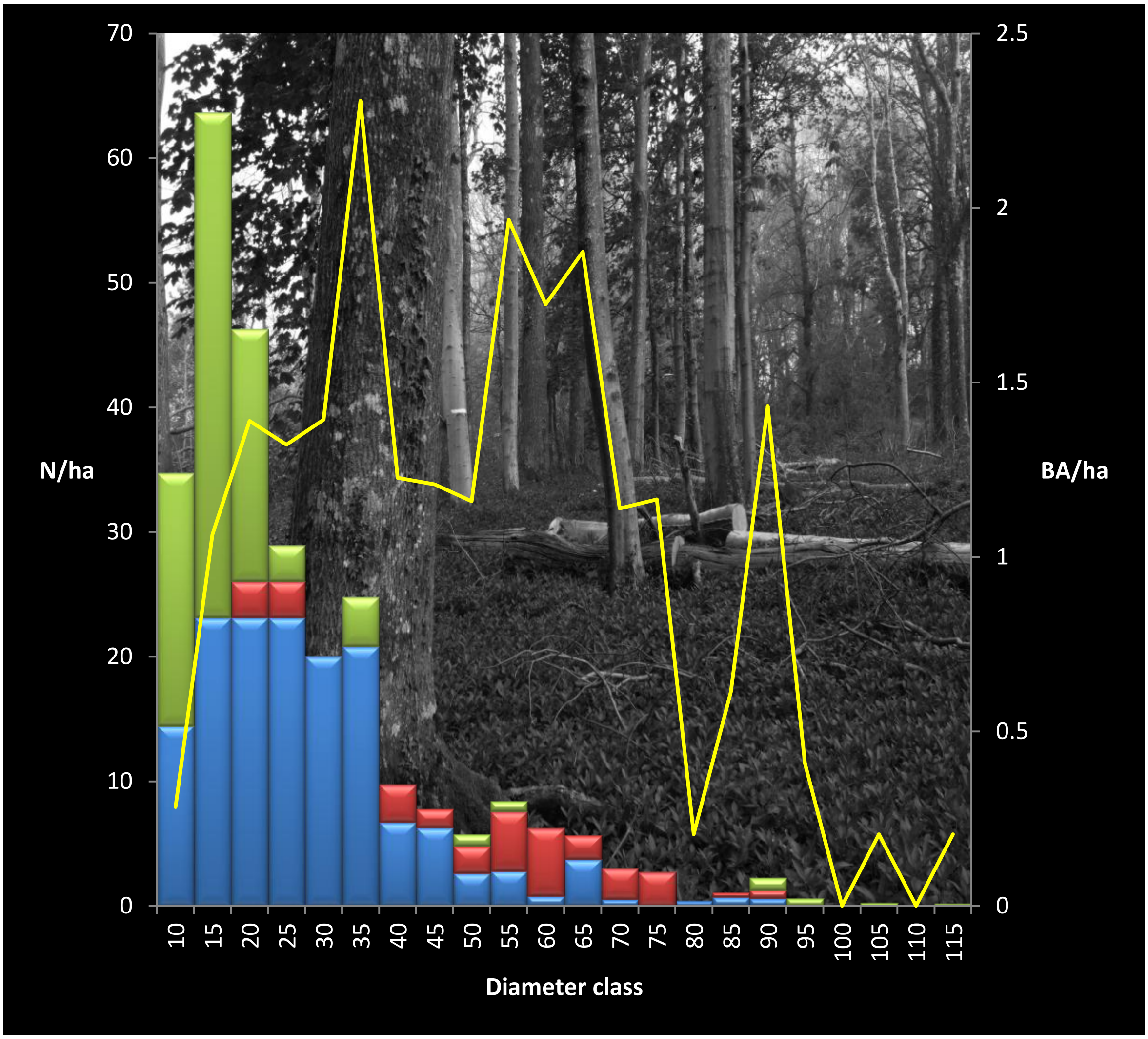

Continual Inventory for Irregular Forest Stands

Experience using the AFI abbreviated inventory method on the Cranborne Estate

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Abstract

There are silvicultural challenges in the transformation of even-aged stands to complex irregular structures, and the sustainable maintenance of these stands on reaching structural achievement. These systems require a strong evidence-base if sustainable production of quality timber is to be realised.

Measurement and the continual monitoring of changes within forests is fundamental to forest science; it is the means to understanding the complex processes which pervade the forest environment. Within the UK the dominant monitoring tool has been that of sampling using fixed-area plots as outlined in Hamilton (1975) and Matthews & Mackie (2007). This study however starts from the hypothesis that plots based on the relascope principle, also known as sampling with probability proportional to size (PPS), may be more efficient than the fixed-area method in monitoring irregular stand conditions.

The inventory method employed was that developed by the *Association Futaie Irrégulière* (AFI) which is expressly aimed at irregular forest stands. It was an abbreviated version of the more in-depth method which has been used in AFI research stands since 1993. Two contrasting local research stands were created within the woodlands on the Cranborne Estate, the main focus being on a complex irregular broadleaf stand, within which a combination of methods was employed. Complete enumeration of this stand was also carried out in order to create baseline data for the comparison of accuracy of the various methods.

The results showed that the AFI inventory method produced detailed dendrometric data which could be applied to single tree economic models for determination of optimum tree size and to the development of a sustainable structure.

Fixed-area plots showed considerably larger margins for error on structure (for larger diameters), and for between plot variance in basal area, than did the PPS sampling when comparing plots of comparable scale. Moreover it was shown that the fixed-area method delivered too few samples within the large trees to gain a reliable estimate for increment under the continual inventory principle.

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I would like to thank the AFI for access to IT materials, and although the tables and figures presented in this study are of my own creation, they are based on those produced by the AFI and in particular the work by Prof. Max Bruciamacchie of the ENGREF University, Nancy, France.

My gratitude goes to my dissertation supervisor Dr Mark Bryce Rayment for steering me away from the potentially disastrous course which was the first draft and setting me on the right path.

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1 Introduction

1.1 Irregular Forest Management

Forestry in the UK has been dominated by the clear-fell silvicultural system, based upon a rotation, for the last century. Under this regime the rotation period is initiated either via planting or natural regeneration and culminates in a clear-felling of one or of several stages. The resultant crop is even-aged and usually consists of one or two species. When many of these even-aged crops were planted the overriding objective was that of the production of timber. At a national level forest objectives have changed dramatically over the last forty years from being predominantly production focused to the current multi-objective ecosystem services approach (Millennium Ecosystem Assessment, 2003; Quine *et al.*, 2011). Irregular silvicultural systems, more common in continental Europe, seek to harmonise these multiple objectives.

Irregular forest management is defined by the selective felling process which is both the means of creating income and at the same time is a cultural activity. It is also characterised by the maintenance of a permanent forest canopy consisting of trees of multiple ages. Renewal is sought via the natural regeneration of the site-adapted species and phenotypes which best meet objectives. Other terms frequently used are; continuous cover forestry, selection forestry, uneven-aged, and plenter forest.

The rationale behind irregular forest management:

- Economics - Cost control by harnessing natural forest processes, optimising with inherent intra-stand variation and an emphasis towards the production of quality timber.
- Ecology - maintaining permanent 'forest condition', safeguarding soil processes, and diversity in species and structure, increasing resilience to external threats.
- Amenity and landscape - the illusion of the wild or natural forest, and permanence at the landscape level.

Irregular forest management, within the UK, has long been a marginal activity adopted by a few forest owners or practised at a small scale for research purposes (see Hart, 1995 for examples). There has, over the last decade, been a resurgence of interest in irregular forestry which may in turn lead to an increasing amount of UK forests being managed under these systems in the future. Indeed, recent forest policy makes explicit mention of irregular forest management and lower impact silvicultural systems (Forestry Commission, 2004; UKWAS, 2008; Welsh Assembly Government, 2009).

1.2 The requirement for long-term monitoring

Although measurement is not essential for the continued provision of many benefits from a forest, if optimising regular net income is to be an objective then measurement of the resource is required. Without mensurational data one cannot develop economic rules, cannot regulate sustainability and one has little upon which to judge the performance of the stand or forest. With an efficiently designed monitoring system in place the costs of the mensuration could be repaid manifold.

The gradual process of arriving at a sustainable irregular structure from an even-aged condition is known as **transformation**. When a forest is undergoing transformation the forest owner/manager may want evidence that the process is meeting predefined targets, that this is happening without production losses, and is ultimately financially sustainable. Moreover Schütz (2001) emphasises the need to estimate the timeframe which is available with the current stand of cover building trees, in order to realise transformation targets. With an estimate at the diameter increment one can predict the time which is available to replenish the existing growing stock. This can only be achieved by monitoring changes within the forest resource over time. Kohl & Baldauf (2012) state that Irregular uneven-aged stands present higher diversity and variability in most population elements than do even-aged stands. Their management requires information about complex forest structures in both space and time.

1.3 Stand dynamics

The transformation to, and continual management of irregular forest structures requires a thorough understanding of stand dynamics (O'Hara, 2001). Stand dynamics is influenced by three important variables: the **growing stock**, the **increment** and the **yield** and how these change over time.

The growing stock is the sum of the volume of all the standing trees within the stand. It represents, by far, the most important part of the forest capital, from which the interest is generated. Interest in this sense (as described by Gurnaud, 1890 quoted in Susse *et al*., 2011) relates to the increment which is the collective annual growth of all the trees. Determination of the increment allows formalisation of the amount in volume which can be harvested (the yield) without degrading the capital and without compromising the replenishment of the interest i.e. the future increment.

The increment, expressed in volume, can be relatively stable within a wide range in volume of potential growing stock. Within a densely stocked stand the increment is divided amongst many, relatively slow-growing trees. Within established open conditions the increment will be taken up by fewer more vigorous trees which will tend to have well-developed crowns. Optimum conditions are achieved when the fewest trees of highest value increment are allowed to sequester this increment without diminishing overall stand increment. The relatively low but vigorous growing stock, which is achieved by optimisation, should also ensure renewal in the form of natural regeneration, and continual recruitment of a pole stage element to the upper canopy due to vertical apportioning of photosynthetic energy down to the forest floor. Once optimisation is accomplished the stand can be said to be in **equilibrium**; in other words the increment is equal to the yield.

These concepts are described in detail by Knuchel (1953), although the theories behind optimisation have been challenged since. Knuchel favoured higher growing stocks, an idea connected partly to the political climate of the time, in order that there was a reserve of timber to be exploited in times of need, but also due to the lack of assigning a quality to individual trees. The theory of 'lower stocking of fast-growing trees'(described above), promoted by the AFI (Susse *et al.*, 2011), is the consequence of applying economic principles which evaluate rates of growth along with a quality-dependent price per unit.

1.4 Inventory methods for irregular forests

A variety of inventory strategies aimed at monitoring irregular stands, or stands in transformation have been trialled in UK forests. Some have sought to adapt methods traditionally used in even-aged stands, whilst others have adopted methods learned from experience in continental Europe where management of irregular forests has been more widely adopted. However there remains no standard approach in the UK for the monitoring of irregular stands for developing the full potential of the forest. It is at present an iterative process based on direct observation and cumulative evidence.

A variety of potential stand inventory methods can be adopted, the main distinction lies between those employing sampling and those that require complete enumeration. When carrying out inventory by sampling, fixed area plots have been the dominant principle tool in

UK forests, whereas the relascope (Bitterlich, 1984) has been generally restricted to the measurement of basal area. However, the principles behind the relascope can be used to estimate other stand variables such as stem number per hectare and diameter distribution.

Complete enumeration - (the check method)

There is a wealth of information on stand inventory in the Swiss selection forests going back to the end of the 19th century. These early attempts at stand monitoring are associated with the names Adolphe Gurnaud and Henri Biolley and are described in detail by Knuchel (1953). The method described is termed the *methode du controle* or check method and involved a complete callipering of all trees within a stand which exceed a specified minimum breast height diameter (DBH). With repeat enumerations at prescribed intervals, a 'check' was carried out to determine stand increment, and would be the basis for the estimation of the amount of the prescribed cut. The objective as described by Knuchel (1953) is to "bring all parts of the forest into a state of highest productive capacity in perpetuity". The check, theoretically, allows one to gradually bring the forest into a state of equilibrium whereby the greatest achievable volume increment is equal to the timber yield (as described in Section 1.3). Examples of use of the check method in the UK can be found in Reade (1956, 1990), Poore (2007), and Poore & Kerr (2010).

The increment calculation (Equation 1) is as follows:

$$Stand\ Increment = (Volume_2 + timber\ yield) - Volume_1 - newly\ recruited\ stems + recruitment\ increment \qquad \text{(Equation 1)}$$

The increment calculation was also carried out by size-class with the Swiss experience, although rarely by species, although there is nothing to prevent this being done, as in Poore (2007). The method used is to list, by size-class, all the stems in the initial inventory against all those measured in the current inventory and those exploited in the interval. Starting with the largest size-class one can cascade the numbers downwards to calculate which have moved up to the next class (*passage* = recruitment) and out of the underwood into the main stand (*passage à la futaie* = recruitment to the main stand), according to Knuchel (1953).

In the 117ha Glentress trial, continuous cover forestry was initiated by Professor Mark Anderson in 1952, and was monitored using the check method during the 'Anderson era' (1952 to 1964), (Kerr *et al.*, 2010). The information presented by Kerr *et al.* (2010) highlights some of the difficulties with the check method, namely that although the thinnings were tariffed no check was made on actual timber harvested. The increment calculation relies heavily on the accuracy of measurement of the yield. If extra trees are taken, or trees which have been marked are left, it can seriously affect the calculation unless these are spotted and the yield calculation corrected. The other issue, highlighted in Kerr *et al*. (2010) is that although the stem size curve showed exponential distribution that would lead one to assume irregular structure, aerial photographs from the same period showed that this could be attributed to a number of even-aged units of different ages and concludes that at a spatial scale of around 20 ha the method is probably too coarse to detect structural changes.

Full inventory may be the only practical option for small compartments, but inventories based on statistical sampling may provide information on structure, growth and yield more efficiently than 100% inventory in large compartments or whole forests (Sterba & Ledermann, 2006).

Inventory by statistical Sampling

Kerr *et al.* (2002) highlight the following as the main decisions which need to be made when embarking on statistical sampling:

I. Random or systematic sampling.
II. Fixed area or variable (the relascope principle) plots.
III. Permanent or temporary sampling points.

The above points however are not strictly ‘black or white’, for instance a combination of permanent and temporary plots can used, this system is known as ‘sampling with partial replacement’ (Van Laar & Akça, 2007), and variable and fixed area plots can be combined to take advantage of the benefits of both systems.

Fixed area plots

The inventory methods used in British forests usually adopt fixed area plots (Hamilton, 1975), examples of which can be found in Kerr *et al.* (2002), Cameron & Hands (2010), Kerr *et al*. (2010), and Tomppo *et al.* (2010).

In the example described by Kerr *et al.* (2002), numerous small fixed-radius plots were used to describe stand structure and monitor regeneration on two study sites (Stourhead Western Estate and Wykeham Wood). Both stands had complete enumeration data, which could be used to assess the accuracy of the output data. The top height method (Hamilton, 1975) was used to assess volume. Kerr *et al.* (2002) contends that "when the diameter data are plotted out in diameter classes it is unlikely to give an exact representation of the whole stand", this was evident with comparison to the data gathered from the complete enumeration. Better representation was found however, when plotted in four broad diameter groups.

Sampling with probability proportional to size (PPS)

In continental Europe there are documented forest inventories which use PPS sampling, more often referred to in these trials as 'angle count sampling'. These methods are based on the 'relescope principle' which was devised by Walter Bitterlich and described in Bitterlich (1984). An example can be found in Sterba (2002), Sterba & Ledermann (2006), and in the work conducted by the AFI (Susse *et al.*, 2011).

The advantage of PPS sampling is that because the chance of any given tree being included in the sample is proportional to its diameter, a more accurate measure of the larger trees is achievable than in an equivalent fixed-area plot. Large trees tend to be fewer and more dispersed than small trees and sequester more of the site resources, therefore the opportunity cost attached to their retention is higher. It is desirable to have good knowledge of the increment of large trees in order to determine optimum harvest diameters (discussed in Section 1.5).

The AFI research network

The *Association Futaie Irrégulière* (AFI) research network was set up in 1991 in order to "study and develop continuous cover, irregular forest management techniques, and to disseminate forest management practices that can provide income to the owner whilst working in harmony with the natural forest functions" (Susse *et al*. 2011). Over 100 research stands now exist, three of which are in the UK. One of these is located on the Cranborne Estate in an irregular broadleaf stand (Research Stand 94).

The process relies on continual inventory of ten systematically selected permanently marked sample plots. There are five separate elements to each plot:

1. Main stand: PPS plot using BAF 1 $m^2\ ha^{-1}$, 2.25 $m^2\ ha^{-1}$ or 4 $m^2\ ha^{-1}$, sampling stems ≥17.5 cm DBH. They are plotted for bearing and distance from plot centre. They are recorded by species, diameter, and quality grade.   The extent of the crown is measured to the drip-line and for crown height. Total height is taken for all trees in

the plot. Additional to this are a variety of ecological codes which can be applied to any tree, e.g. for ivy, forked stems or stems with lichen interest.

2. Poles: 10 m fixed-radius plot (same plot centre) sampling stems <17.5 cm and >7.5 cm DBH. They are recorded for species, diameter, bearing and distance from plot centre.

3. Regeneration: three 1.5 m radius plots are generated along equidistant radial lines 10 m from plot centre.

4. All fallen deadwood $\geq$5 cm diameter is recorded along three equidistant 20 m long radial transects.

5. All deadwood $\geq$50 cm diameter are measured within a 20 m fixed-radius plot.

Successive measurements are made at five-year intervals wherein the original plots are relocated. This procedure combines the benefits described above for PPS, for the trees in the main stand, and the benefits of fixed-radius plots for pole-sized material, which would otherwise be little represented. Experience of installing AFI research stands in the UK would suggest 2 to 3 days set-up time for a two-man team depending on the BAF used and individual stand conditions.

A peculiarity with the AFI method is that a tree of pole size can potentially disappear from the record when it ceases to be a pole only to reappear in the main stand some measures later. If one is using BAF 2.25 m^2ha^{-1} and there is a tree of pole size located 9 m from plot centre, the tree will be recorded as a pole up to 17 cm DBH (within the 10 m fixed-radius plot) beyond which it ceases to be a pole and is considered to be part of the main stand when it is subject to measurement via PPS. It will however not be recorded again until it reaches at least 27 cm DBH (three times in centimetres its distance in metres). The issue is exacerbated if a factor of 4 m^2ha^{-1} is used, in which case it won't reappear until it is equal to or greater than 32 cm DBH. This is not necessarily a problem as the two nested plots can be considered as separate entities. It does however mean that one is paying greater attention to pole stage material than to the small wood.

Volume estimation

There are a variety of methods which can be employed in order to determine volume (Hamilton, 1978; Philip, 1994; Matthews & Mackie, 2006; van Laar & Akça, 2007). During the early stages of transformation from an even-aged structure Forestry Commission (FC) stand tariff tables (Hamilton 1978, Matthews & Mackie 2006) derived from measurement of top-height are simple and easy to use. However, for stands which possess more complex structures these may not be appropriate. The FC tariff system is designed for even-aged stands with a normal diameter distribution and a relatively narrow range in DBH, as a stand ages the tariff number increases to reflect a higher ratio between DBH and volume.

Schaeffer (1949) created two tariff tables, the first *'tarif rapide'* (fast tariff) was based on a formula devised by Algan in 1901; to this he added *'tarif lents'* (slow tariff). The Schaeffer tables have been used extensively in France and Switzerland within irregular stands (Philip, 1994; van Laar & Akça, 2007) – these tariffs are used for volume determination across the AFI research network.

Both methods described are two parameter volume tables; height samples are required to determine which tariff is appropriate for the stand.

1.5 Economic indicators

In pursuing optimisation, inventory and economics are closely linked. Single tree economic models seek to answer two fundamental questions which arise when marking trees for selective felling: how does one determine **how much** volume to remove and **from which stems** this volume should arise?

Whereas classic forest economics focuses on the 'stand level' as the basis for economic optimisation, in irregular stands analysis is conducted at the 'individual tree' level (Härtl *et al.,* 2010). Considerable developments have been made in adapting the Faustmann model to calculate value increment rates in single trees and economic equilibrium conditions in irregular stands, where the production process and renewal are continuous, and where there is no beginning or end (Bruciamacchie & Tomasini, 2005; Chang & Von Gadow, 2010; Härtl *et al.,* 2010). This requires a freely selectable discount rate. Choice of discount rates and the effects of using different rates have been discussed widely (Price, 1989; Härtl *et al.*, 2010). Discount rates of between 3% and 5% are commonly observed in forest economics.

Bruciamacchie & Tomasini, (2005), devised the **potential value** concept in order to evaluate a tree by income which will arise in the future, paralleling the expectation value used in even-aged stands described by Price (1989). It stems from the idea that in the fullness of time a small tree, especially one of good quality, is worth more than its current standing value, and that there comes a point at which the site resources (soil space, moisture, nutrients and photosynthetic energy) sequestered by an individual would be better spent on neighbouring trees or promoting stems from the understorey. The point at which a tree's potential value is equal to it's current value indicates a target diameter beyond which a tree passes its financial optimum. Calculating optimum target diameters requires an accurate assessment of the value increment by species, quality grade, and size class. Moreover, the accuracy of the data becomes increasingly important as trees get larger.

1.6 Objectives

The objective of this study was to trial an abbreviated version of the full AFI method, for use at a local level. The focus was on measuring the content of the stand by species, diameter arrangement, quality, and (from repeat inventory) the increment. The measurement of crown diameters, deadwood and other ecological parameters were cut from the procedure. Although these elements may be vitally important in the realm of wider research, for forest managers aiming to secure productive capacity in irregular stands, measurement of these parameters may be an unnecessary use of time. The aim was to lessen the time it takes to install an effective monitoring system with the intention of reducing measurement costs.

The phrase 'sampling with probability proportional to size' (PPS) is a useful descriptive expression of how the relascope principle works and was adopted in this study, not least because the 'relascope' itself was not used, only the principles behind it. In a study by Piqué *et al.* (2011) a comparison of fixed-area and relascope plots showed no large differences in the estimates of stem density and basal area through a wide range of simulated stand types. Oderwald (1981) proved mathematically that both methods produced unbiased estimates of stem number per hectare and basal area. However, here we are also concerned with the accuracy delivered over the full range of stem sizes present in a fully irregular structure with particular regard to their increment.

The objective of this study was to:

- Demonstrate application of an abbreviated version of the inventory method developed by the Association Futaie Irrégulière (AFI), which is expressly aimed at irregular forest stands.
- Reveal the range of data provided in a variety of useful formats.

- Demonstrate appliance of economic optimisation models with the synthesised data and application of the information gathered in devising management prescriptions.
- Compare the efficiency of PPS and fixed-radius plots when estimating the three variables; stem density, basal area, and diameter class distribution in a highly irregular stand.
- Assess the number of stems likely to be available in successive inventories for increment calculation under the 'continual inventory' principle.
- Provide recommendations as to the minimum compartment size that can practicably be measured using this method.

2 Methods

2.1 Study sites

The Cranborne Estate woodland is situated in east Dorset and lies on the junction between the chalk downland of the Cranborne chase to the north west, and Bagshot sand heathland, typical to the New Forest, to the south east. The intergrade consists of London clay and the Reading formation. These intergrade soils are capable of supporting a wide variety of species both broadleaf and coniferous. Many of the woods are designated ancient semi-natural woodland (ASNW). The Cranborne woodlands are fairly typical of lowland estate woodlands in that they consist of a mosaic of small sub-compartments, in which can be seen the various trends over decades for species and species arrangements.

Continuous Cover Forestry has been practised in the Cranborne woodlands since 2007. The coniferous stands are in the early stages of transformation from an even-aged structure to an irregular one. Some of the mixed broadleaf stands however have fairly diverse structures, mostly due to long periods of neglect following major disturbance events. They are relatively uneven-aged of mixed species and of variable quality. As a result they are good test-beds for accelerated transformation – the dominant trees have been used to fairly open conditions, have large crowns and provide a stable framework. The many poor quality stems of all sizes provide a useful tool for manipulation of the stand as well as providing financial returns in a currently buoyant firewood market.

Stand selection

Stands were selected for monitoring based on the following criteria:

- Species composition is well represented within the wider forest
- Species are site appropriate and suitable for CCF systems
- The stand is mature enough to produce viable seed
- The stand is sufficiently advanced compared to others of a similar make-up
- The stand or stands are large enough to hold at least ten sample plots

With these criteria in mind six broad stand types were identified for implementation of local research stands within the Cranborne woodland. Two of these were selected for analysis in this study. Of the six identified stand types most were in the process of transformation from even-aged plantation management. Research Stand 91 was the exception in that it was very varied in species composition, age, and structure. It was this heterogeneity, as well as meeting the criteria for stand selection, which made Research Stand 91 pertinent for this study. It presented an ideal test subject for statistical analysis and the types of problem solving required for data collection and, volume and increment calculation in fully irregular structures. Research Stand 37c was chosen as the antithesis to Research Stand 91, it is an even-aged, relatively young conifer stand in the early stages of transformation to an irregular structure. Both sites are located at 50° 93'N latitude, at an elevation of between 100-130 m above sea level. Average annual rainfall is 950 mm per year.

Study Site – Local Research Stand 91

Figure 2.1 Local Research Stand 91 (Boulsbury Wood)

Research Stand 91 (figure 2.1) sits within Boulsbury Wood - a 225 ha woodland block. It is a typical lowland mixed broadleaf stand, which has been neglected for many decades. It is designated ancient semi-natural woodland (ASNW) and is part of a larger site of special scientific interest (SSSI). The SSSI designation is due to the wide range of Peterken Stand Types after Peterken (1982). The upper part of the stand sits on the pebble-bed sub-group of the Reading formation (BGS, sheet 314, 2004). This moderately acid soil accounts for approximately 10% of stand net area. The lower 90% is a complex intergrade of silty loess and clay soils, more calacareous in nature, which eventually runs out onto the Portsdown chalk formation at the woodland margin. Even where soils are thin and over chalk, long-term continuity of woodland condition has led to a de-calcified surface horizon devoid of free chalk (Poore, 2008). The Peterken Stand Types (PSTs) were identified by George Peterken in 1982 and are shown in Table 2.1 along with the equivalent NVC communities (after Cox, 1999).

Table 2.1 Soil types, PSTs and NVC communities for research stand 91

Soil types (BGS, *England and Wales*, sheet 314, 2004)	**Peterken Stand Type** (Peterken, 1982). *Ph measurements from limited samples.*	**Equivalent NVC community** (Cox 1999)	**NVC sub-community present** (Cox 1999)
Reading formation – pebble bed. (approx. 10%)	6Db Lowland birch-Penduncualate oak (ph 3.6)	W10 *Quercus robur-Pteridiunm aquilinum-Rubus fruticosus.* W16 *Quercus spp-Deschampsia flexuosa*	Transitional community between W10b *Anemone nemorosa* and W16 *Quercus spp-Deschampsia flexuosa*
Reading intergrade to Portsdown chalk formation (approx. 90%)	3Ab Acid Pedunculate oak-hazel-ash: light soil (ph 4.6-5.0)	W8 *Fraxinus excelsior-Acer campestre-Mercurialis perennis*	W8b *Anemone nemorosa* and W8e *Geranium robertianum*

With regard to Table 2.1 it should be pointed out that the NVC communities and PSTs do not match up exactly and that there are transitional communities which are difficult to define.

Early history of the stand is largely unknown although evidence on site suggests that some conversion to plantation using beech, sweet chestnut and sycamore, and to a lesser extent Scots pine and Norway spruce took place probably in the first half of the 19th century – some specimens of these species still survive. Many large elm were removed from the stand in the 1970s which gave rise to opportunities for regeneration. The stand has been little touched since, and is now considered fully stocked.

Study site – Local Research Stand 37c

Figure 2.2 Local Research Stand 37c (Hither Daggons Wood)

Research Stand 37c (Figure 2.2) sits within the Hither Daggons woodland block on the London clay formation (BGS, sheet 314, 2004). Soils are complex lenses of sand and clay. The woodland is designated ASNW and is therefore considered a plantation on ancient woodland site (PAWS). The wood is shown as broadleaved on the OS map of 1902 and is described as hazel coppice with oak standards in a management plan of 1951. The present stand of Norway spruce was planted in 1970. One large yew remains from the previous stand. The stand has been subject to two thinnings with conversion to irregular forestry in mind, one in 2008 – volume removed 87.3$m^3 ha^{-1}$, and another in 2012 – volume removed 57$m^3 ha^{-1}$. The basal area has been reduced over the two thinnings from a pre-thin basal area in 2008 of 42$m^2 ha^{-1}$, down to post thin 26.8$m^2 ha^{-1}$ basal area in 2012. Permanent extraction routes were installed at 24m spacing in 2012.

2.2 Inventory Method

Conventions and equipment

Standard measurement conventions were adopted as outlined in Hamilton (1975). The principle tools employed were the Vertex telemeter and ultrasound transponder, Walktax distance measurer, Suunto compass (Figure 2.3), and tree callipers. To avoid the complication of adding slope correction factors steeply sloping sites were not considered. Gentle slopes were compensated for by the mensurationist raising or lowering the vertex or transponder to achieve a level sight from plot centre to tree. Slope was ignored for plot location as distances are slope-distances.

Figure 2.3 Equipment: (Left) from left to right Suunto compass, Vertex telemeter, and Walktax distance measurer. (Right) Transponder on plot centre staff.

Measurement of trees in the main stand (>17.5cm dbh)

A basal area factor (BAF) 2.25 $m^2 ha^{-1}$ was chosen for both study sites with the aim of sampling an average of between 10 and 20 trees per plot. The horizontal limiting distance (HLD), in metres, with this BAF is three times the diameter of the target tree in centimetres, and was easily calculable in the field without having to use a look-up table.

In Research Stand 91 a combination of fixed area and PPS plot was trialled where all trees <30 cm DBH were subjected to the 10 m fixed-radius plot. As well as providing greater knowledge of the material in the small wood it will, in the future, provide for a seamless transition when monitoring recruitment of poles to the main stand. As the poles and trees were monitored within the same circular sweep it did not complicate the measuring process.

Poles and regeneration

Pole stage material was categorised as being trees 7.5 cm to 17.5 cm DBH (size classes 10 cm and 15 cm from the 5 cm gradations) and was measured within the 10 m fixed-radius plot.

Trees below 7.5 cm DBH were considered to be regeneration and were classified in four stages as follows (Susse *et al* 2011):

- Class 1 – seedlings between 50 cm and 1.5 m in height
- Class 2 – saplings greater than 1.5 m in height and smaller than 2.5 cm DBH
- Class 3 – saplings between 2.5 cm DBH and 7.5 cm DBH
- Seedlings less than 50 cm

The number by species and class were recorded in each regeneration sub-plot. Seedlings less than 50 cm were estimated by percentage cover.

Three regeneration sub-plots were used in Research Stand 91 and six in Research Stand 37c.

Quality grading

The four quality grades used by the AFI (Susse *et al.*, 2011) were applied to Research Stands 91 and 37c. They are coded A, B, C and D, trees of quality 'A' being of highest value. Experience suggests that these four categories work well with a variety of species, although (at the time of measurement) most conifers grown in the UK (with the exception of Douglas fir, larch and western red cedar), have no top-end market, resulting in grades A and B being of the same value. Personal bias was limited by applying strict rules to define each grade. These were tailored to product specifications based on local markets. The biggest distinction lies between categories B and C, the assumption being that trees of grade A and B will be retained until they have reached a financially optimum diameter, whilst trees of grade C and D are used as tools for manipulation of the structure and are generally removed at smaller diameters. Table 2.2 shows the grades used for Research Stand 91.

Table 2.2 Quality grading of oak and ash on the Cranborne Estate.

Grade	***Description – oak/ash, Cranborne***
A	Veneer and furniture 1st grade – straight with no visible knots or defects for the first 3 m
B	Furniture 2nd grade – straight/slight sweep, live knots <4 cm tolerable for the first 3 m
C	Post and beam material/ hurling sticks (ash only) – straight/slight sweep, live and dead knots <8 cm tolerable for first 3 m
D	Low grade small round-wood, firewood & woodfuel

Figure 2.4 Ash quality grade 'A' (left). Ash quality grade 'C'(right), marked for production of hurling sticks.

Mapping

To ensure that plots would not be partially located outside of the compartment a plot centre exclusion zone was created around the edge of the mapped area; the width of the zone taking into account an assumed largest measurable tree of 90 cm DBH and a BAF of $2.25\ m^2ha^{-1}$. The minimum between plot distance was twice this distance in order to avoid potential overlap. A series of parallel lines were laid over the map with plots located at minimum distance along these lines. Their distance, from a suitable tie point, was measured using a scale rule (see Figure 2.5). Stratification was not carried out because the compartments were small and had no discernibly distinctive sub-areas.

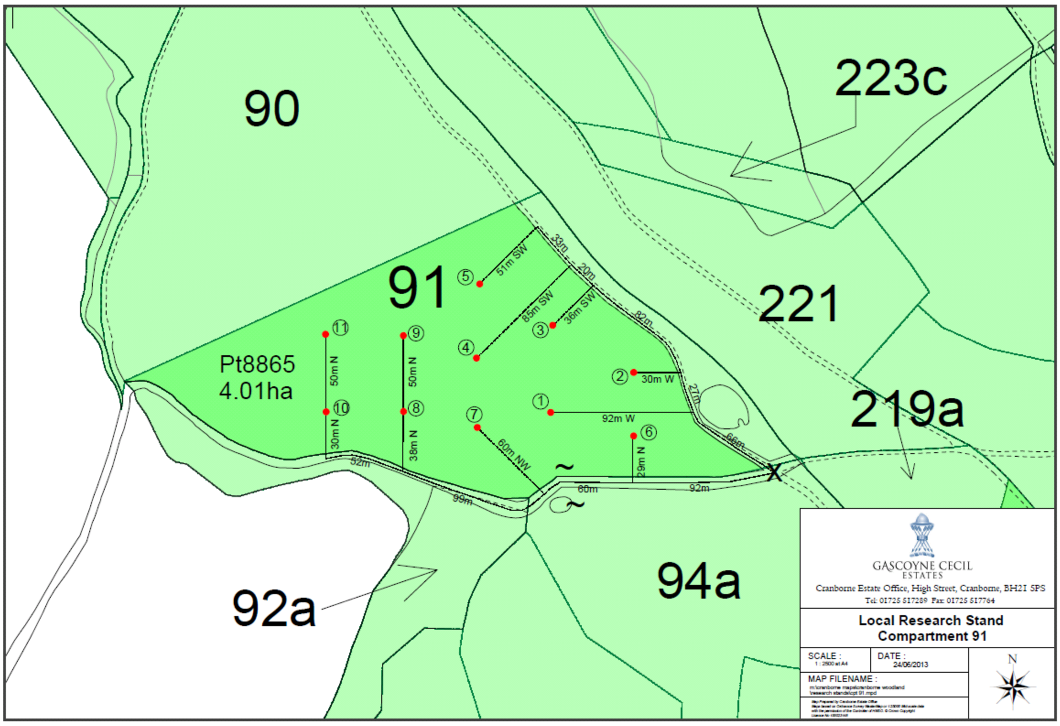

Figure 2.5 Plot location in Research Stand 91

Plot location

The plot tie-points were located along the forest road and were measured out using a Walktax distance measurer. Once found, the plots were located by bearing and distance using a compass and the Walktax.

Inventory Procedure

The following procedure was followed:

1. A metal peg was inserted below ground. The plot remains invisible between inventories so that bias is not introduced during interventions.
2. The transponder staff was placed at plot centre.
3. The regeneration plot-centre rods were set up at 10 m from main plot centre at 360°, 120° and 240°. Within Research Stand 37c an additional 3 plots were set up at 20 m along the same lines. As a secondary function the rods served as a useful distance guide when measuring the poles, and the trees within the main stand.
4. Beginning directly north trees and poles which fall into the plot were measured in a clockwise direction. Tree distance was measured using the vertex telemeter and transponder. Two diameters were callipered at right angles for trees >17.5 cm DBH;

the first (diameter 1) facing plot centre and the second (diameter 2) at 90° to the first. Species and qualitative information were then recorded. Trees which were just out, but were likely to grow into the plot for the next measure were recorded as ‘limit trees’ by species, diameter one, distance and bearing only. Poles were also recorded by species, diameter 1, distance and bearing. For the measurement of coppice just the coordinates for the centre of each stool were recorded. Dead and windblown trees were recorded by diameter 1 and coordinates only.

5. Height samples were taken.
6. Regeneration was measured within the 1.5m radius sub-plots and described by class, species and number for each plot.
7. Additional observations were recorded and finally the time taken to install the plot.

How the structure was described

Breast height diameter ($DBH_{1.3m}$) of those trees counted ‘in’ was recorded and stem number per hectare calculated by 5cm diameter classes. With this information a stem number curve was generated. The criterion for structural achievement was based on the ‘De Liocourt’ negative exponential curve and calculated ‘q factor’ described by Meyer (1952) and Gül *et al.* (2005). The q factor was calculated by dividing the number of stems in each diameter class by those in the next highest class and applying an average.

Basal area was also broken down by species and broad diameter groups. Within the AFI these are categorised in three classes as; small wood (SW = 17.5 cm – 27.5 cm), medium wood (MW = 27.5 cm – 47.5 cm), and large wood (LW = 47.5 cm +). Due to a large range of diameters beyond 47.5 cm in Research Stand 91 an additional very large wood (VLW) category was created for trees over 67.5 cm.

Volume Calculation

Volume determination in 37c was fairly straightforward. It was effectively an even-aged stand and as such was predicted to have a simple structure and normal stem size distribution. Volume by top-height and tariff number (as described by Hamilton, 1975 and Matthews & Mackie, 2006) was used, and is likely to remain the case, in the short term, until younger material is beginning to be recruited from the under-storey. Until this time (perhaps 20 years from first inventory) height samples must be taken anew with each repeat inventory to determine a new tariff number. Eventually a different approach more applicable to irregular structures can gradually replace the FC tariff principle.

Research Stand 91 presented a complex structure, volume determination via mean top-height was inappropriate due to a wide range in tree size. For simplicity and for ease of computation volume was estimated from a regression function that relates volume (difficult to measure) to the predictor variable BA (easy to measure). The result is a volume to basal area ratio (VBAR). Four height samples were taken in each plot to develop a height curve: heights were taken from the two trees closest to plot centre, and the height of the tree of median DBH, and the tree of largest DBH to ensure an adequate range of samples. In order to establish the VBAR for Research Stand 91 the stand heights were stratified by 5 cm DBH classes to represent multiple layers of even-aged units. An FC tariff number was applied to each strata and the VBAR calculated from the entry in the tariff table. This was then smoothed out with a logarithm function trend-line.

2.3 Economics

Single tree economic models proposed by Bruciamacchie & Tomasini (2005) were adopted and the plot level data analysed to see how well it served the model. The economic model was constructed using the following calculations:

- Individual tree volume (V) was derived from the VBAR and taken to be the volume of the mid-value tree within the 5cm diameter classes.
- The diameter increment (DI) was estimated from typical values recorded in AFI stands in northern France (Susse *et al.*, 2011). In time, actual increment will be determined at the point of second inventory and calculated as: $(DI_2 - DI_1)/t$ (Equation 2) where t is the time which has passed between two inventories.
- Price per unit (PU) is derived from the price-size relationship.
- Standing value (SV) is calculated as: $SV = V \cdot PU$ (Equation 3)
- The value increment (VI) is the tree's mean annual increase in value between diameter class (dc):

$$VI = SV \cdot DI \cdot \left(\frac{((PU_2 - PU_1)/PU_1) + ((V_2 - V_1)/V_1)}{dc_2 - dc_1} \right) \text{ (Equation 4)}$$

- The indicating per cent, as described by Price (1989), represents the tree's current rate of return and combines the trees' annual increase in volume with the annual increase in price per unit: $indicating\ \% = \frac{VI}{SV} \cdot 100\%$(Equation 5)
- The potential value (PV) requires a discount rate (r). PV is calculated: $PV = \frac{VI}{r}$ (Equation 6)

A price-size relationship was established for those species present in Research Stand 91 to reflect the potential market value of the expected product breakout within any given tree. The values which make up the price-size relationship were obtained from recent sales to local sawmills.

2.4 Statistical methods

A by-product of the combination plot approach used in Research Stand 91 was that it was possible to analyse the data had the inventory been carried out by relascope or fixed-area plots alone. Complete enumeration of the whole stand was carried out in order to provide a baseline to compare the percentage margin of error on the three main stand variables; basal area ($BA,\ m^2/ha$), stem density ($N, trees/ha$), and structure (by 5cm diameter classes), for the plot types; fixed-area, relascope, and combination. The statistical analysis was that used by Piqué *et al.* (2011). For the diameter distributions the error for each class was calculated separately. Then the mean sampling error (%) was taken from the absolute value of the difference between the sample estimate and the true value divided by the true value (that obtained from the complete enumeration).

Plot level data was disaggregated by 5cm classes, and by the broader diameter groups, and the number sampled was compared to each diameter-group's basal area contribution. From this it was possible to gauge the number of stems which could typically be made available in the future for increment measurement under the three sample methods.

Statistical analysis was performed for each sample method. Standard deviation (s), the coefficient of variation (CV%), and the error percent (E%) were based on between plot variance in basal area.

3 Results

3.1 Stand structure

It can be seen that Research Stand 37c presented the relatively normal stem-size distribution expected of a typical even-aged stand (Figure 3.1). This histogram represents trees in the main stand (trees >17.5 cm DBH), and the poles (7.5 cm – 17.5 cm DBH) recruiting into the stand. The contribution made by other species is so small that it can be considered single species stand.

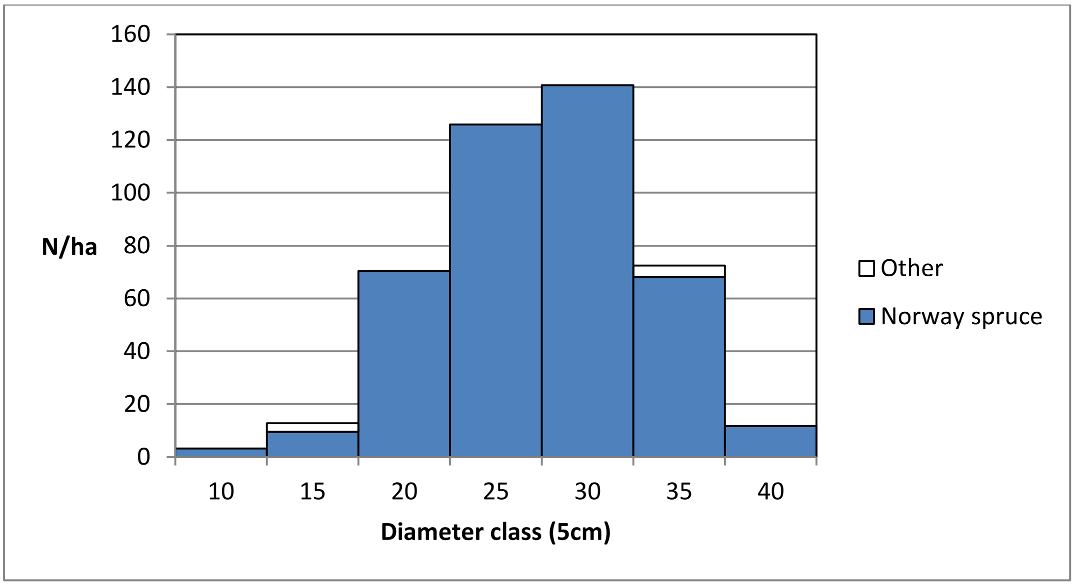

Figure 3.1 Histogram N/ha for trees in the main stand and the poles, by 5 cm diameter class in Research Stand 37c. The figure shown under each class represents the mid-alue of that class.

Research Stand 91, by contrast, shows the classic negative exponential stem size distribution of an irregular all-aged stand (Figure 3.2) despite having received little by way of recorded silvicultural management for at least four decades. The calculated diminution quotient, q factor (Meyer, 1952), was $q = 1.74$ for stems of the main stand between the 20 cm and 95 cm diameter classes. This is a little higher than the range of $\sim 1.3 - 1.6$ typically found in continental Europe (Gül *et al.*, 2007).

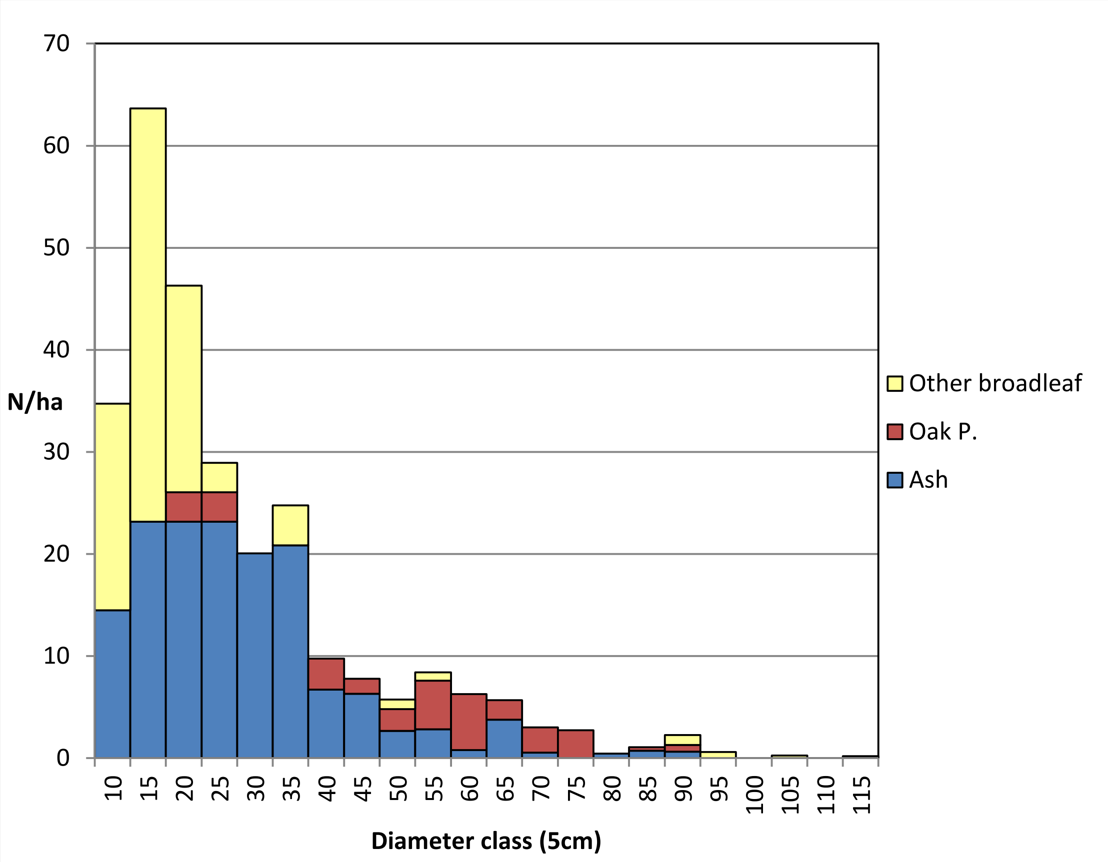

Figure 3.2 Histogram N/ha for trees in the main stand and the poles, by 5cm diameter class in Research Stand 91. The figure shown under each class represents the mid-value of that class.

Structure by broad diameter groups

Figure 3.3 demonstrates the relationship between quality and broad diameter groups in basal area contribution for stems of the main stand (Research Stand 91). The lack of trees of qualities A and B (only 22% overall) and the decline towards the smaller sizes is symptomatic of a history of neglect. The lack of silvicultural selection, and prolonged, intense between-stem competition has fostered bad form in the smaller diameter trees. When Figures 3.2 and 3.3 are compared the relationship between stem diameter and basal area contribution is made apparent. The pole size material although relatively numerous contributes very little to overall basal area whereas the large trees (>47.5 cm) although few in number contribute the majority (56%).

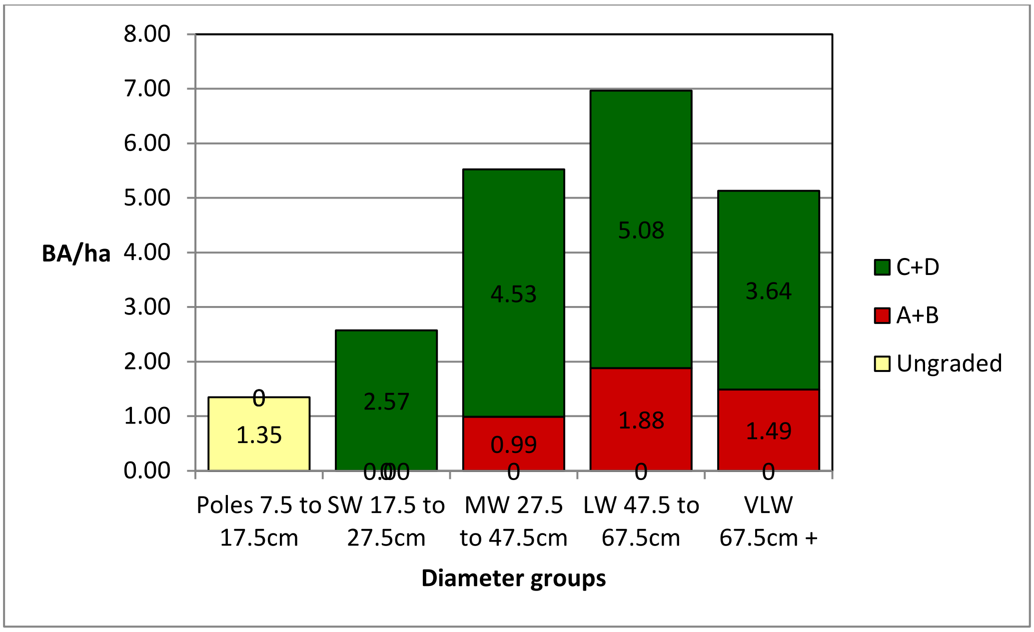

Figure 3.3 Basal area contribution by quality grade and broad diameter groups – Research Stand 91.

Species composition by basal area and by value

In Figure 3.4 a clear difference can be seen between the distribution of species in basal area and in value. Penduncualate oak comprises 62% of the standing capital although it only occupies 35% of the basal area. When cross-referenced with the stem size distribution (Figure 3.2) it can be seen that oak is dominant in the larger stem sizes which command higher prices.

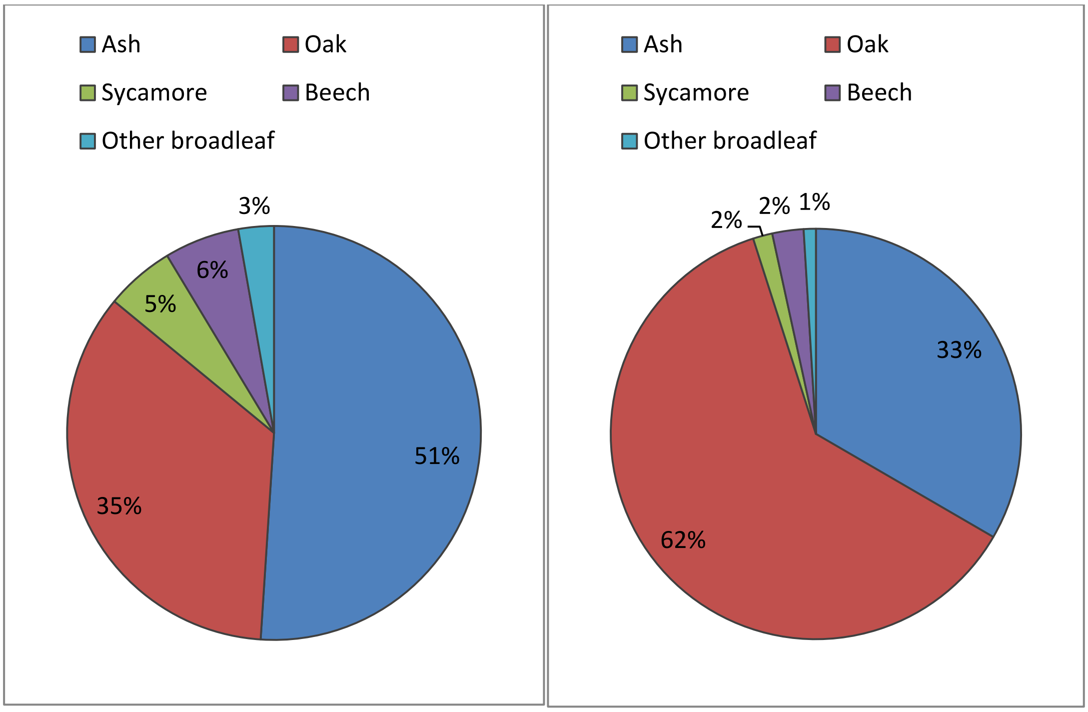

Figure 3.4 Species composition by basal area (left) and by value (right) – Research Stand 91.

Regeneration

Table 3.1 Number by size class of regenerating seedlings and saplings per hectare – Research Stand 91.

	% cover/ha	N/ha			
	Seedlings <50cm height	class 1 50cm - 1.5m height	class 2 1.5m height - 2.5cm dbh	class 3 2.5cm – 7.5cm dbh	Total
Ash	1%				
Sycamore	0%				
Beech	0%	189			189
Other Broadleaf	2%	519	141	141	802
Total	3%	707	141	141	990

Table 3.1 shows number by species and by class of regeneration. Other broadleaf in this instance consisted mostly of understorey species; hazel, holly and hawthorn, with only 19%

in the sapling classes coming from target species (oak, ash, sycamore, beech). This would indicate that at some point in time light levels became too low for target tree species, with the exception of beech, to regenerate.

3.2 Volume determination

FC tariff method for even-aged conifer stands

In Research Stand 37c the resultant tariff from the mean of the ten height samples was tariff number 35. The volume/DBH curve of FC tariff together with the closest fit on the two Schaeffer tables (*tarif rapide 13* and *tarif lents 10*), are displayed in Figure 3.5.

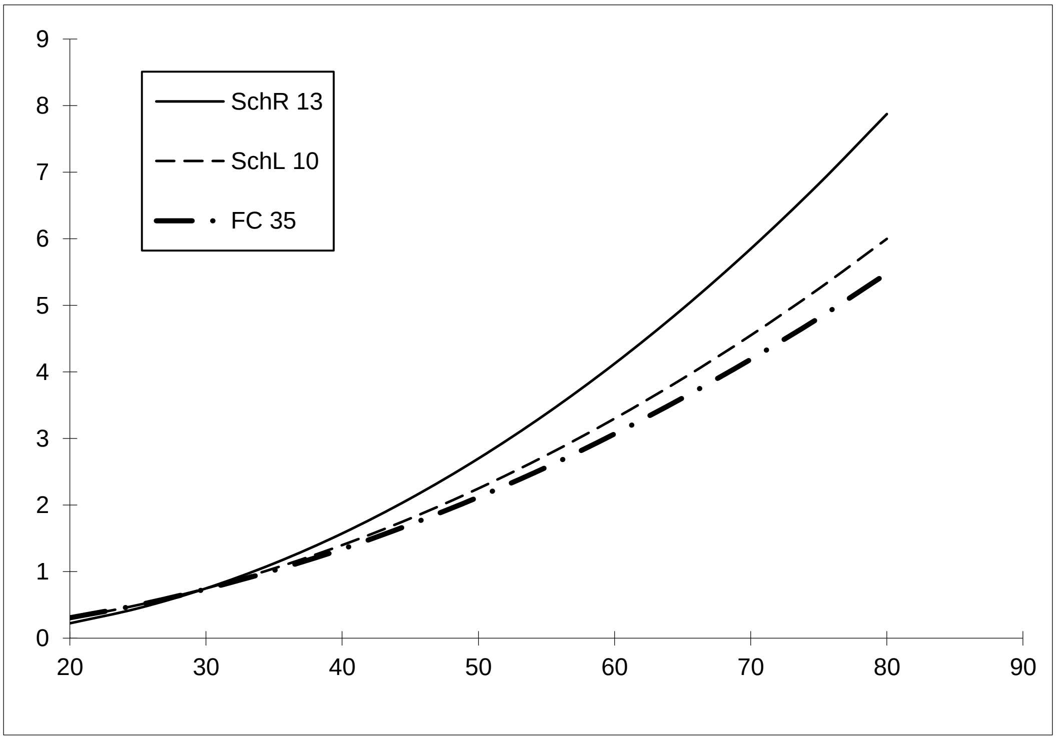

Figure 3.5 Comparison of single tree volume curves for Research Stand 37c.

VBAR calculation for broadleaves

The 44 height samples taken within the sample plots in Research Stand 91 were plotted (Figure 3.6) and a fitted height-curve generated to provide a function between a tree's diameter and it's height.

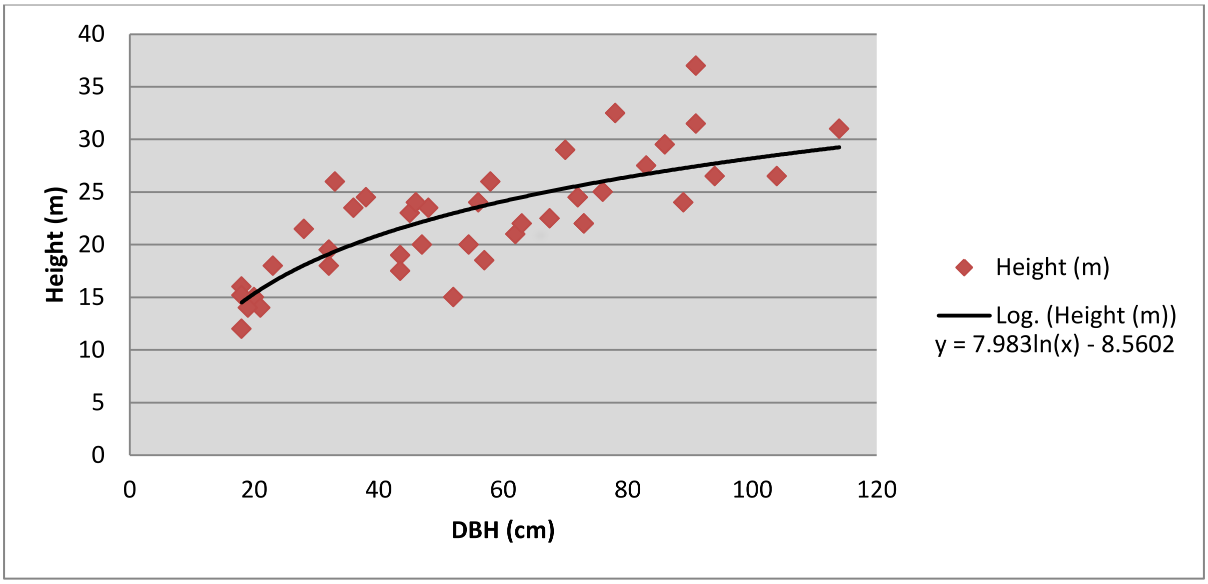

Figure 3.6 Fitted height curve from the 44 height samples - Research Stand 91

When the stratified heights, provided from the regression function, were applied to FC tariff numbers a VBAR formula was generated - volume from basal area Research Stand 91:

$$VBAR = 2.345\ Log_e(DBH) - 0.1165 \qquad \text{(Equation 7)}$$

The VBAR derived from the Log_e function is displayed in Figure 3.7 and the single tree volume curve in Figure 3.8, together with the closest fit Schaeffer tariffs and the FC tariffs for the smallest and largest DBH classes used (tariff 24 and tariff 34). Note how flat the VBAR is for the FC tariffs in Figure 3.7 and how close to the measured data the Schaeffer curves are in Figure 3.8 - the measured data lying somewhere between *tarif rapide 6* and *tarif lents 7*.

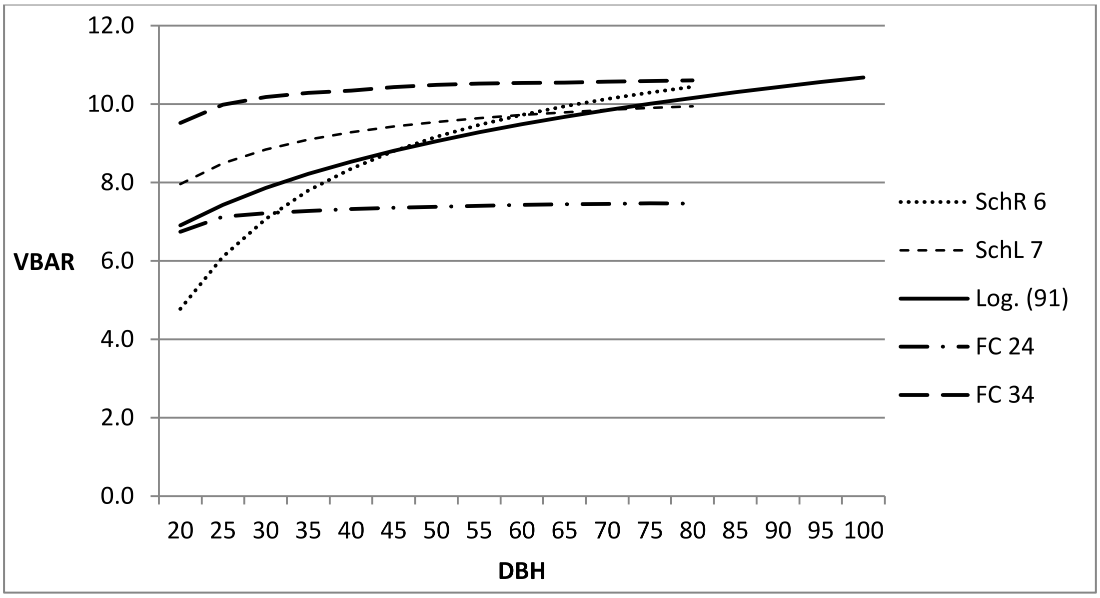

Figure 3.7 VBAR comparison: research stand 91, FC tariffs, and Schaeffer tariffs.

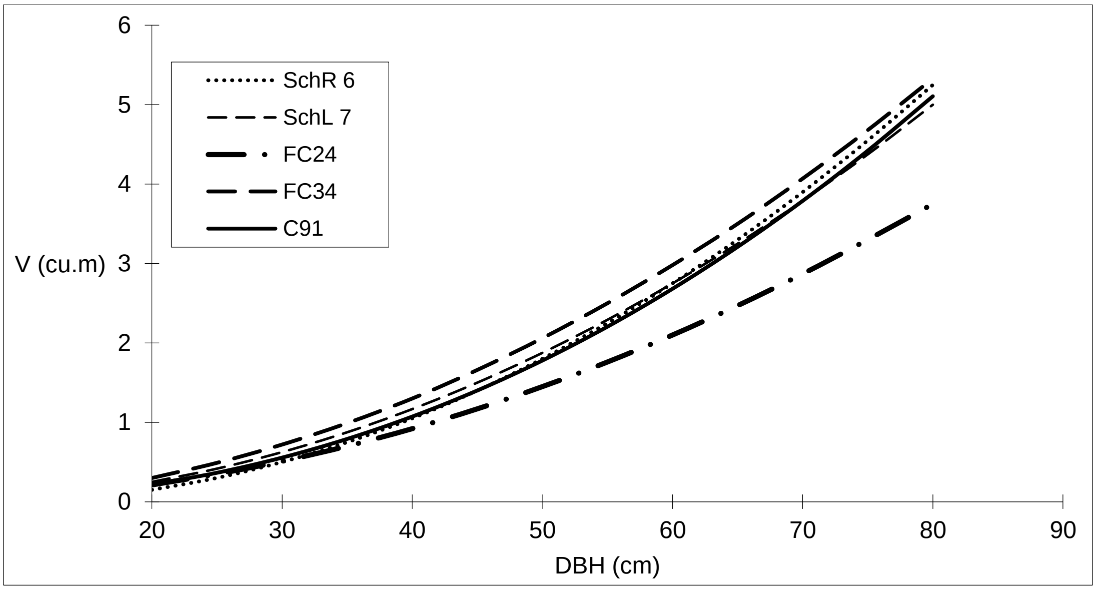

Figure 3.8 Comparison of single tree volume curves - research stand 91

The VBAR formula will be used for all broadleaf high-forest species in repeat inventories although subject to periodic checks. This method represents a more fixed and localised solution to volume determination than that used for research stand 37c.

3.3 Economic outputs

Table 3.2 shows an example of optimum diameter calculations applied to ash of quality grade 'A' although the actual value increment cannot be assigned until the second inventory without invasive forms of increment analysis such as boring. In the meantime typical values recorded in AFI stands in northern France were used (Susse *et al.*, 2011). Unlike even-aged stands, evidence from broadleaved AFI stands which have received four measures show little correlation with increase in diameter; diameter increment can remain stable due to unrestricted crown space in the upper canopy.

Table 3.2 Ash quality grade 'A', determination of optimum diameter using a discount rate of 3.5%. DI= diameter increment, PU= price per unit, VI= value increment, SV= standing value and PV= potential value.

r = 3.5%							
AH (A)							
Diam cm	**Volume cu m**	**DI cm/an**	**PU £/m^3**	**VI £**	**Indicating per cent**	**SV £**	**PV £**
15	0.11	0.6	15.0	0.26	15.6%	1.7	7.4
20	0.22	0.6	20.0	0.48	11.2%	4.3	13.9
25	0.36	0.6	25.0	0.79	8.7%	9.1	22.6
30	0.56	0.6	30.0	1.51	9.1%	16.7	43.3
35	0.79	0.6	40.0	2.30	7.3%	31.6	65.7
40	1.07	0.6	50.0	3.26	6.1%	53.6	93.1
45	1.40	0.6	60.0	3.56	4.2%	84.1	101.6
50	1.78	0.6	65.0	5.46	4.7%	115.6	156.0
55	2.20	0.6	75.0	6.94	4.2%	165.4	198.2
60	2.68	0.6	85.0	10.21	4.5%	227.9	291.8
65	3.21	0.6	100.0	10.81	3.4%	321.0	308.8
70	3.79	0.6	110.0	9.71	2.3%	416.8	277.4
75	4.42	0.6	113.0	10.35	2.1%	499.6	295.8
80	5.11	0.6	115.0	10.20	1.7%	587.3	291.4
85	5.85	0.6	115.0				

Optimisation (as shown in Table 3.2) is found at the point where the potential value falls below the current standing value (highlighted), the optimum diameter being 65 cm for ash of quality grade 'A'. This is reinforced by the indicating per cent; optimum being when the indicating per cent is equal to the chosen discount rate. When this calculation was applied to all target species and quality grades in the stand it provided a general guide when marking for selective felling.

The potential value concept is shown graphically in Figure 3.9 for ash, penduncular oak, and beech. Diameter increments of 0.6 cm per annum have been used for ash and beech, and 0.4

cm for oak, based on averages experienced in AFI stands in northern France (Susse *et al.*, 2011).

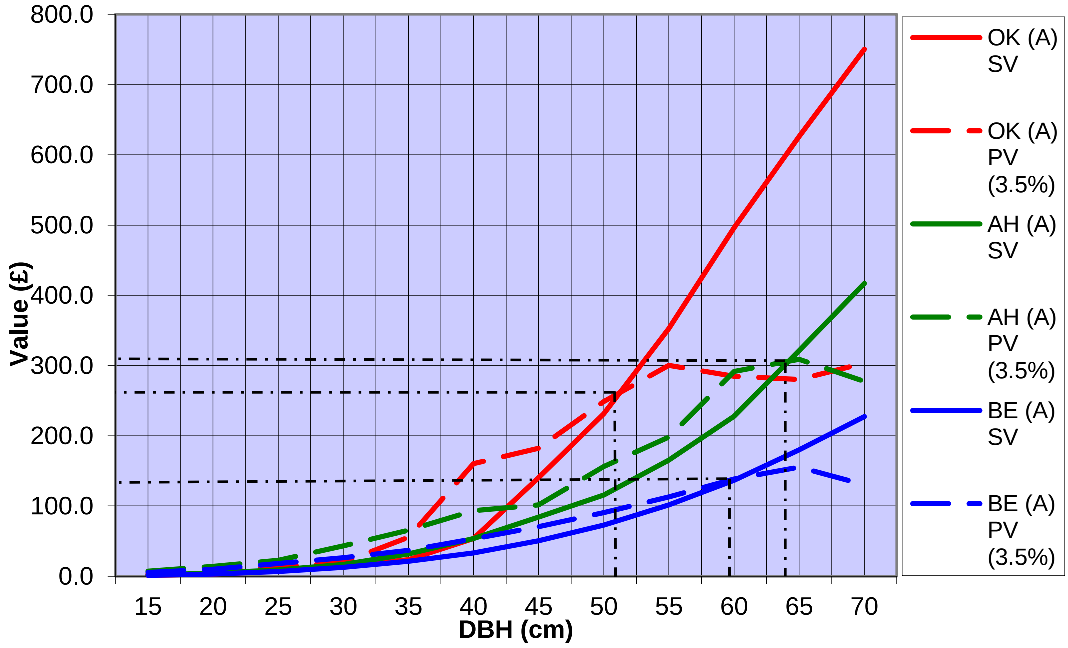

Figure 3.9 Tree grade A standing value (SV) & potential value (PV) – Research Stand 91

When comparing performance between species, those species which can attain the highest value at the point where potential value falls below current value are economically preferable. In this example ash would appear to be the best performing species. The surprise here is oak, which despite being able to achieve very high value in the longer term reaches optimum at between 50 cm and 55 cm due to a lower assigned increment.

Local Research Stands 91 and 37c – standing capital value and potential value

Table 3.3 compares the stand level current standing value (SV) per hectare, of the two research stands, against stand potential value (PV). Research Stand 37c is even-aged, relatively young and contains many stems which have not yet reached the minimum diameter for saw log material. For Research Stand 91 the potential value is slightly lower than the standing value.

Table 3.3 Stand level valuation – comparison of SV and PV for Research Stands 91 and 37c.

	Research stand compartment no.	
	37c	91
2013 current standing value SV/ha	£ 3,219.00	£ 10,570.00
2013 Potential value PV/ha	£ 10,236.00	£ 10,394.00
Variation	**£ 7,017.00**	**-£ 176.00**

3.4 Statistical outputs

Figures 3.10 to 3.13 show the results for the different inventory methods: complete enumeration, PPS, fixed area, and the combination approach for trees in the main stand (>17.5 cm DBH).

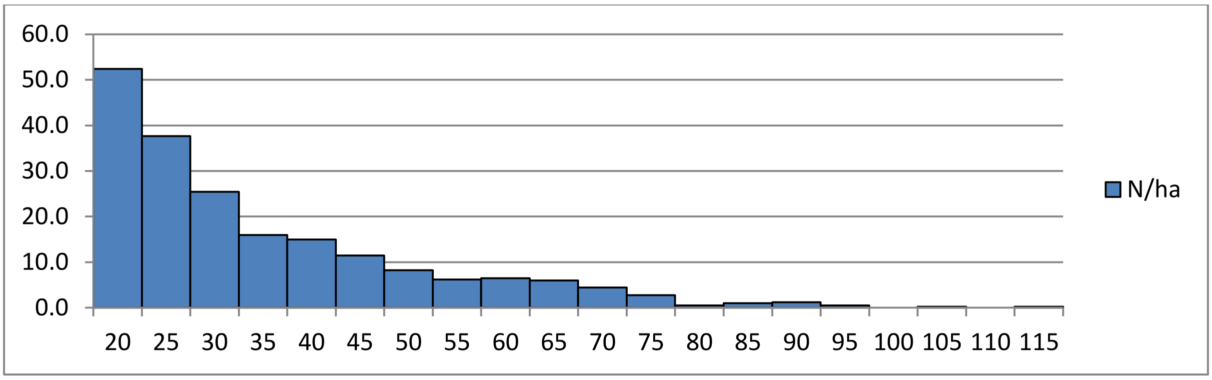

Figure 3.10 Complete enumeration – N/ha by 5 cm classes in Research Stand 91

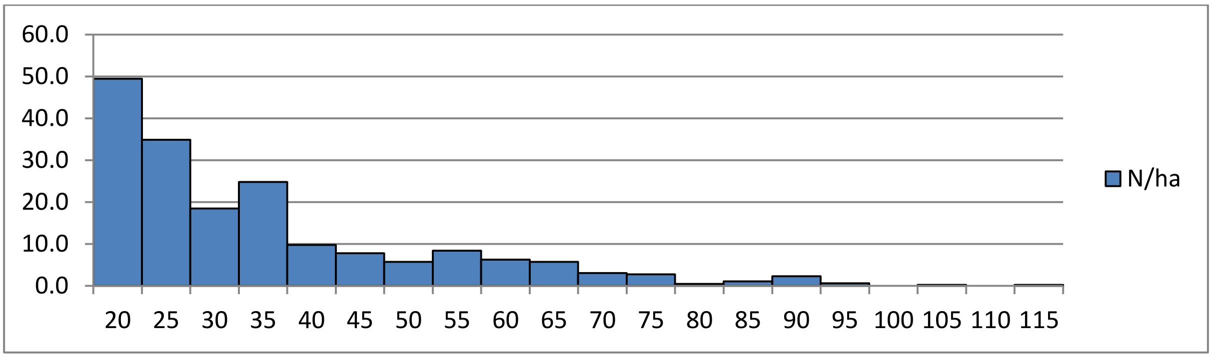

Figure 3.11 Sampling by PPS ($2.25m^2ha^{-1}$) – N/ha by 5 cm classes in Research Stand 91

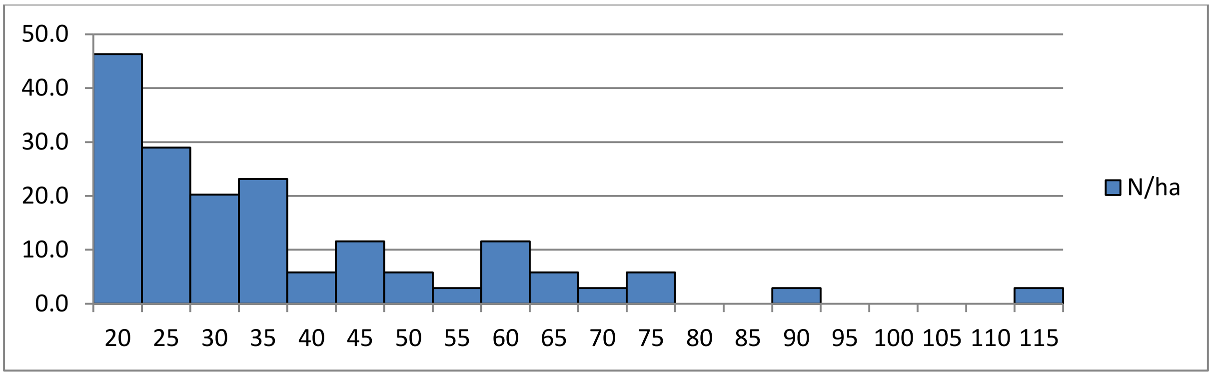

Figure 3.12 Sampling by fixed area 10m radius plots – N/ha by 5 cm classes in Research Stand 91

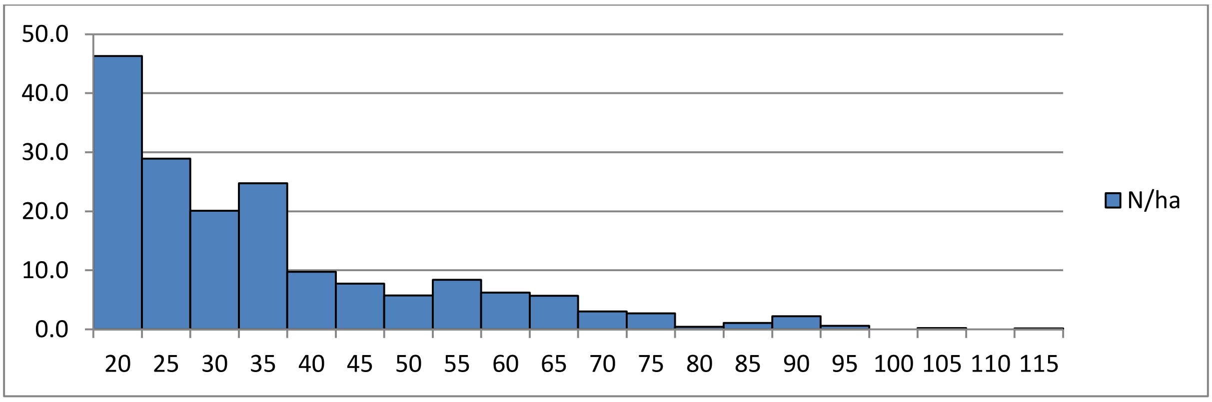

Figure 3.13 Sampling by combination PPS and fixed-radius plots – N/ha by 5 cm classes in Research Stand 91

A summary of the error found between the output data of the three different sampling methods (Figures 3.11 to 3.13) when compared to the full enumeration (Figure 3.10) is shown in Table 3.4. The variation in error for stem density and basal area was very slight in all three cases, however when analysing output data on structure a large disparity was found in the case of the larger 5 cm diameter classes. Even with the removal of a very extreme result in the 115 cm class the fixed-area method showed a very high average error (65%) in the 35 cm to 95 cm range. The results were better for both the PPS and combination methods (both 27%) in this range and for the full range (21% and 22% respectively). All methods performed equally well when describing the smaller stem sizes (<30cm DBH).

Table 3.4 The error per cent for the three plot types: fixed area, PPS, and the combination approach on the three stand variables; basal area, stem density and structure by 5cm diameter classes for Research Stand 91.

<table>
<tr><th colspan="2"></th><th>Fixed area (E%)</th><th>PPS (E%)</th><th>Combination (E%)</th></tr>
<tr><td colspan="2">Stem density N/ha</td><td>10%</td><td>7%</td><td>8%</td></tr>
<tr><td colspan="2">BA/ha</td><td>8%</td><td>5%</td><td>7%</td></tr>
<tr><td rowspan="3">Structure (5cm diameter classes)</td><td>Range 20-30 cm</td><td>18%</td><td>13%</td><td>19%</td></tr>
<tr><td>Range 35-95 cm</td><td>65%</td><td>27%</td><td>27%</td></tr>
<tr><td>Full range 20-115 cm</td><td>103%</td><td>21%</td><td>22%</td></tr>
</table>

Plot-level study

In Table 3.5 the number of stems sampled were disaggregated by 5 cm classes, and by the diameter groups, under the three sample methods. Apart from the poles (which were measured under the fixed 10 m radius plot in all methods) the numbers sampled under the PPS technique, for the grouped data, closely mirrored the basal area contribution of that group. The combination approach was the better for evenness of data across diameter groups. The fixed area method however, provided fewer samples with increasing diameter; had the stand been measured using fixed-radius plots alone, only 14 trees of 47.5 cm> would have been included for the delivery of information on 56% of stand basal area.

Table 3.5 Number of stems sampled by 5cm size class and broad diameter groups for the three sample plot types: fixed area, PPS, and combination in Research Stand 91.

5cm d classes	n per plot			Broad diameter groups	n per group			BA/ha contribution
	combi.	fixed	PPS		combi.	fixed	PPS	
10	12	12	12	POLES	35	35	35	6%
15	23	23	23					
20	16	16	7	SW	26	26	15	14%
25	10	10	8					
30	7	7	6	MW	30	21	29	29%
35	11	8	11					
40	6	2	6					
45	6	4	6					
50	6	2	6	LW	33	9	33	29%
55	10	1	10					
60	8	4	8					
65	9	2	9					
70	5	1	5	VLW	26	5	26	22%
75	6	2	6					
80	1	0	1					
85	3	0	3					
90	7	1	7					
95	2	0	2					
100	0	0	0					
105	1	0	1					
110	0	0	0					
115	1	1	1					
Total (n)	**150**	**96**	**138**					

Error comparison

Table 3.6 Statistical analysis – between plot variance in basal area for the three sample methods trialled in Research Stand 91 and comparison with other UK-based AFI stands.

Location	Cranborne	Cranborne	Cranborne	Cranborne	Cranborne	Melbury	Stourhead	Cranborne	Rushmore
Date of 1st inventory	2013	2013	2013	2013	2013	2012	2006	2011	2012
BAF	Combi.	2.25	fixed r = 10m	2.25	2.25	1	2.25	2.25	1
Species	MB	MB	MB	NS	DF/SP	NS/POK	MC	MB	NS
Development stage	Selection (4)	Selection (4)	Selection (4)	Trans. (2)	Trans. (2)	Trans. (2)	Selection (3)	Selection (3)	Trans. (2)
Method	Abb. AFI	Abb. AFI	Abb. AFI	Abb. AFI	Abb. AFI	Abb. AFI	Full AFI	Full AFI	Full AFI
Plots	**91**	**91**	**91**	37c	208/213	H5d *	AFI No. 67	AFI No. 94	AFI No.
1	21.2	20.3	12.0	24.8	29.3	17	29.3	13.5	34
2	23.2	23.3	44.7	24.8	31.5	13	38.3	29.3	32
3	11.9	10.8	14.4	31.5	29.3	18	36.0	22.5	32
4	22.4	22.4	4.7	24.8	29.3	13	27.0	20.3	25
5	11.5	10.5	15.3	22.5	24.8	13	20.3	18.0	30
6	25.6	27.7	35.7	22.5	29.3	25	33.8	9.0	26
7	21.9	22.5	46.7	33.8	20.3	21	31.5	24.8	26
8	39.5	40.6	34.2	29.3	42.8	33	20.3	18.0	25
9	20.7	20.4	15.8	27.0	33.8	22	31.5	22.5	36
10	22.8	23.1	7.2	27.0	45.0	32	22.5	24.8	27
11	9.9	11.2	33.7				27.0		
12							20.3		
BA/ha	**20.9**	**21.2**	**24.0**	**26.8**	**31.5**	**20.7**	**28.2**	**20.3**	**29.3**
S	8.2	8.7	15.2	3.7	7.5	5.5	6.3	5.9	4.0
CV	**39%**	**41%**	**63%**	**14%**	**24%**	**25%**	**22%**	**29%**	**14%**
E % (p=0.05)	**26%**	**28%**	**42%**	**10%**	**17%**	**18%**	**14%**	**21%**	**10%**

*** Research stand H5d was stratified**

The error per cent for Research Stand 91 (as shown in Table 3.6) was considerably higher for the fixed radius method, with little difference between the relascope and combined approach. All of the other AFI stands shown in Table 3.6 have a history of recent management; the range in plot-level basal area and percentage error, in all cases was lower than 'the neglected' Research Stand 91. This reflects the variable spatial arrangement in the neglected stand;

whereby in some parts large canopy gaps were present whilst in others stem density was locally high. Research stand 37c (as shown in Table 3.6) was essentially an even-aged stand with a history of active management. The calculated error in this case was within $\pm 10\%$ of the true value 95 times out of 100.

4. Discussion

4.1 Analysis – Local Research Stand 37c

The economic analysis revealed a large variation between current and potential value in Research Stand 37c (Table 3.3), which indicates that this stand is economically suitable for transformation because a significant time period needs to elapse before the PV is approaching SV. At the time of inventory however, few market opportunities exist for Norway spruce beyond 60 cm DBH which sets an upper limit on the time available for transformation. If optimisation is to occur at the level of the individual tree, and one were to estimate a diameter increment of 1 cm per annum, few stems from the current stand will remain for cover-building trees beyond 25-35 years based on the peak of the stem size curve (Figure 3.1). This would indicate that a fully developed structure is unlikely to be achieved with the current generation and will have to wait until elements of the next generation mature. This is anticipated where stands are in transformation as there is often an insurmountable age gap between seed production within the even-aged stand and the beginnings of the new generation. O'Hara (2001) encourages acceptance of a variety of uneven-aged structures, not just the classic examples and it is reasonable to suppose that this stand will pass through what could be described as an 'irregular shelterwood' (Knuchel, 1953; Smith *et al.,* 1997; Matthews, 1989,1992) before complete transformation to an all-aged structure is achieved. Indeed this technique has been successfully used as a transitional means to fully all-aged stands in continental Europe (Schütz, 2001).

The recorded basal area of $26.8m^2ha^{-1}$ is perceived to be in line with current thinking, Poore (2007) recommends an after thin basal area of $27m^2ha^{-1}$ as being appropriate for initiating regeneration. The stand at the time of measurement was on a felling cycle of four to five years which remains the case until further knowledge is available, the next intervention being due in 2016/17. Target removals will consist of the poorer quality larger trees using principles conventionally known as 'thinning from above' or 'crown thinning', as has been the case for the last two interventions.

4.2 Analysis – Local Research Stand 91

The output data for Research Stand 91 revealed that the larger stem size classes were oak dominated, with ash as the secondary species, but oak was squeezed out of contention in the smaller size classes by ash and sycamore (Figure 3.2). The under-storey consisted almost entirely of shade tolerant shrub and tree species, beech being the only target species present (Table 3.1). The distribution by species in the main stand, through poles, to regeneration revealed a standard successional sequence (Aber & Melillo, 2001; Thomas & Packham, 2007) which began when the elm were removed approximately 40 years previously. Experience within AFI stands which have received four measures is that sufficient regeneration is difficult to achieve above $20m^2ha^{-1}$ basal area (Susse *et al.*, 2011) with stands of oak typically ranging from $12\ to\ 15m^2ha^{-1}$ plus $1\ to\ 2m^2ha$ of pole stage material. Research stand 91 is currently standing at $21.5m^2ha^{-1}$ including $1.3m^2$ of poles. Removal of 20-25% of the current standing volume would leave a post-felling basal area of $16\ to\ 17m^2ha^{-1}$. This yield ($4.5\ to\ 5m^2ha^{-1}$) could come from the numerous quality 'D' material of all sizes, along with a selective felling of timber trees in the 'large wood' size class, which exceed the perceived optimum diameter.

The results of the economic analysis in Table 3.3 back up the recommendation to de-capitalise the stand. In irregular stands it is not ideal for potential value to be equal to current standing value at the stand level, but rather that the majority of trees will have potential value in excess of current value with a few individuals approaching, or around optimum to provide trees for harvest. If a comparison is made between the target diameters (Figure 3.9) and the stem size distribution (Figures 3.2 and 3.3) it can be seen that the stand contains many very large trees which are considerably larger than optimum. The potential value of these large trees is well below the current standing value with the result that they are collectively pushing up the stand capital value beyond the potential value.

The height curve generated in this all-aged stand revealed a VBAR more similar to the Schaeffer curves than to those derived from a single FC tariff number. In calculating a regression function which relates volume to basal area no tables are required, although it would be prudent to take some height samples during each successive inventory to corroborate and refine the height curve.

4.3 The structural optimum

The ideal structure as defined by the broad diameter groups (Figure 3.3) will vary between species and species mixtures. Knuchel (1953) suggests that on good sites for silver fir-beech-spruce selection forests of the Swiss Jura, a proportion of large-sized timber of 55% may be accepted as normal. The more species which occupy the stand, the more complex the ideal arrangement is to quantify; it is an iterative process largely driven by economics, influenced by market demands, and will be gradually arrived at over time.

The interactions between individual trees are very complex and the calculated optimum diameters should only be considered as a guide. Other factors such as neighbourhood effects, ecological functions or retention as a source for seed may take a higher priority and there is unlikely to be any significant loss in economic returns 5 cm either side of the calculated optimum diameter.

4.4 Statistics

The statistical analysis shown in Tables 3.4, 3.5, and 3.6, demonstrates the level of information delivered by PPS sampling and fixed-radius plots. There is a difference in the total number of trees measured within the various plot types, and, by calculation, a 12m radius plot would have provided for closer comparison. Yet the 10 m radius plots were sufficient to highlight the issues; it is shown that in this case fixed-radius plots alone are not as efficient for the monitoring of irregular stands. During early transformation fixed-area plots may seem to be delivering results but as the original trees grow bigger, and fewer in number the quality of information will decline. Alternatively if the plots are very large, or high in number, unnecessary time will be spent measuring numerous small trees and sampling efficiency will be lost.

The combination approach required a greater level of skill and attention in the field but delivered a good spread of data across all diameter classes, and within the broader groups. Both the PPS and combination plots performed equally well when analysed for error on the three stand variables basal area, stem density and structure by 5cm diameter classes.

The level of accuracy achieved with ten plots in the even-aged spruce stand was well within accepted boundaries for error (10%). The coefficient of variation here was only 14%. It is expected that this will increase as the stand becomes more spatially variable. The 11 sample plots in the broadleaf stand showed a relatively high error in spatial variance (26%).

However because subsequent selective felling would target areas of higher accumulated stocking whilst leaving areas of poor stocking to accrue, the between plot variance is expected to be less in the future than within the stand's unmanaged state. Nevertheless where stands show a high coefficient of variation perhaps 15 plots would be a better recommendation, or alternatively a change to BAF $1m^2ha^{-1}$ which would have the effect of reducing between plot variance in basal area. This places a lower limit of at least 5 ha on the size of compartment which can be assessed using this method (depending on the shape of the stand and the maximum expected diameter).

4.5 The increment

Despite the issues experienced with accuracy at the stand level, the information at plot level was high with a very direct measure of increment achievable at next inventory. It is clear from the plot level data that there are too few samples (from Table 3.5) within the 5cm classes to gain an accurate mean for increment, especially considering the number of species of potential interest within an irregular broadleaf stand. The PPS and combination plots did however, supply a good stem number count within the broader diameter groups. This would deliver a larger sample for the estimation of increment but with reduced detail.

4.6 Time and motion

Plot set-up took little time so most of the time was spent measuring. With BAF $2.25m^2ha^{-1}$ each plot took between 45 and 60 minutes for two people, depending on site conditions, including location and set-up. With only one mensurationist, the time taken was between 60 and 80 minutes. Although it was apparently more efficient with one person, there was a lot of equipment to carry and plot location was challenging when there were obstacles to climb over or sight lines were obscured. With two, a research stand of ten plots can easily be set up in one day (longer when using BAF $1m^2ha^{-1}$). This is however no faster than complete enumeration for a small (~5ha) site: Reade (1990) stated an average working rate of 2.5ac per hour for three men which equates to approximately 2.7ha per-man per-day assuming an eight-hour day (this agrees with the complete enumeration of research stand 91). However no measurement of poles or regeneration was accounted for and there are other issues with complete enumeration such as increment calculation. With sites larger than 5ha sampling is the more efficient.

5. Conclusion

Maintenance of an economically sustainable condition within complex heterogeneous forest structures is a major challenge. The results from the AFI abbreviated inventory provided a range of information about the stand which would not have been explicitly apparent from a purely visual analysis or from intuitive conjecture, although a fuller picture will not be revealed until successive inventories have been completed.

The PPS sampling system employed by the AFI method produced a good range of data across all diameter classes. When combined with a fixed-radius plot for the measurement of a sufficient number of pole-size trees, and smaller still plots for the measurement of regeneration, a complete picture of the stand was revealed. This comprehensive assessment of all material from large trees to seedlings means that there are no gaps in knowledge (at least at plot level) which allows for deviations from management objectives to be quickly recognised. The fact that individual trees can be relocated allows one a very direct assessment of diameter increment which can be easily broken down by species and size class. The method is not vulnerable to potential mistakes in record-keeping between enumerations, as was described for the check method, as each measurement is a snapshot directly comparable to the previous measure. If the plot locations are fixed and are periodically measured, predictions about dynamics within complex forest structures over time can eventually be made. Economic tools can be applied to mensurational data to aid the manager in decision-making when marking trees for selective harvesting, with the aim of achieving that level of growing stock which produces permanently the highest value increment.

Further studies would be needed to attach statistical significance, but the evidence within this study is that fixed-area plots showed considerably larger margins for error on structure (for larger diameters), and for between plot variance in basal area, than did the PPS sampling when comparing plots of comparable scale. Moreover it was shown that the fixed area method delivered too few samples within the large trees to gain a reliable estimate for increment under the continual inventory principle.

It is important to note that the economic analysis relies on good quality increment data, only achievable by repeated measurement of a wide sample of individual trees over time.

6. Recommendations and Further Work

The AFI research stands are monitored every five years but this does not have to be the case. For better coherence the period between measurements could be synchronised with the felling cycle. Kerr et al. (2002) recommends a period of between five and ten years as being suitable for measuring structural change.

Once the permanent plot framework is set up, additional applications may be added. The marginal cost of adding another parameter to be measured may be fairly small, however each additional measurement needs to be considered with benefit weighed against cost. With a greater number of plots, inventory can be carried out at forest level where other parameters such as within stand and between stand diversity could be assessed over time, along with increment and yield at forest level. In the long term, given continuity in stand monitoring, the adaptive ability of stands to climate change and to pests and diseases can be assessed by site types, species, species mixtures and forest structure. Vitally important lessons may be learned which could aid in prescribing sustainable forest management in meeting multiple objectives in a changing climate.

To get a true measure of stand level profit and loss all income and expenditure over the monitoring period must be recorded, including the costs of mensuration. All of the economic information can then be pooled together as the **stand profit and loss potential value (SPLPV)** (Susse *et al.*, 2011):

$$SPLPV = \sum SV_i + \sum \frac{DI}{r} - \sum Expenses \qquad \text{(Equation 10)}$$

Or alternatively the **stand profit and loss standing value (SPLSV)**, where the net income is added to the change in value between enumerations.

$$SPLSV = SV_2 - SV_1 + \sum Yeild\ returns - \sum Expenses \qquad \text{(Equation 11)}$$

A similar approach is discussed by Härtl *et al*. (2010), under this model a thinning is deemed profitable if the interest income arising from thinning returns, plus the increase in value increment of the remaining trees compensates the lost value increment of the cut trees, such that the profitability of the stand is not diminished. The calculation of optimum diameters using the potential value concept would benefit from further sensitivity analysis: how sensitive is the output data to changes in the price size curve, increment, and perhaps most importantly, to different discount rates?

As a final note; perhaps of greatest importance is the archiving of data so that information is readily available to future management. Without meticulous data storage all the efforts put into the gathering and computation of dendrometric data could be wasted.

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