of these stands. It is possible to derive the actual timber and monetary returns which are accruing for specific classes of trees in the stand. In the case of the Stourhead (Western) Estate we have been able to show that individual stems in the larger tree sizes are returning up to 9% per annum in value. This provides the basis for an approach to economic optimisation based on the individual tree rather than the whole compartment as is the case with even-aged silviculture. The economic data derived from this exercise will form the basis of a further article.

The other key conclusion is the value of the silvicultural data produced by periodic enumeration. Once structures become diversified it begins to be impossible to derive important data by eye. A good example of this is the very swift movements between the medium and large size-classes at Dropping Gutter over a short 6 year period.

The Check Method, or periodic enumeration, allows the direct measurement of production which is essential if the size and composition of the developing irregular structure is to be evaluated. Such direct measurement of timber output also allows accurate assessment of sustainable production levels and can also be used in the developing methodology with regard to carbon accounting at estate level. Because our forests are relatively small and the person marking and monitoring the stands are often the same we have adopted the *sample stand* approach in which a representative set of compartments are completely enumerated. This has cost £80 per hectare across the 37.5 ha of enumerated sample stands for the second enumeration; spread across the.470 ha of coniferous forest on the estate, this amounts to £6.80 per ha. With a re-measurement period of 7 years this amounts to 90p per ha per year.

An alternative approach would be to establish permanent sample plots across larger areas of forest and this might be more cost-effective for large organizations and for larger forest areas.

The sample stand at Dropping Gutter is very large at over 24 ha. However, with regard to the diameter increment calculation and to the high degree of species diversity here it became clear that more data produced more meaningful results. If this parameter is of particular interest and there are a number of main species present, then larger sample stands would be preferable to smaller ones or to the permanent sample plot approach.

Such data is clearly important at the woodland estate level. However, if data becomes available on a series of sites then we would have a more solid foundation on which to base recommendations relating to growing stock size and size-class distributions for a variety of species and sites. Overall a range of methodologies will be appropriate at different levels of complexity and a framework of these is needed across the UK.

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Table 2. Description of Local Research Stands

Stand Name & Area (ha)	Site	Composition *(% by BA)*	Stand Development Stage at 2006 (*after Table 1*)
Dropping Gutter 24.34	Mid to lower slope site on the Upper Greensand landslip with wet flushes distributed across the whole area. Fertility increases downslope.	Very mixed species composition with 32% Douglas fir, including very large size-classes (80-120 cm dbh), spruce & other evergreen conifers 34%, larch 8% and 25% broadleaved species (mainly oak, ash and alder)	Stage 3 across significant parts with diversifying structure and regeneration well established, some parts less developed and still in Stage 2.
Great Combe Middle 7.68	Fertile, valley bottom site	Douglas fir dominated stand (56%), again with large trees, plus 36% other evergreen conifers and 8% broadleaves.	Stage 2 with some even-aged elements remaining; regeneration starting.
Berridge 5.46	Ridge top site on clay cap. Reasonable fertility with extensive bracken.	Larch dominated (44%) with 31% other evergreen conifers and 25% broadleaves (sweet chestnut)	Stage 2 with history of rather low stocking. Enrichment planting used plus natural regeneration.

Table 3. Growing Stock Data

minimum measurable size 16 cm dbh	Dropping Gutter		Great Combe		Berridge	
	Autumn 2006 (For Yr 2007)	**Spring 2000 (For Yr 2000)**	**Autumn 2006 (For Yr 2007)**	**Spring 2002 (For Yr 2002)**	**Autumn 2006 (For Yr 2007)**	**Spring 2002 (For Yr 2002)**
Overall Basal Area (sq m/ha)	28.13	29.78	31.1	29.14	23.3	25.57
Volume (st cu m/ha)	279.86	284.62	330.23	302.48	214.53	229.95
Stems (no/ha)	196.3	239.3	293.5	334.4	263.7	305.9
Years of Main Interventions (Financial Yrs)	00/01 & 06/07		02/03 & 04/05 (large timber only)		03/04	
% of Volume by Diameter Group						
Small (16-32 cm dbh)	8.1	11.3	21.8	29.0	23.3	21.2
Medium (32-52 cm dbh)	39.3	49.6	29.4	23.9	58.5	65.2
Large & V.Large (over 52 cm dbh)	52.6	39.1	48.8	47.2	18.3	13.7
Large (52-72 cm dbh)	*36.1*	*26.5*	*7.7*	*4.6*	*14.3*	*10.7*
Very Large (over 72 cm dbh)	*16.4*	*12.6*	*41.1*	*42.6*	*3.9*	*3.0*

Average Tree (st cu m/tree)	Dropping Gutter				Great Combe				Berridge			
	Conifers		**B/leaves**		**Conifers**		**B/leaves**		**Conifers**		**B/leaves**	
	Autumn 2006	Spring 2000	Autumn 2006	Spring 2000	Autumn 2006	Spring 2000	Autumn 2006	Spring 2000	Autumn 2006	Spring 2000	Autumn 2006	Spring 2000
stand at enumeration	1.59	1.34	0.78	0.74	1.15	0.91	0.32	0.28	0.87	0.83	0.55	0.47
removals between enumerations	1.58		0.43		0.73		0.28		0.85		0.31	

Table 4. Increment Data by Species

minimum measurable size 16 cm dbh

Dropping Gutter

Species	**Douglas Fir**		**Other Evergreen Conifers**		**Larch**		**Mixed Broadleaves**		**Total**		All Conifers at 100% equivalent stocking		**Removals**	
% of Basal Area in Final Growing Stock (2006)	31.9%		34.3%		8.6%		25.1%							
	BA/ha	Vol (st cu m/ha)	BA/ha	Vol (st cu m/ha)	BA/ha	Vol (st cu m/ha)	BA/ha	Vol (st cu m/ha)	**BA/ha**	**Vol (st cu m/ha)**	BA/ha	Vol (st cu m/ha)	**BA/ha**	Vol (st cu m/ha)
Increment on Initial GS	0.34	4.31	0.51	6.20	0.05	0.62	0.02	0.10	**0.91**	**11.23**	1.20	14.87		
Recruitment	0.01	0.06	0.05	0.41	0.00	-0.02	0.03	0.08	**0.08**	**0.54**	0.08	0.61		
Total Increment	**0.35**	**4.37**	**0.56**	**6.61**	**0.05**	**0.60**	**0.04**	**0.18**	1.00	11.77	1.28	15.48	**1.23**	**12.38**

Great Combe

Species	**Douglas Fir**		**Other Conifers**				**Mixed Broadleaves**		**Total**		All Conifers at 100% equivalent stocking		**Removals**	
% of Basal Area in Final Growing Stock (2006)	56.4%		35.9%				7.7%							
	BA/ha	Vol (st cu m/ha)	BA/ha	Vol (st cu m/ha)			BA/ha	Vol (st cu m/ha)	**BA/ha**	**Vol (st cu m/ha)**	BA/ha	Vol (st cu m/ha)	**BA/ha**	Vol (st cu m/ha)
Increment on Initial GS	0.54	6.68	0.69	7.83			0.04	0.26	**1.27**	**14.77**	1.33	15.72		
Recruitment	0.06	0.49	0.07	0.56			0.01	0.04	**0.15**	**1.10**	0.15	1.15		
Total Increment	**0.61**	**7.18**	**0.76**	**8.39**			**0.05**	**0.30**	1.41	15.86	1.48	16.87	**1.03**	**10.31**

Berridge

Species			**Other Conifers**		**Larch**		**Mixed Broadleaves**		**Total**		All Conifers at 100% equivalent stocking		**Removals**	
% of Basal Area in Final Growing Stock (2006)			31.2%		44.1%		24.6%							
			BA/ha	Vol (st cu m/ha)	BA/ha	Vol (st cu m/ha)	BA/ha	Vol (st cu m/ha)	**BA/ha**	**Vol (st cu m/ha)**	BA/ha	Vol (st cu m/ha)	**BA/ha**	Vol (st cu m/ha)
Increment on Initial GS			0.36	3.96	0.24	2.84	0.09	0.72	**0.70**	**7.52**	0.80	9.03		
Recruitment			0.15	1.16	0.04	0.28	0.04	0.13	**0.23**	**1.58**	0.25	1.92		
Total Increment			**0.51**	**5.13**	**0.28**	**3.13**	**0.13**	**0.85**	0.93	9.10	1.05	10.94	**1.40**	**12.25**

Table 5. Provisional Growing Stock Basal Area Thresholds for Coniferous Stands during Stages 1 & 2 of Transformation

Species	Approx Age (yrs)	After-thin Basal Area (sq m per ha)	Equivalent Before-thin Basal Area Ranges assuming 15-20% Removal Rate (sq m per ha)	% of Basal Area shown in Management Tables (after Christie & Edwards, 1981)	Relevant Yield Model and Entry
Towards End of Stage 1: Preparatory Stage					
DF	30-35	28	33-35	96%	YC 18, 1.7 m spacing, Age 32
NS	35-40	31	36.5-39	93%	YC 16, 1.8 m spacing, Age 37
LA	30-35	20	23.5-25	95%	YC 12, 1.7 m spacing, Age 32
Stage 2: Regeneration Initiation Stage					
DF	40-45	27	32-34	82%	YC 18, 1.7 m spacing, Age 42
NS	45-50	27	32-34	70%	YC 16, 1.8 m spacing, Age 47
LA	40-45	19	22.5-24	85%	YC 12, 1.7 m spacing, Age 42

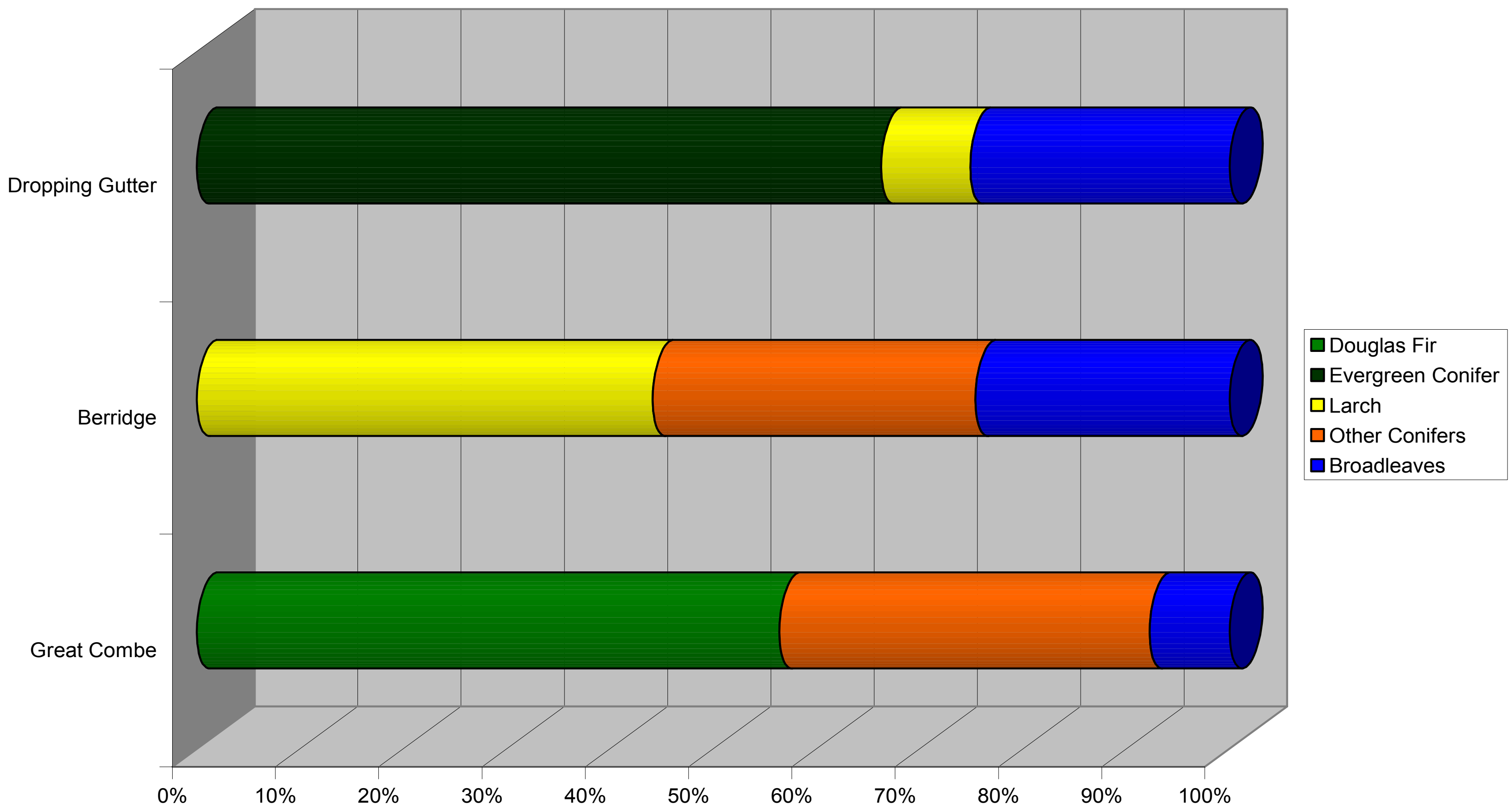


Figure 1: Species Composition in 2006

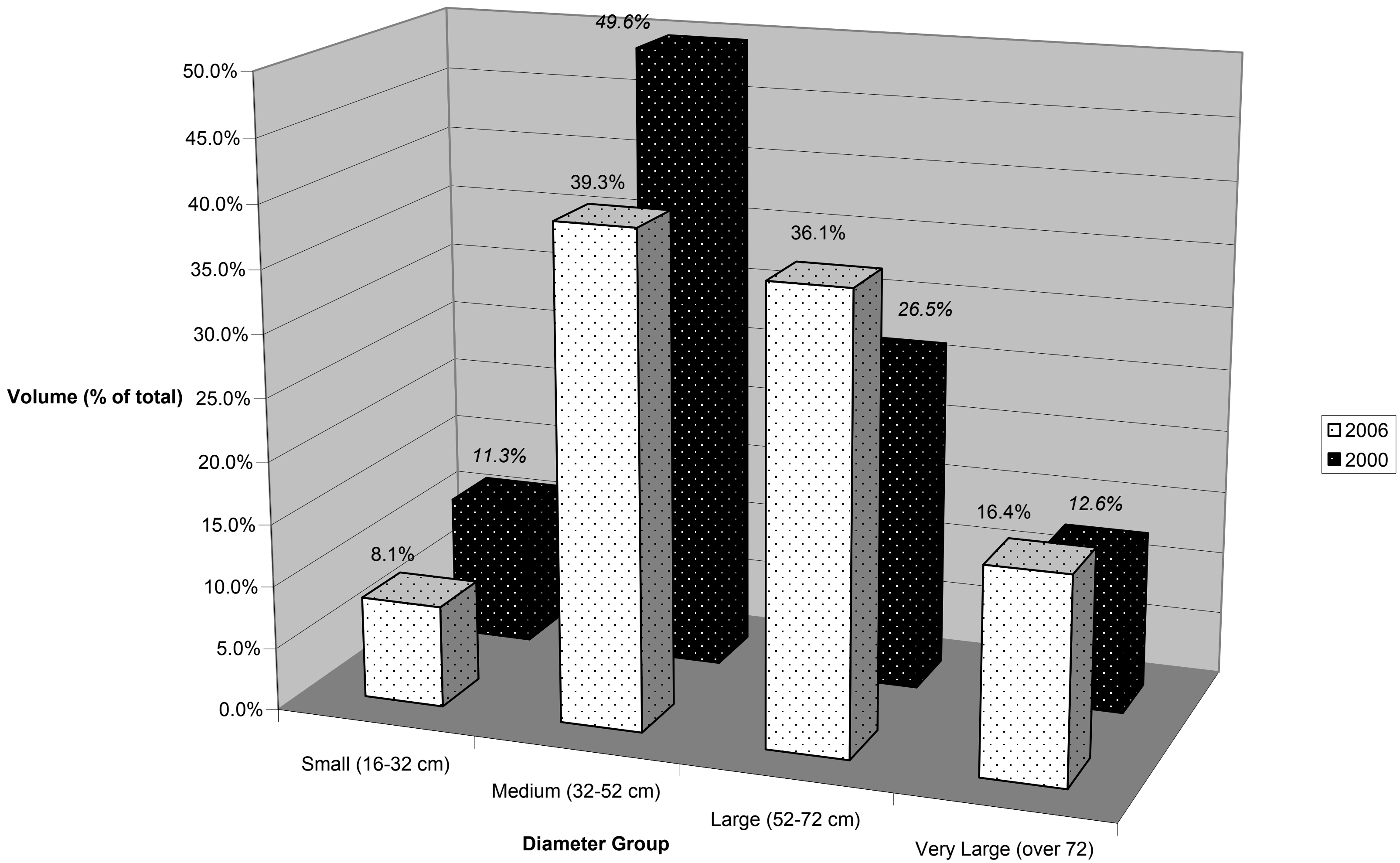


Figure 2: Dropping Gutter: Growing Stock by Diameter-group 2006 & 2000

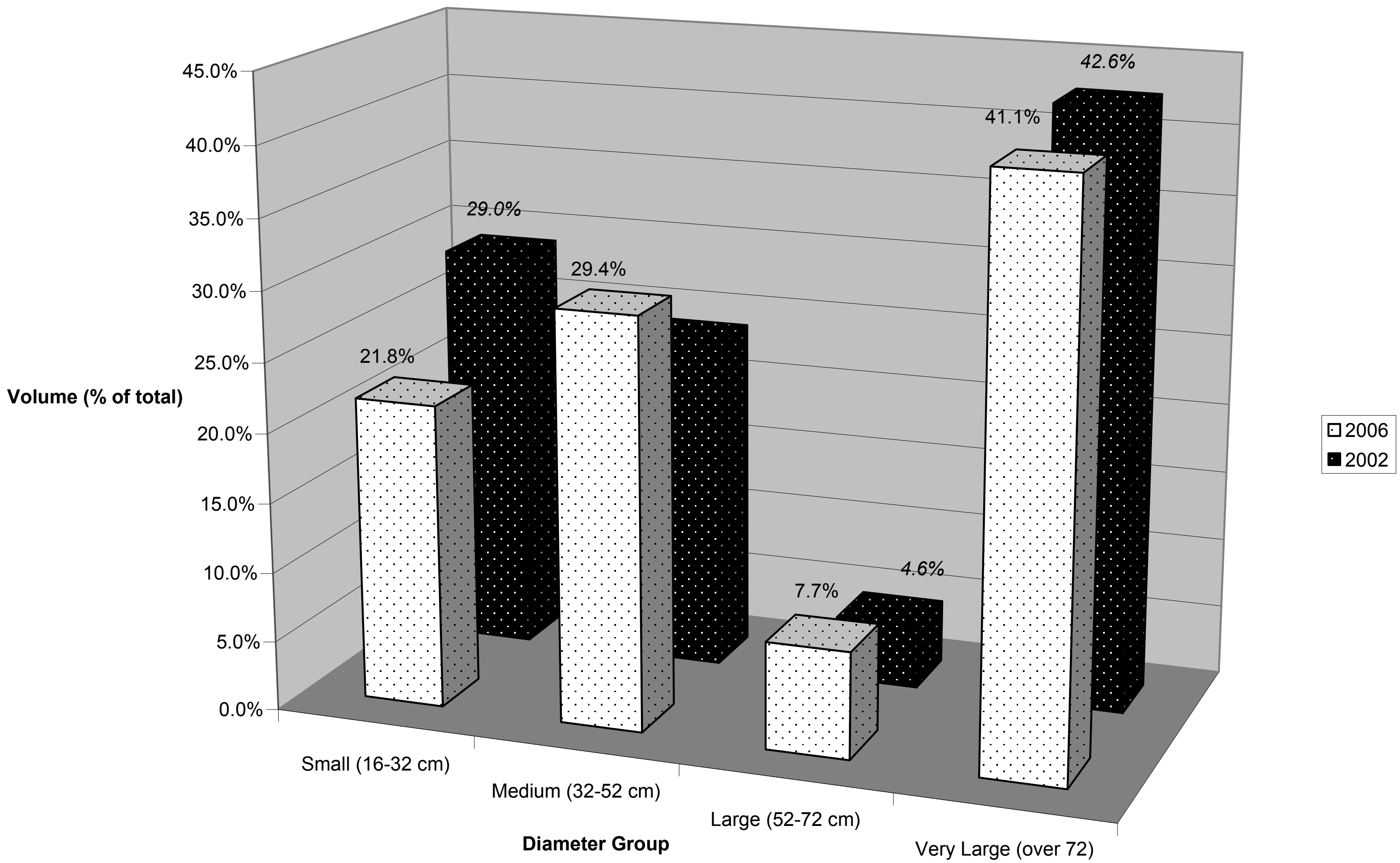


Figure 3: Great Combe: Growing Stock by Diameter-group 2006 & 2000

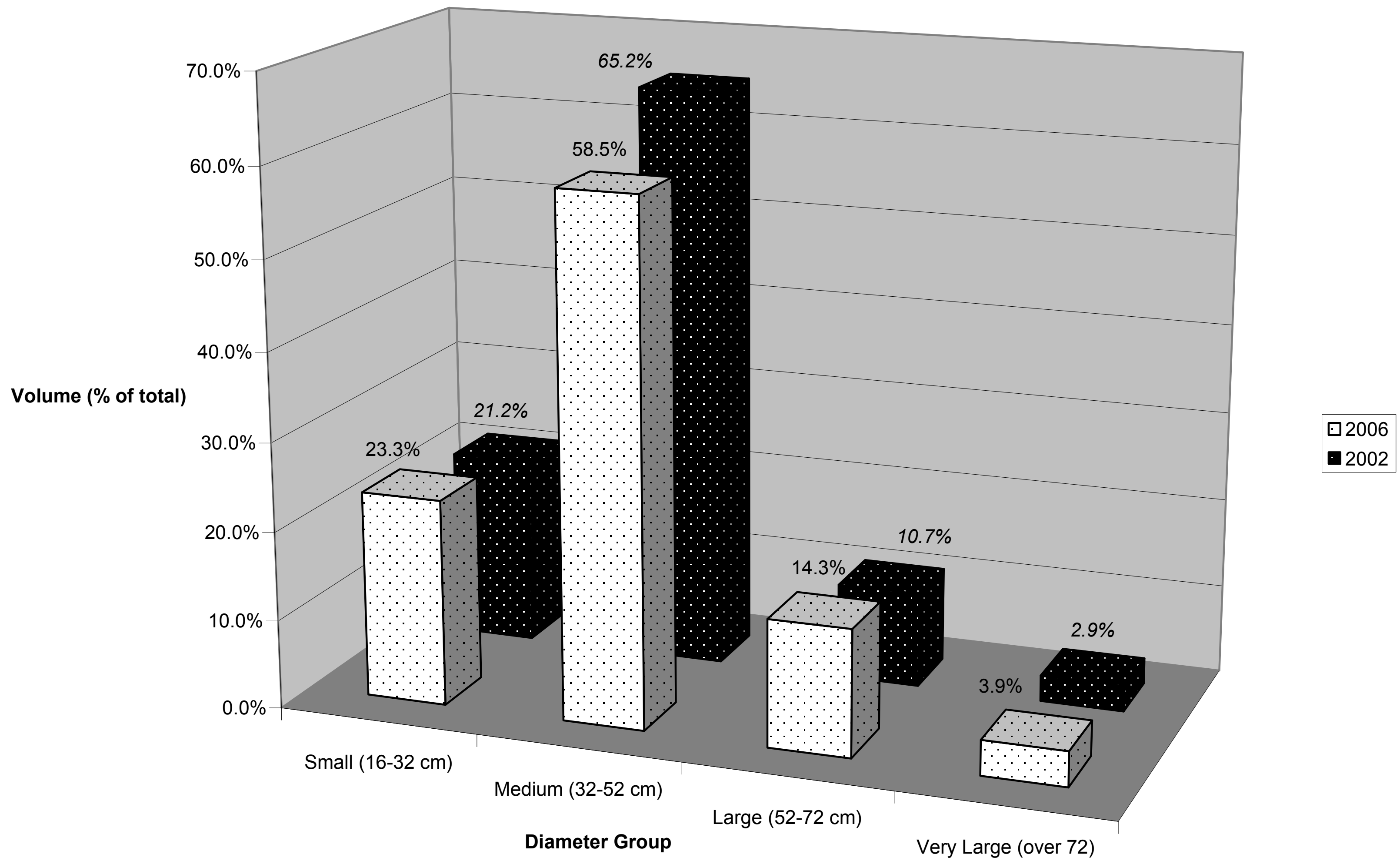


Figure 4: Berridge: Growing Stock by Diameter-group 2006 & 2002

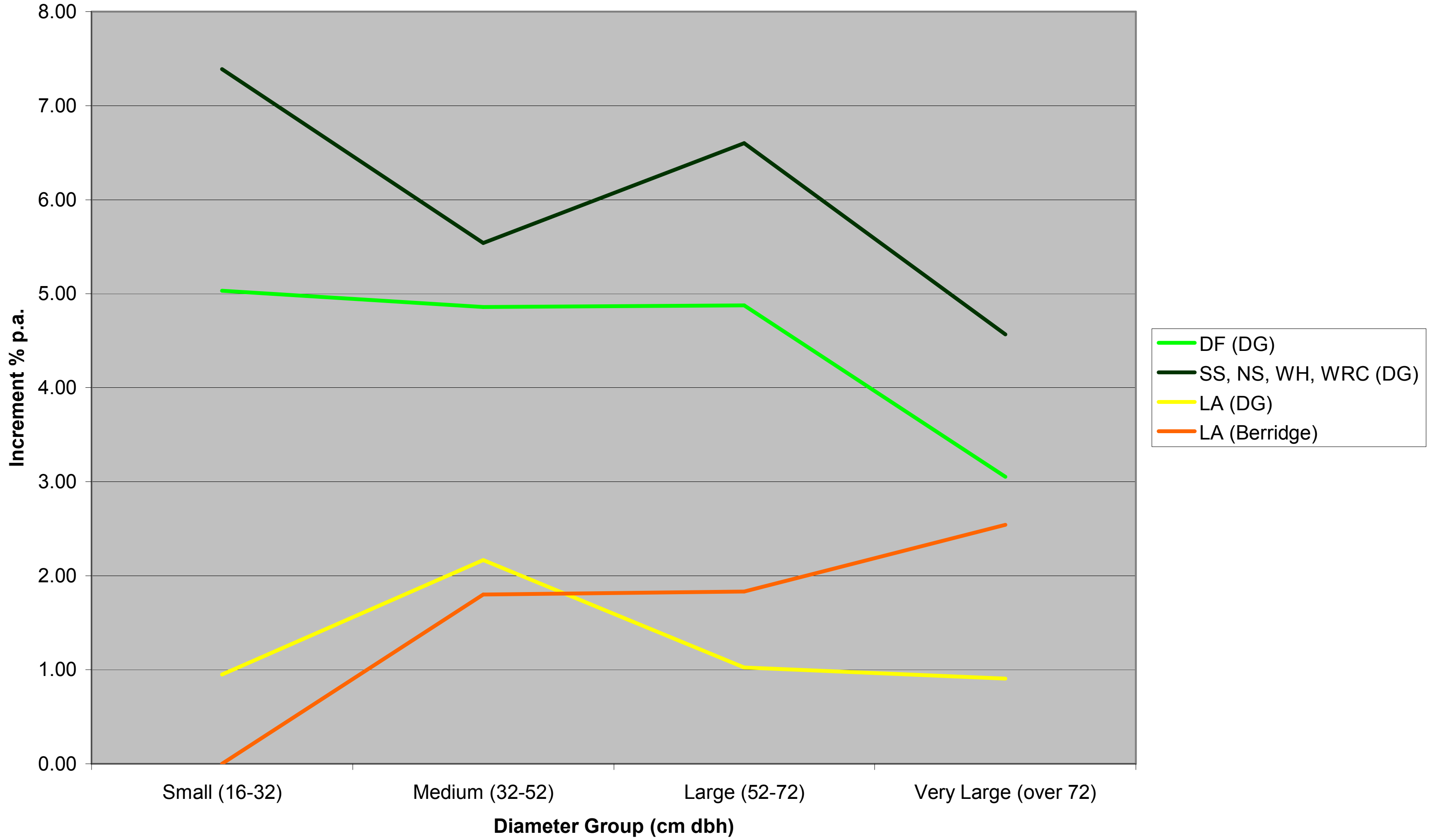


Figure 5: Dropping Gutter & Berridge: Annual Volume Increment Percentage for Coniferous Species by Diameter-group

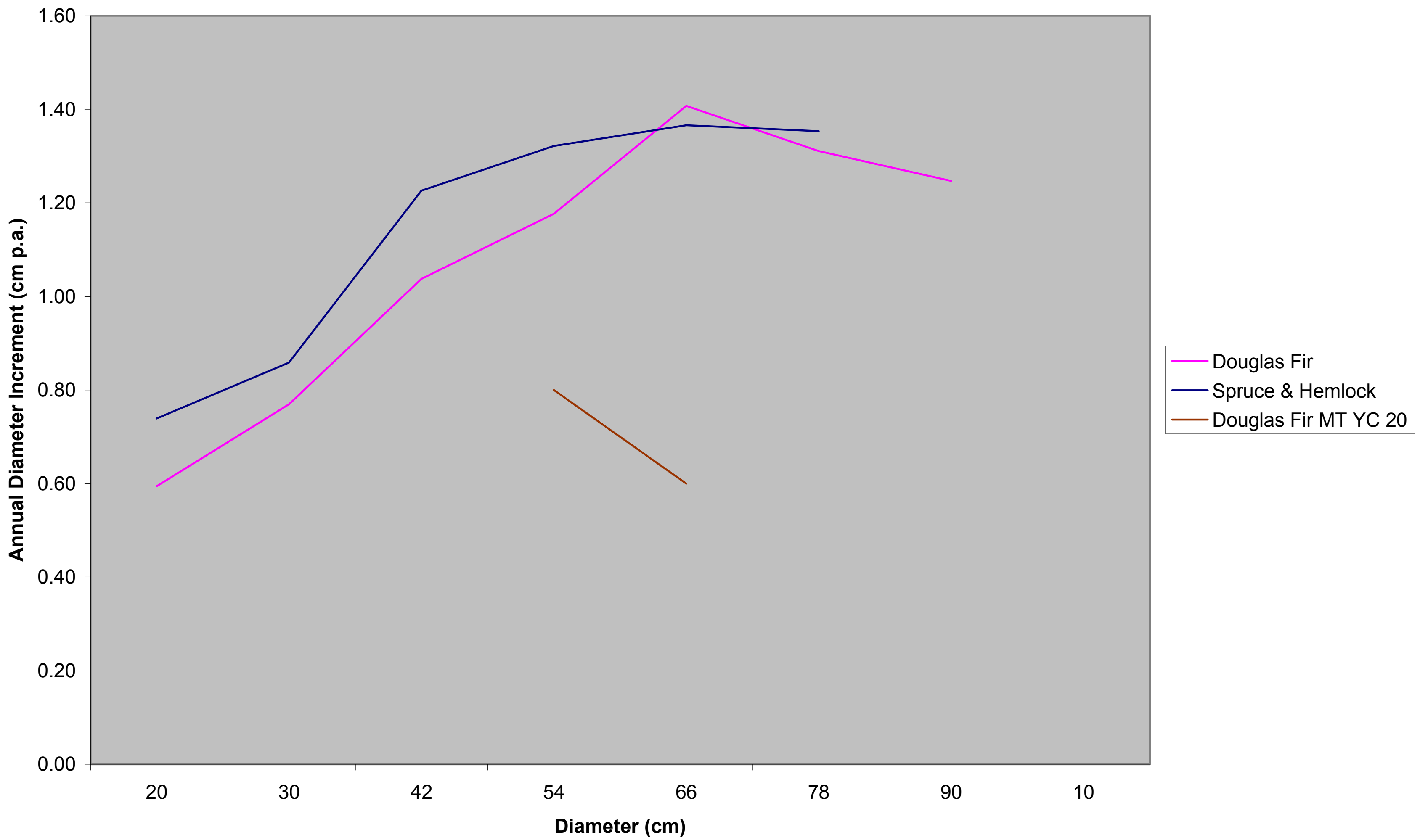


Figure 6: Dropping Gutter: Annual Diameter Increment for Douglas Fir & Spruce & Hemlock

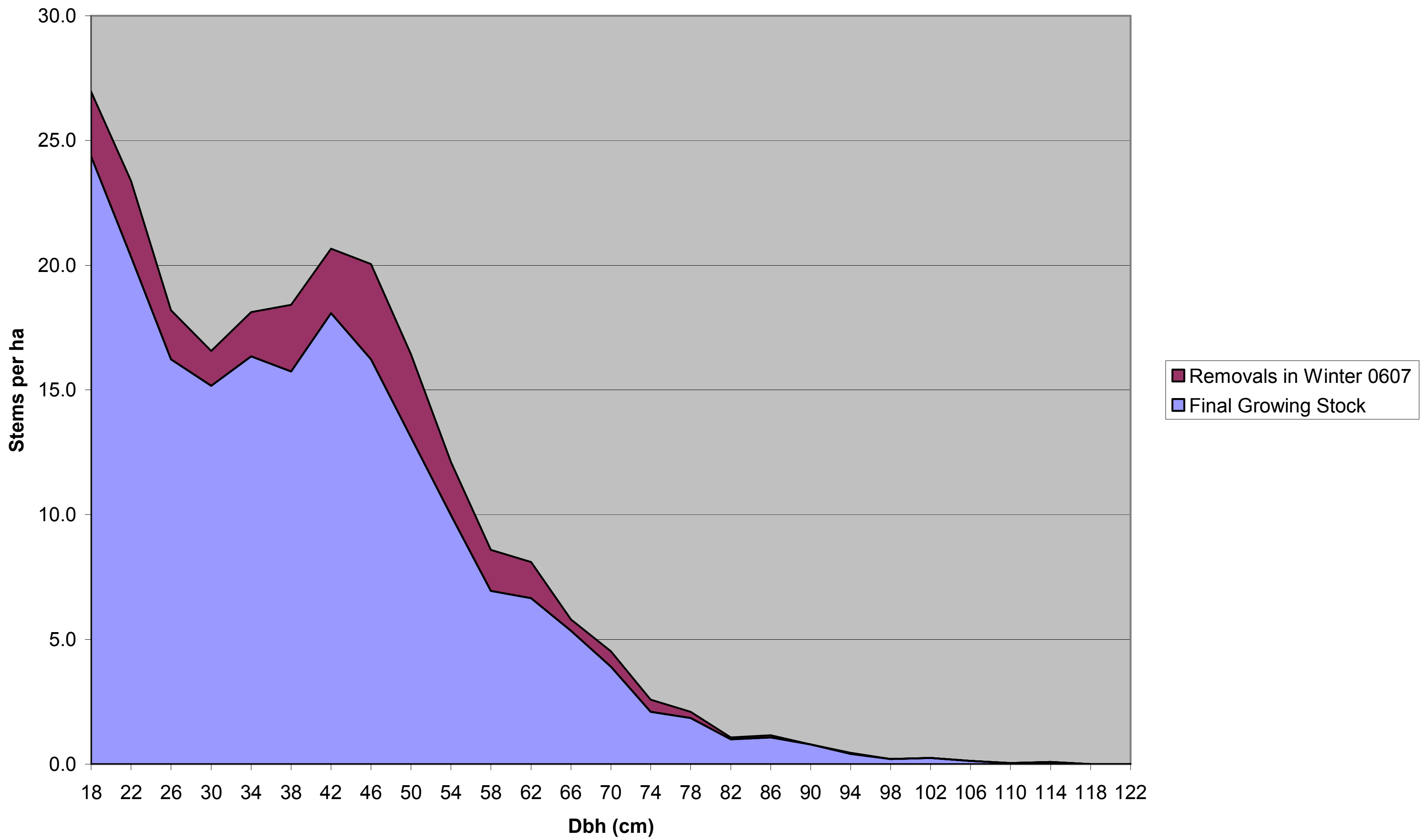


Figure 7a: Dropping Gutter: Impact of Last Intervention on Stem Number Distribution

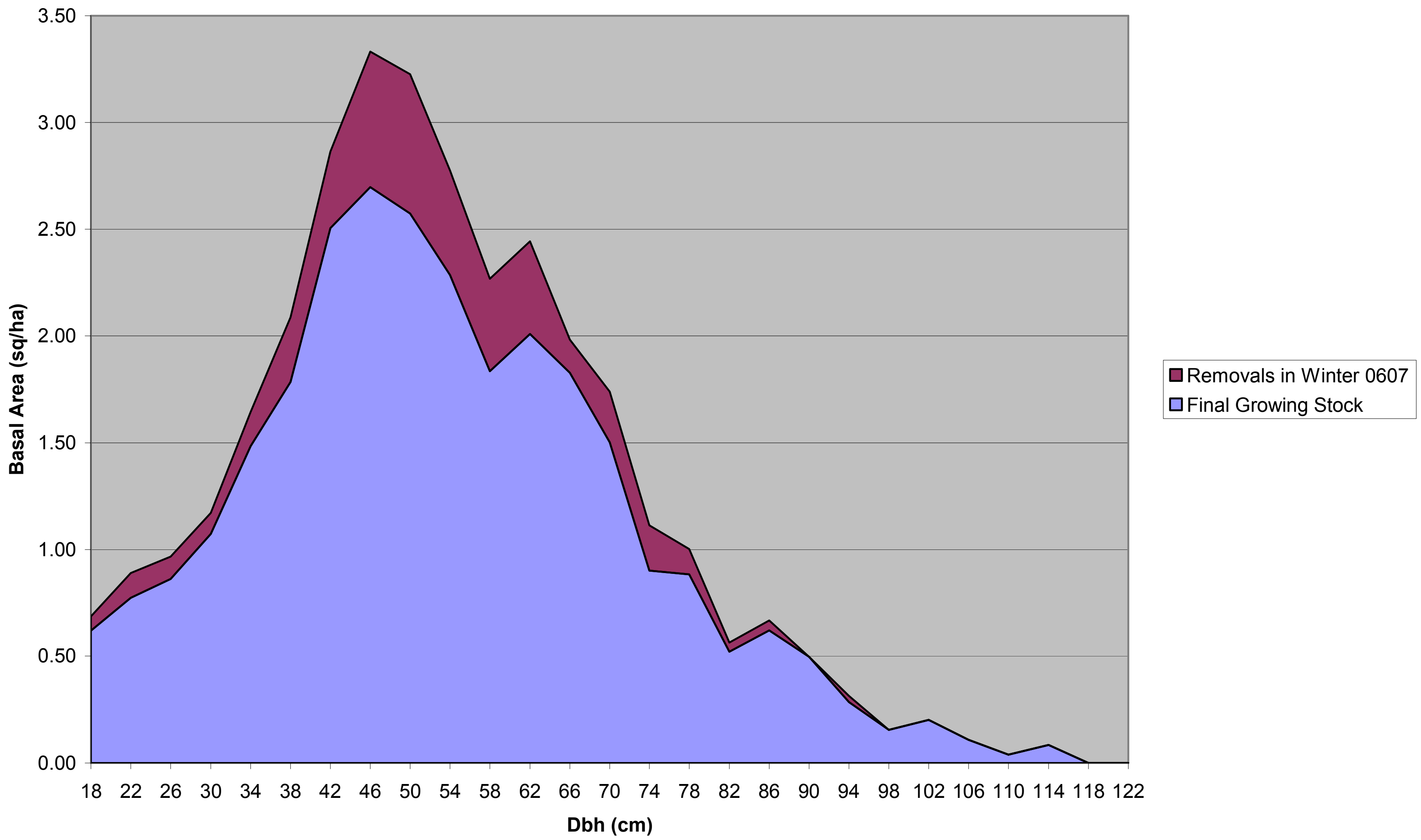
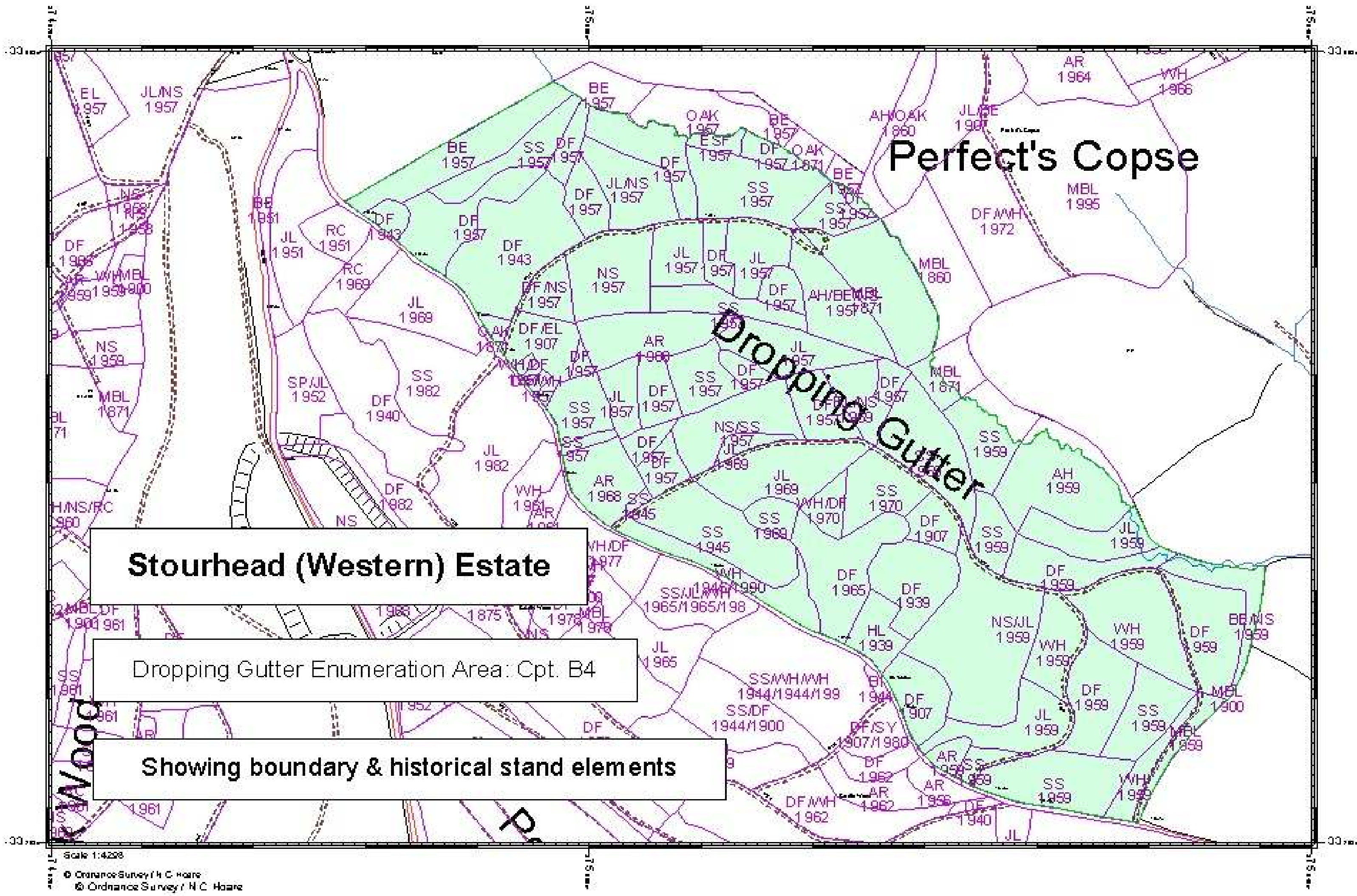
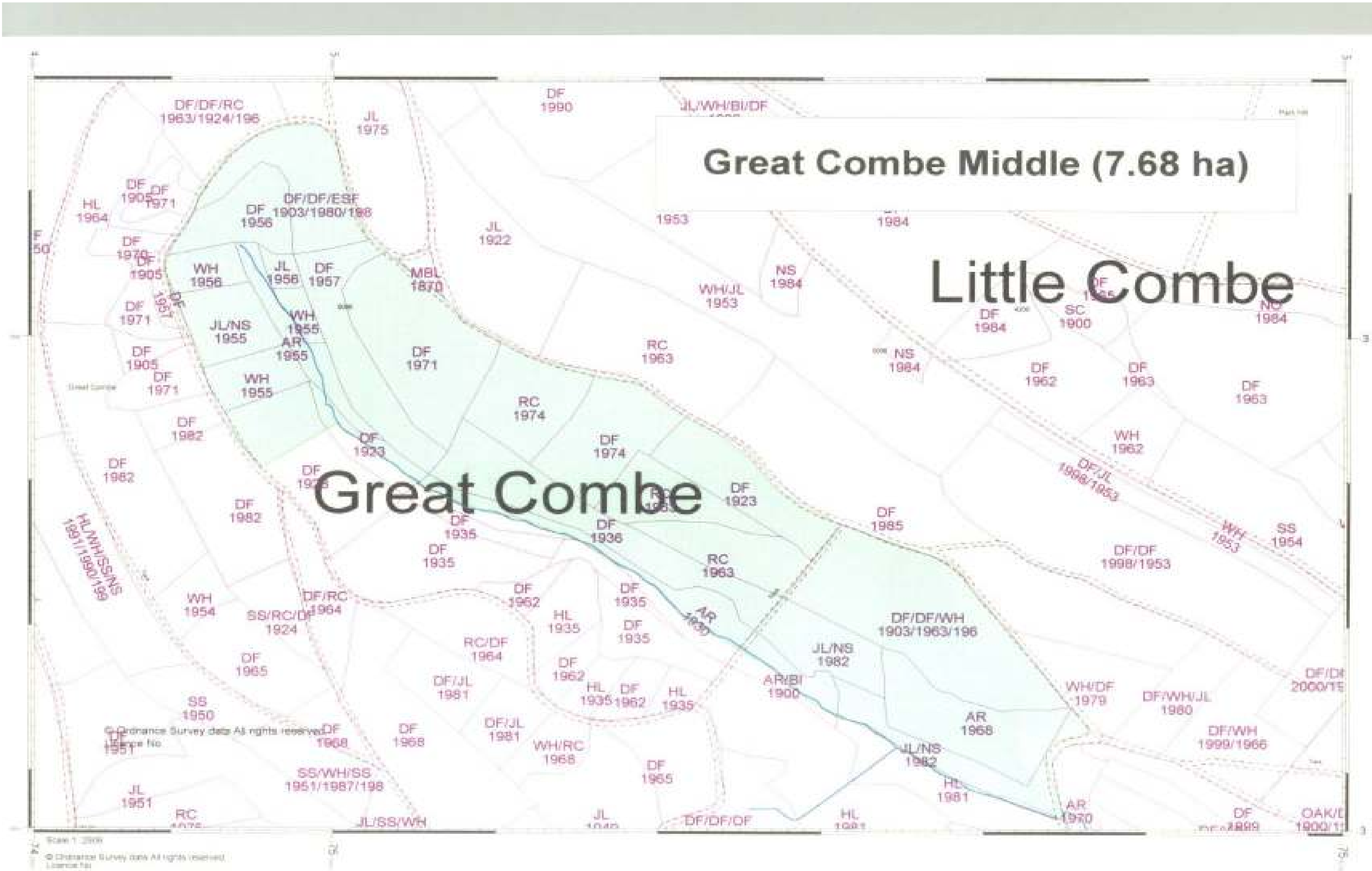


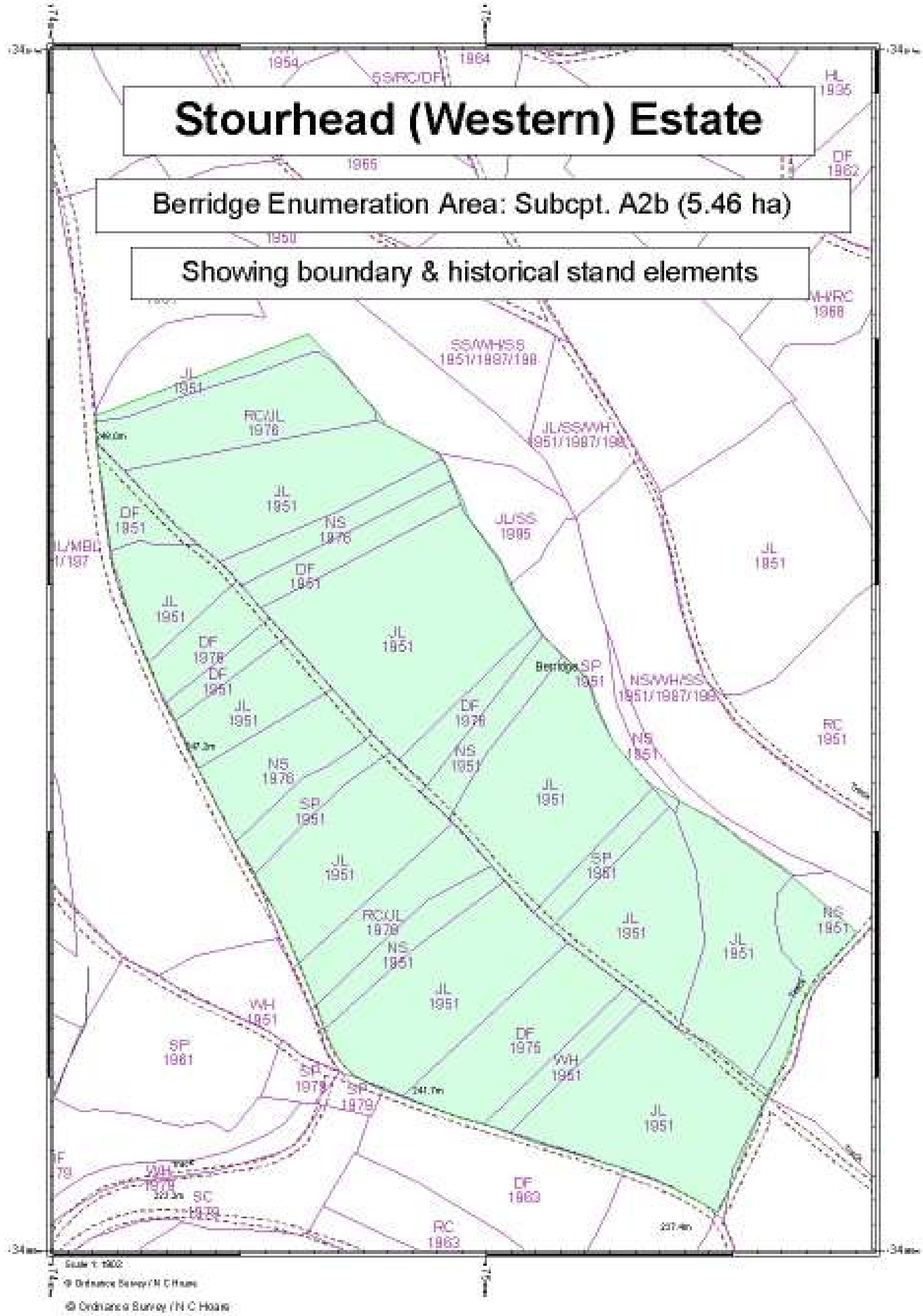
Figure 7b: Dropping Gutter: Impact of Last Intervention on Basal Area Distribution

Appendix 1: Research Stands: Plantation History


Stourhead (Western) Estate
Dropping Gutter Enumeration Area: Cpt. B4
Showing boundary & historical stand elements
Perfect's Copse
Dropping Gutter
Scale 1:4298
© Ordnance Survey / N C Hoare



Great Combe Middle (7.68 ha)
Little Combe
Great Combe



Stourhead (Western) Estate
Berridge Enumeration Area: Subcpt. A2b (5.46 ha)
Showing boundary & historical stand elements
JL 1951
RC/JL 1976
DF 1951
NS 1976
DF 1976
JL 1951
SP 1951
RC/JL 1976
NS 1951
DF 1976
WH 1951
SS/WH/SS 1951/1987/198
JL/SS/WH 1951/1987/198
JL/SS 1985
NS/WH/SS 1951/1987/198
RC 1951
NS 1951
WH 1951
SP 1981
SP 1979
DF 1963
RC 1963
SC 1979
WH 1979
HL 1935
DF 1962
© Ordnance Survey / N C Hoare

Appendix 2: Research Stands: Photographs

Dropping Gutter

Dropping Gutter Cont

Dropping Gutter Contd

Great Combe

Great Combe Contd.

Berridge

Berridge Contd.