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# The Costs and Revenues of Transformation to Continuous Cover Forestry

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# The costs and revenues of transformation to continuous cover forestry: Modelling silvicultural options with Sitka spruce


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## Executive summary


Forest Research was asked by the Forestry Commission Working Group on continuous cover forestry to examine the cost and revenue implications of transformation.

This study presents four different management scenarios for a stand of Sitka spruce (GYC 14):

SS1 Clearfell and replant
SS2 Transformation to a simple structure using natural regeneration
SS3 Transformation to a simple structure using underplanting after the failure of natural regeneration
SS4 Transformation to a complex structure

The M1 yield model, which is more flexible than the Booklet 48 yield tables, has been used to predict growing stock and harvesting yields for programmes of thinnings which follow current guidance on transformation.

Detailed information on the costs of operations in all four scenarios has been collected from work study reports, England Woodland Grant Scheme standard costs and Forestry Commission staff. Cost and revenue assumptions are given in full in the report. These include higher overhead costs of management for transformation to a simple structure (150 %) and to a complex structure (200 %) relative to clearfell and replant, to reflect most managers' relative inexperience of these approaches to management.

Economic comparisons begin at a stand age of 25 years, when management practices begin to diverge. They cover three time periods; 20 years, 100 years, and the infinite series of rotations typically used in economic comparisons to account for the effects of, for example, different rotation lengths. The results below are presented in terms of net present values (NPVs) at a declining discount rate starting at 3.5 %.

| Scenario | Net present value per hectare considering cash flows… | | |
|---|---|---|---|
| | to 20 years | to 100 years | in perpetuity |
| SS1 | -£724 | £3,790 | £4,689 |
| SS2 | -£600 | £3,611 | £5,621 |
| SS3 | -£600 | £1,653 | £2,802 |
| SS4 | -£651 | £1,465 | £4,293 |

Transformation (SS2-4) is less costly than conventional management (SS1) over a 20 year period because of high initial thinning returns. Over 100 years scenario SS2 has a similar NPV to conventional practice (SS1), and it has the highest NPV in perpetuity because even with respacing costs natural regeneration is cheaper than artificial regeneration, and the establishment of each successor crop under an existing stand shortens the delay before thinning and felling revenues are realised relative to clearfelling and replanting (SS1). Even with unfavourable management cost assumptions, the NPV in perpetuity for transformation to a complex structure (SS4) is close to that for conventional practice (SS1).  The importance of obtaining successful natural regeneration during transformation is emphasized by the relatively poor performance of SS3.

The results are examined for their sensitivity to changes in the level of management overheads, product prices and discount rate. The changes investigated have relatively little effect on the ranking of scenarios in terms of NPV, although low discount rates favour SS2 and SS4 and high rates favour SS1.

An important outcome of this study is the creation of an analysis spreadsheet used to calculate the NPVs for each scenario. This is available to practitioners and policy makers to allow them to investigate the effects of local conditions on results. While users cannot change the schedule of operations in each scenario, they do have complete freedom to change all inputs in terms of costs, product specifications, roadside prices and the discount rate, which will immediately update the NPV outputs.

Forest managers face many uncertainties when they embark upon the transformation of even-aged stands to continuous cover forestry. It is hoped that, by quantifying the possible cost and revenue implications, this report may help to relieve concerns that transformation is a costly option compared with conventional practice of clearfell and replant.

# Contents

# 1 Introduction

While interest in Britain in the concept of continuous cover forestry (CCF) is longstanding (Troup, 1927), it is only in relatively recent years that it has begun to feature strongly in British forestry policy as a favoured management approach. Explicit mention of CCF is made in the *UK Forestry Standard* (Forestry Commission, 2004) and *Woodlands for Wales* (Welsh Assembly Government, 2009), and both the *Scottish Forestry Strategy* (Scottish Executive, 2006) and the *UK Woodland Assurance Standard* (UKWAS, 2008) favour lower impact silvicultural systems which include CCF. Although the perceived importance of CCF in meeting policy objectives is clear, experience of silvicultural alternatives to patch clearfelling is limited in Britain and the consequences of transforming stands to CCF management, particularly in terms of costs, remain uncertain (Mason *et al*., 1999). This uncertainty could be a significant barrier to implementation.

In this context, the main aim of this study is to quantify as accurately as possible the costs, timber yields and associated revenues for three realistic transformation scenarios, and to compare them with those from a clearfell and replant scenario representing common current practice. As the study was requested by the Forestry Commission's Working Group on Continuous Cover Forestry, the definitions and terminology used are those of the Forestry Commission (Mason *et al*., 1999; Mason and Kerr, 2004) as are the practices and standards. No attempt has been made to quantify the changes in the provision of ecosystem services (Krieger, 2001) which may arise from the various scenarios, which could be positive or negative (Price, 2003; Price and Price, 2008). As such the comparison is a financial rather than an economic cost-benefit analysis (*sensu* Price and Price, 2008), and as the non-market benefits arising from the proposed management changes are not quantified it is not possible to suggest whether any additional costs are justified. Discounted cash flows are presented for three different timescales, namely 20 years, 100 years and in perpetuity. Although the third timescale, the infinite series of rotations, is the more traditional approach to comparing silvicultural alternatives (e.g. Andreassen and Øyen, 2002), it is considered pertinent in the light of ongoing government spending reviews to ask what will be the short term costs, if any, of implementing the changes to management practice advocated by national forestry policies.

It will be appreciated that this case study approach cannot provide any indication of the financial consequences of changes in forest management at a national scale. Indeed it is the authors' contention that no meaningful indication of the consequences at such a scale can be produced, as for every species on every site type there will be different silvicultural approaches, different degrees of success, and unknown consequences for stand development and timber yields. Furthermore, accurate cost data for many operations simply do not exist at the present time. The current approach has been chosen so that the assumptions made in each scenario are clear and can be scrutinised accordingly. Important British studies have investigated the effects of, for example, different harvesting and establishment costs on the relative profitability of silvicultural scenarios, with the aim of illustrating the relative important of such factors (Price, 2003; Price and Price, 2008). While other studies have to a greater or lesser extent provided sources and details of cost, revenue, growth and yield assumptions (e.g. Hubert *et al*., 2000; Tarp *et al*., 2000; Hanewinkel, 2001, 2002; Knoke and Plusczyk, 2001; Knoke *et al*., 2001; Andreassen and Øyen, 2002; Price and Price, 2006; Tahvonen *et al*., 2010), in this study it is hoped to explore exactly why costs and revenues might differ between scenarios and to what extent by providing complete details of all assumptions regarding operations and the growth of stands. An important outcome of the study is the creation of an analysis spreadsheet which allows users to adjust all of the cost and revenue assumptions to match their own local conditions to determine what the cash flow consequences might be. It is hoped that this will prove useful to practitioners considering the implications of changes to management practices when local factors are quite different to those presented in this report.

**The reader should be aware that much of this document is made up of detailed accounts of the assumptions made in constructing and analysing the scenarios investigated. Section 2.1 gives an outline of each scenario which should be sufficient to furnish a broad understanding of the forestry practice involved. Unless specific operations or details of calculations are of interest, the general reader is advised to omit the remainder of section 2 and proceed to the results, discussion and conclusions in sections 3, 4 and 5.**

# 2 Materials and methods

## 2.1 The scenarios

The starting point for all of the scenarios is a stand of Sitka spruce (*Picea sitchensis* (Bong.) Carrière) planted at 2 m square spacing and growing at yield class 14, i.e. the maximum mean annual increment expected under conventional management is 14 $m^3$ per hectare per year (Edwards and Christie, 1981). Sitka spruce was chosen as it is the most common species in British forestry, accounting for approximately 29 % of woodland by area (Smith and Gilbert, 2003). Establishment at 2 m spacing gives an initial stocking density of 2,500 stems per ha, the minimum requirement in Forestry Commission guidance (Forestry Commission, 2010). The yield class of 14 is the average for the species in Forestry Commission forests (Justin Gilbert, pers. comm.). Cash flows and yields are expressed on a per hectare basis but some costs depend on total stand area, which affects, for example, the intensity of sampling required in monitoring operations. For these purposes, the total stand area is assumed to be 10 ha. Management of this initial stand is assumed to be identical for all four scenarios up to and including a first line thinning at age 23 years, so the detailed scheduling of operations and cash flows begins at age 25 after which the scenarios begin to diverge. The first thinning age was chosen to coincide with the standard thinning age for yield class 14 Sitka spruce at 2 m spacing (Rollinson, 1985), the earliest age at which thinning can occur without sacrificing cumulative volume production. Line thinning removing one row in seven is assumed.

### 2.1.1 Scenario SS1 - Clearfell and replant

This is the baseline scenario representing current conventional practice. After the first thinning at age 23, thinning interventions are carried out on a seven year cycle. This assumes that managers will aim for a five year cycle but that various delays in planning and executing operations will effectively extend the thinning cycle. Thinnings at age 30, 37, 44 and 51 are intermediate in type and remove volume at the marginal thinning intensity (Rollinson, 1985). Clearfelling, preceded by a B6 abbreviated tariff (Matthews and Mackie, 2006) two years earlier, is at age 58 when the stand reaches its maximum mean annual increment (see section 2.2). The rotation length is therefore based on maximising volume production rather than an economic optimum, which might vary with, for example, product assortments, prices and the discount rate (Price, 1989). It should be noted that none of the scenarios has been economically optimised, but represents the form that management might be expected to take given current norms. Thinning and felling operations for this scenario are outlined in Table 1.

Restocking by planting occurs after a five year fallow period primarily intended to minimise the risk of damage from the large pine weevil, *Hylobius abietis* (Moore, 2004). The fallow period means that there are no direct costs of weevil control, but there are issues with weed control. The restocking site receives an overall herbicide spray four years after clearfelling, and is cultivated and planted the following year. Spot spraying around planted trees is carried out annually for the next three years. Beating up is carried out two years after planting in accordance with *Operational Guidance Booklet 4* (OGB4, Forestry Commission, 2010), which also requires assessments of stocking at one and four years after planting. Cleaning of the crop takes place ten years after planting, and when the trees reach 23 years of age the cycle of thinnings and other operations is repeated. The schedule of operations during the first 100 years of the scenario is outlined in Table 2. Full details of all the assumptions made in specifying and costing operations are given in section 2.3.

**Table 1** Summary of thinning and felling operations in scenarios SS1-3.

| Crop age | Scenario SS1 | | Scenario SS2 | | Scenario SS3 | |
|---|---|---|---|---|---|---|
| | Thinning type | Thinning intensity [a] | Thinning type | Thinning intensity [a] | Thinning type | Thinning intensity [a] |
| 23 | Line | 1 row in 7 | Line | 1 row in 7 | Line | 1 row in 7 |
| 30 | Intermediate | 100 % MTI | Crown | 120 % MTI | Crown | 120 % MTI |
| 37 | Intermediate | 100 % MTI | Crown | 120 % MTI | Crown | 120 % MTI |
| 44 | Intermediate | 100 % MTI | Crown | 140 % MTI | Crown | 140 % MTI |
| 51 | Intermediate | 100 % MTI | Intermediate | 160 % MTI | Intermediate | 160 % MTI |
| 58 | Fell | | Low | 200 % MTI | Low | 200 % MTI |
| 65 | | | Fell | | Low | 200 % MTI |
| 72 | | | | | Fell | |

a MTI = Marginal Thinning Intensity (Edwards and Christie, 1981; Rollinson, 1985).

### 2.1.2 Scenario SS2 - Transformation to a simple structure using natural regeneration

This scenario represents transformation to a simple structure (*sensu* Mason and Kerr, 2004). Heavier thinning than in scenario SS1 is used to promote the establishment of natural regeneration throughout the stand. After a brief period where the structure of the stand is two-storeyed, the overstorey is removed and the natural regeneration is allowed to grow on to form a stand that is eventually regenerated in the same way. This management may be considered to represent a more or less uniform shelterwood (Matthews, 1989).

Thinning operations are summarised in Table 1. After the first line thinning, thinnings are based on the guidance of Mason and Kerr (2004) that early thinnings should be crown thinnings 10-20 % heavier than marginal intensity, aiming for 100-200 stems per ha at the start of regeneration. Thinnings at ages 30 and 37 are at 120 % of marginal thinning intensity. To achieve reductions in basal area to or below the threshold of 30 $m^2$ per ha assumed to be required for natural regeneration of Sitka spruce(Hale, 2004), the subsequent thinnings are increasingly heavy and, as the dominants are assumed to have been thinned to leave only desired seed trees/final crop trees by this stage, move from crown to intermediate to low in type. The final thinning at age 58 leaves 216 stems per ha at a basal area of 26.2 $m^2$ per ha (see section 2.2).

Adequate levels of natural regeneration are assumed to arise at age 55, well beyond the age at which adequate levels of seeding can be expected (Matthews, 1955). Various levels of regeneration could be assumed which would have different consequences for future management. On the basis of experience in forests such as Clocaenog in North Wales it is assumed that regeneration is dense and relatively uniform over the entire stand. This affects visibility in harvesting operations and also means that there is a requirement for respacing the regeneration. Felling of the overstorey at age 65 attracts a harvesting penalty (see section 2.3.3.3) because of the restrictions on visibility and the extra care required to minimise damage to regeneration.

**Table 2** Summary of operations during the first 100 years of scenario SS1.

| Year | Crop age | Harvesting | Other operations & notes |
|---|---|---|---|
| 6 | 30 | Thin | |
| 13 | 37 | Thin | |
| 20 | 44 | Thin | |
| 27 | 51 | Thin | |
| 32 | 56 | | B6 tariff |
| 34 | 58 | Clearfell | |
| 38 | | | Overall herbicide |
| 39 | 0 | | Cultivate, plant |
| 40 | 1 | | Spot herbicide, OGB4 initial |
| 41 | 2 | | Spot herbicide, beat up |
| 42 | 3 | | Spot herbicide |
| 43 | 4 | | OGB4 final |
| 49 | 10 | | Clean |
| 62 | 23 | Thin | |
| 69 | 30 | Thin | |
| 76 | 37 | Thin | |
| 83 | 44 | Thin | |
| 90 | 51 | Thin | |
| 95 | 56 | | B6 tariff |
| 97 | 58 | Clearfell | |

Monitoring operations and the respacing of natural regeneration are shown alongside harvesting operations in Table 3. Monitoring of regeneration and stand basal area follows guidance in *Forestry Commission Information Note 45* (FCIN45, Kerr *et al*., 2002); the distinction between abbreviated and full FCIN45 monitoring is explained in section 2.3.1.2. The respacing of regeneration occurs when the saplings reach age ten, at the upper limit of the likely optimal age range suggested by Nixon and Worrell (1999), having been delayed until after the final felling of the overstorey to allow any harvesting damage to be taken into account. Studies in dense Sitka spruce regeneration in Fernworthy and Clocaenog forests have shown that following one harvesting operation there can still be around 1,900 undamaged saplings greater than 2 m in height and around 12,000 undamaged seedlings and saplings between 0.5 and 2 m in height, alongside even greater numbers of damaged stems (Stokes *et al*., 2009). After respacing, the naturally regenerated crop is managed as per the initial stand.

**Table 3** Summary of operations during the first 100 years of scenario SS2.

| Year | Crop age | | Harvesting [a] | Other operations & notes |
|---|---|---|---|---|
| 6 | 30 | | Thin | |
| 13 | 37 | | Thin | |
| 20 | 44 | | Thin | |
| 24 | 48 | | | FCIN45 abbreviated |
| 27 | 51 | | Thin | |
| 31 | 55 | 0 | | FCIN45 abbreviated, regeneration occurs |
| 34 | 58 | 3 | Thin | |
| 39 | 63 | 8 | | B6 tariff |
| 41 | 65 | 10 | **Fell** | |
| 42 | | 11 | | FCIN45 abbreviated |
| 43 | | 12 | | Respace regeneration |
| 54 | | 23 | Thin | |
| 61 | | 30 | Thin | |
| 68 | | 37 | Thin | |
| 75 | | 44 | Thin | |
| 79 | | 48 | | FCIN45 abbreviated |
| 82 | | 51 | Thin | |
| 86 | 0 | 55 | | FCIN45 abbreviated, regeneration occurs |
| 89 | 3 | 58 | Thin | |
| 94 | 8 | 63 | | B6 tariff |
| 96 | 10 | 65 | **Fell** | |
| 97 | 11 | | | FCIN45 abbreviated |
| 98 | 12 | | | Respace regeneration |

a Harvesting operations in bold attract a productivity/cost penalty.

### 2.1.3 Scenario SS3 - Transformation to a simple structure using underplanting after the failure of natural regeneration

This scenario is very similar to SS2 except that heavy thinning fails to result in adequate natural regeneration and, after unsuccessful attempts to encourage regeneration by spraying weeds and scarifying the ground, the stand is eventually underplanted. The overstorey is removed shortly afterwards to minimise damage to the underplanting.

Up to a crop age of 55 years, the schedule of operations is the same as for scenario SS2 (Table 4). As the FCIN45 survey at this time shows that there is inadequate natural regeneration, weeds are sprayed off at age 56 and at age 57 the ground is scarified to improve seed bed conditions (Nixon and Worrell, 1999). Following thinning and another FCIN45 survey again showing inadequate regeneration, ground treatments are repeated, before a final thinning as per Table 1, and cultivation and planting as per Table 4. Post-planting treatment is as per scenario SS1, except that sporadic natural regeneration is assumed to remove the necessity for beating up, and the overstorey is felled two years after underplanting with a productivity penalty. Management of the successor crop is as per the initial stand.

### 2.1.4 Scenario SS4 - Transformation to a complex structure

The fourth scenario represents transformation to a complex structure (*sensu* Mason and Kerr, 2004), which requires that the stand have three or more canopy layers. Such a structure may be achieved in practice by adopting an irregular shelterwood system or a single tree or group selection system (Matthews, 1989; Mason and Kerr, 2004). The development of such a structure is represented in a simplified way in this study, because of the nature of the growth and yield model available (discussed in section 2.2) and the lack of knowledge of the silviculture of complex structures in Britain. Where areas of felling and areas of regeneration are described below, no assumptions are made about their spatial arrangement, which may be in groups of various sizes. The crucial point is that, from the end of the transformation period, there are always at least three cohorts or canopy layers coexisting at the stand level. The precise spatial arrangement of cohorts might have an effect on harvesting efficiency, but it is hoped that this is accounted for by a productivity modifier (see section 2.3.3.3) and in any case it is assumed that machines must travel the entire site to intervene in all size classes.

The initial stand (Table 5) is assumed to be managed on an extended rotation during the transformation period, with felling of final crop trees at 107 years. The seven year thinning cycle is retained, as experience in one of very few stands with a complex structure managed by the Forestry Commission, at Faskally, has shown that this cycle gives an acceptable yield of log material in each intervention (Charlie Taylor, pers. comm.). Thinnings from age 30 to 72 aim to maintain stand basal area at around 30 m² per ha, while crown thinnings from 79 to 100 years are intended to represent target diameter harvesting. Regeneration is assumed to occur at age 56, forming a second canopy layer, and 20 % of the initial stand is felled at age 65 to accommodate this layer. A third canopy layer is assumed to establish when the initial stand is 77 years old, and a further 20 % of the initial stand is felled when it is 86 years old. A fourth canopy layer arises at age 98, effectively completing the replacement of the initial stand. Thinning and felling from age 65 to final felling at 107 attract a harvesting productivity penalty.

**Table 4** Summary of operations during the first 100 years of scenario SS3.

| Year | Crop age | | Harvesting [a] | Other operations & notes |
|---|---|---|---|---|
| 6 | 30 | | Thin | |
| 13 | 37 | | Thin | |
| 20 | 44 | | Thin | |
| 24 | 48 | | | FCIN45 abbreviated |
| 27 | 51 | | Thin | |
| 31 | 55 | | | FCIN45 abbreviated |
| 32 | 56 | | | Overall herbicide |
| 33 | 57 | | | Scarify |
| 34 | 58 | | Thin | |
| 38 | 62 | | | FCIN45 abbreviated |
| 39 | 63 | | | Overall herbicide |
| 40 | 64 | | | Scarify |
| 41 | 65 | | Thin | |
| 46 | 70 | 0 | | Cultivate, underplant, B6 tariff |
| 47 | 71 | 1 | | Spot herbicide, OGB4 initial |
| 48 | 72 | 2 | **Fell** | Spot herbicide |
| 50 | | 4 | | OGB4 final |
| 56 | | 10 | | Clean |
| 69 | | 23 | Thin | |
| 76 | | 30 | Thin | |
| 83 | | 37 | Thin | |
| 90 | | 44 | Thin | |
| 94 | | 48 | | FCIN45 abbreviated |
| 97 | | 51 | Thin | |

a Harvesting operations in bold attract a productivity/cost penalty.

**Table 5** Summary of thinning and felling operations in scenario SS4.

| Crop age | Initial stand | | Second and subsequent cohorts | |
|---|---|---|---|---|
| | Thinning type | Thinning intensity [a] | Thinning type | Thinning intensity [a] |
| 23 | Line | 1 row in 7 | Intermediate | 60 % MTI |
| 30 | Crown | 140 % MTI | Crown | 120 % MTI |
| 37 | Crown | 140 % MTI | Crown | 120 % MTI |
| 44 | Crown | 120 % MTI | Crown | 120 % MTI |
| 51 | Intermediate | 120 % MTI | Intermediate | 120 % MTI |
| 58 | Intermediate | 120 % MTI | Intermediate | 120 % MTI |
| 65 | Intermediate & fell 20 % | 100 % MTI | Intermediate | 100 % MTI |
| 72 | Intermediate | 100 % MTI | Intermediate | 100 % MTI |
| 79 | Crown | 100 % MTI | Fell | |
| 86 | Crown & fell 20 % | 100 % MTI | | |
| 93 | Crown | 100 % MTI | | |
| 100 | Crown | 100 % MTI | | |
| 107 | Fell | | | |

a MTI = Marginal Thinning Intensity (Edwards and Christie, 1981; Rollinson, 1985).

Starting with the second cohort, a new cohort is recruited every 21 years, and for modelling purposes each is managed on a 79 year 'rotation' (Table 5). In reality management would be on the basis of tree size, and the 79 year rotation simulates target diameter harvesting at approximately 55 cm dbh (diameter at breast height, 1.3 m). The first thinning at age 23 is intermediate rather than line on the assumption that respacing of regeneration and operations in other canopy layers would have maintained racks; rather than establishing access to the stand, this thinning is assumed to remove poorly formed or damaged stems. Each canopy layer is assumed to be replaced by regeneration occurring at age 63. Thinning and felling from age 72 attract a harvesting productivity penalty.

From the establishment of the third canopy layer there are always at least three layers present. Second and subsequent canopy layers are each taken to occupy 40 % of the stand area, on the assumption that there will always be some overlap of younger layers into the understorey of older cohorts.

Harvesting and other operations are summarised in Table 6. Abbreviated FCIN45 surveys are carried out at ages 48, 55 and 62 of the initial stand. Full FCIN45 surveys are carried out on a ten year cycle from age 72 and are continued through all subsequent cohorts. Regeneration is respaced 12 years after establishment.

**Table 6** Summary of operations during the first 100 years of scenario SS4.

| Year | Crop age | | | | Harvesting [a] | Other operations & notes |
|---|---|---|---|---|---|---|
| 6 | 30 | | | | Thin cohort 1 | |
| 13 | 37 | | | | Thin cohort 1 | |
| 20 | 44 | | | | Thin cohort 1 | |
| 24 | 48 | | | | | FCIN45 abbreviated |
| 27 | 51 | | | | Thin cohort 1 | |
| 31 | 55 | | | | | FCIN45 abbreviated |
| 32 | 56 | 0 | | | | Cohort 2 arises |
| 34 | 58 | 2 | | | Thin cohort 1 | |
| 38 | 62 | 6 | | | | FCIN45 abbreviated |
| 41 | 65 | 9 | | | **Fell 20 % cohort 1, thin cohort 1** | |
| 44 | 68 | 12 | | | | Respace cohort 2 |
| 48 | 72 | 16 | | | **Thin cohort 1** | FCIN45 full |
| 53 | 77 | 21 | 0 | | | Cohort 3 arises |
| 55 | 79 | 23 | 2 | | Thin cohorts **1** & 2 | |
| 58 | 82 | 26 | 5 | | | FCIN45 full |
| 62 | 86 | 30 | 9 | | **Fell 20 % cohort 1**, thin cohorts **1** & 2 | |
| 65 | 89 | 33 | 12 | | | Respace cohort 3 |
| 68 | 92 | 36 | 15 | | | FCIN45 full |
| 69 | 93 | 37 | 16 | | Thin cohorts **1** & 2 | |
| 74 | 98 | 42 | 21 | 0 | | Cohort 4 arises |
| 76 | 100 | 44 | 23 | 2 | Thin cohorts **1**, 2 & 3 | |
| 78 | 102 | 46 | 25 | 4 | | FCIN45 full |
| 83 | 107 | 51 | 30 | 9 | **Fell cohort 1**, thin cohorts 2 & 3 | |
| 86 | | 54 | 33 | 12 | | Respace cohort 4 |
| 88 | | 56 | 35 | 14 | | FCIN45 full |
| 90 | | 58 | 37 | 16 | Thin cohorts 2 & 3 | |
| 95 | 0 | 63 | 42 | 21 | | Cohort 5 arises |
| 97 | 2 | 65 | 44 | 23 | Thin cohorts 2, 3 & 4 | |
| 98 | 3 | 66 | 45 | 24 | | FCIN45 full |

a Harvesting operations in bold attract a productivity/cost penalty.

## 2.2 Growth and yield data

Previous attempts to model continuous cover forestry scenarios in Britain (e.g. Price and Price, 2006) have been limited in some respects by their reliance on the relatively inflexible growth and yield models available in this country (Edwards and Christie, 1981). These are in tabular form, showing for various combinations of species, yield class and initial spacing the post-thinning stand characteristics and harvested timber yield for thinnings of a specified type repeated on a five year cycle. There is no scope for modelling different thinning cycles or intensities, or changes in thinning type. A major step forward in modelling silvicultural scenarios more flexibly has been the development by Forest Research of the M1 growth and yield model (currently only available for use within Forest Research). It combines features of the M1 and M2 model types in the classification of Matthews and Methley (1998). Like the tabular models of Edwards and Christie (1981), M1 is a stand level model for even-aged single species crops and cannot readily be used to predict the growth of uneven-aged stands with intimate mixtures of tree ages and species. Crucially for the current work, however, it does allow the user a great deal of flexibility in specifying growth rate (as yield class), initial spacing, and the timing, type and intensity of thinning operations.

Thinnings for the four scenarios were specified in M1 as per Tables 1 and 5. Model output is summarised in Tables 7-11, which show stand characteristics at 15 years, the earliest available from the model, and harvesting yields and post-harvesting stand characteristics for every year in which interventions are made. The M1 model also produces growing stock data for all intermediate years, but these are omitted for brevity. The first thinnings in scenarios SS1-3 and the first canopy layer of SS4 (Tables 7-10) are identical line thinnings, and it is only after this point that management diverges. As noted previously, clearfelling in scenario SS1 occurs at the age of maximum mean annual increment (Table 7). The maximum of 13.7 $m^3$ per ha per year approximates the yield class of 14. Thinnings in scenario SS2 and SS3 are identical up to stand age 58, after which the stand is felled in SS2 (Table 8) but undergoes a further thinning before felling in SS3 (Table 9).

Tables 10 and 11 show data for the various canopy layers in scenario SS4 without any adjustment of the M1 output, i.e. the per hectare values assume that each canopy layer occupies the entire area. Tables 12 and 13 show the same data adjusted for the area occupancy of each layer. In the initial stand (Table 12), this is reflected in additional harvested volume from the 20 % fellings at ages 65 and 86 which reduce the growing stock to 80 % and then 60 % of that shown in Table 10. In the second and subsequent canopy layers (Table 13), the growing stock and harvesting yields are reduced uniformly to 40 % of those in Table 11. Using the figures in Tables 12 and 13, the growing stock and yields of all canopy layers can be summed to calculate the total per hectare for the stand. Figures 1 and 2 show the development of the total basal area and standing volume of the stand over the first 100 years of all four scenarios.

**Table 7** M1 model output for one rotation in scenario SS1.

| Age | Thinning / felling yields (per ha) | | | | | Stand after thinning and mortality (per ha) | | | | | MAI [a] ($m^3$/ha/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. of stems | Basal area ($m^2$) | Mean dbh (cm) | Mean volume ($m^3$) | Total volume ($m^3$) | No. of stems | Basal area ($m^2$) | Mean dbh (cm) | Mean volume ($m^3$) | Total volume ($m^3$) | |
| 15 | - | - | - | - | - | 2311.0 | 15.3 | 9.2 | 0.01 | 29.3 | 2.0 |
| 23 | 385.2 | 5.9 | 13.9 | 0.06 | 23.2 | 1925.8 | 29.3 | 13.9 | 0.06 | 115.9 | 6.0 |
| 30 | 780.3 | 13.1 | 14.6 | 0.09 | 68.6 | 1145.6 | 30.7 | 18.5 | 0.16 | 181.1 | 9.1 |
| 37 | 343.4 | 9.6 | 18.8 | 0.20 | 68.6 | 802.2 | 34.0 | 23.2 | 0.32 | 260.1 | 11.4 |
| 44 | 192.1 | 7.8 | 22.7 | 0.36 | 68.6 | 610.1 | 36.4 | 27.6 | 0.55 | 334.6 | 12.8 |
| 51 | 111.2 | 6.0 | 26.2 | 0.54 | 60.5 | 498.9 | 38.3 | 31.3 | 0.80 | 399.9 | 13.5 |
| 58 | 498.9 | 44.7 | 33.8 | 1.01 | 506.1 | - | - | - | - | - | 13.7 |

a MAI = Mean Annual Increment (Edwards and Christie, 1981; Rollinson, 1985).

**Table 8** M1 model output for one rotation in scenario SS2.

| Age | Thinning / felling yields (per ha) | | | | | Stand after thinning and mortality (per ha) | | | | | MAI [a] ($m^3$ / ha / yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. of stems | Basal area ($m^2$) | Mean dbh (cm) | Mean volume ($m^3$) | Total volume ($m^3$) | No. of stems | Basal area ($m^2$) | Mean dbh (cm) | Mean volume ($m^3$) | Total volume ($m^3$) | |
| 15 | - | - | - | - | - | 2311.0 | 15.3 | 9.2 | 0.01 | 29.3 | 2.0 |
| 23 | 385.2 | 5.9 | 13.9 | 0.06 | 23.2 | 1925.8 | 29.3 | 13.9 | 0.06 | 115.9 | 6.0 |
| 30 | 825.1 | 14.4 | 14.9 | 0.10 | 82.3 | 1100.7 | 29.4 | 18.4 | 0.15 | 167.4 | 9.1 |
| 37 | 404.8 | 11.0 | 18.6 | 0.20 | 82.3 | 695.9 | 31.2 | 23.9 | 0.33 | 232.6 | 11.4 |
| 44 | 239.3 | 10.6 | 23.7 | 0.40 | 96.0 | 456.6 | 30.8 | 29.3 | 0.61 | 279.6 | 12.8 |
| 51 | 145.2 | 9.4 | 28.8 | 0.67 | 96.8 | 311.4 | 29.0 | 34.4 | 0.98 | 304.6 | 13.4 |
| 58 | 94.9 | 8.4 | 33.5 | 1.00 | 94.8 | 216.4 | 26.2 | 39.3 | 1.40 | 302.1 | 13.4 |
| 65 | 216.4 | 29.8 | 41.9 | 1.68 | 364.3 | - | - | - | - | - | 12.9 |

a MAI = Mean Annual Increment (Edwards and Christie, 1981; Rollinson, 1985).

**Table 9** M1 model output for one rotation in scenario SS3.

| Age | Thinning / felling yields (per ha) | | | | | Stand after thinning and mortality (per ha) | | | | | MAI [a] (m³ / ha / yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. of stems | Basal area (m²) | Mean dbh (cm) | Mean volume (m³) | Total volume (m³) | No. of stems | Basal area (m²) | Mean dbh (cm) | Mean volume (m³) | Total volume (m³) | |
| 15 | - | - | - | - | - | 2311.0 | 15.3 | 9.2 | 0.01 | 29.3 | 2.0 |
| 23 | 385.2 | 5.9 | 13.9 | 0.06 | 23.2 | 1925.8 | 29.3 | 13.9 | 0.06 | 115.9 | 6.0 |
| 30 | 825.1 | 14.4 | 14.9 | 0.10 | 82.3 | 1100.7 | 29.4 | 18.4 | 0.15 | 167.4 | 9.1 |
| 37 | 404.8 | 11.0 | 18.6 | 0.20 | 82.3 | 695.9 | 31.2 | 23.9 | 0.33 | 232.6 | 11.4 |
| 44 | 239.3 | 10.6 | 23.7 | 0.40 | 96.0 | 456.6 | 30.8 | 29.3 | 0.61 | 279.6 | 12.8 |
| 51 | 145.2 | 9.4 | 28.8 | 0.67 | 96.8 | 311.4 | 29.0 | 34.4 | 0.98 | 304.6 | 13.4 |
| 58 | 94.9 | 8.4 | 33.5 | 1.00 | 94.8 | 216.4 | 26.2 | 39.3 | 1.40 | 302.1 | 13.4 |
| 65 | 59.3 | 6.7 | 37.8 | 1.36 | 80.6 | 157.1 | 23.1 | 43.3 | 1.80 | 283.6 | 12.9 |
| 72 | 157.1 | 25.6 | 45.6 | 2.09 | 328.3 | - | - | - | - | - | 12.3 |

a MAI = Mean Annual Increment (Edwards and Christie, 1981; Rollinson, 1985).

**Table 10** M1 model output for the first cohort in scenario SS4.

| Age | Thinning / felling yields (per ha) | | | | | Stand after thinning and mortality (per ha) | | | | | MAI [a] (m³ / ha / yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. of stems | Basal area (m²) | Mean dbh (cm) | Mean volume (m³) | Total volume (m³) | No. of stems | Basal area (m²) | Mean dbh (cm) | Mean volume (m³) | Total volume (m³) | |
| 15 | - | - | - | - | - | 2311.0 | 15.3 | 9.2 | 0.01 | 29.3 | 2.0 |
| 23 | 385.2 | 5.9 | 13.9 | 0.06 | 23.2 | 1925.8 | 29.3 | 13.9 | 0.06 | 115.9 | 6.0 |
| 30 | 949.2 | 16.9 | 15.0 | 0.10 | 96.0 | 976.6 | 27.0 | 18.8 | 0.16 | 153.7 | 9.1 |
| 37 | 428.1 | 12.7 | 19.4 | 0.22 | 96.0 | 548.6 | 27.1 | 25.1 | 0.37 | 205.0 | 11.4 |
| 44 | 171.5 | 8.9 | 25.7 | 0.48 | 82.3 | 377.0 | 28.0 | 30.7 | 0.69 | 259.7 | 12.7 |
| 51 | 95.7 | 6.9 | 30.4 | 0.76 | 72.6 | 281.3 | 28.2 | 35.8 | 1.07 | 302.2 | 13.2 |
| 58 | 52.3 | 4.9 | 34.7 | 1.09 | 56.9 | 229.1 | 28.8 | 40.0 | 1.47 | 336.8 | 13.2 |
| 65 | 28.8 | 3.3 | 38.1 | 1.40 | 40.3 | 200.2 | 29.6 | 43.4 | 1.83 | 365.9 | 12.8 |
| 72 | 20.4 | 2.7 | 41.0 | 1.69 | 34.4 | 179.8 | 30.1 | 46.2 | 2.16 | 389.1 | 12.4 |
| 79 | 13.9 | 2.2 | 45.3 | 2.16 | 30.0 | 165.9 | 30.3 | 48.3 | 2.45 | 406.7 | 11.9 |
| 86 | 11.1 | 1.9 | 47.1 | 2.40 | 26.6 | 154.8 | 30.4 | 50.0 | 2.70 | 418.3 | 11.4 |
| 93 | 8.8 | 1.6 | 48.6 | 2.61 | 22.9 | 146.0 | 30.3 | 51.4 | 2.92 | 426.5 | 10.8 |
| 100 | 7.3 | 1.4 | 49.9 | 2.80 | 20.3 | 138.8 | 30.1 | 52.5 | 3.11 | 431.8 | 10.3 |
| 107 | 138.8 | 31.0 | 53.4 | 3.26 | 452.7 | - | - | - | - | - | 9.9 |

a MAI = Mean Annual Increment (Edwards and Christie, 1981; Rollinson, 1985).

**Table 11** M1 model output for the second and subsequent cohorts in scenario SS4.

| Age | Thinning / felling yields (per ha) | | | | | Stand after thinning and mortality (per ha) | | | | | MAI [a] (m³ / ha / yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. of stems | Basal area ($m^2$) | Mean dbh (cm) | Mean volume ($m^3$) | Total volume ($m^3$) | No. of stems | Basal area ($m^2$) | Mean dbh (cm) | Mean volume ($m^3$) | Total volume ($m^3$) | |
| 15 | - | - | - | - | - | 2311.0 | 15.3 | 9.2 | 0.01 | 29.3 | 2.0 |
| 23 | 1020.1 | 11.5 | 12.0 | 0.04 | 41.2 | 1290.9 | 23.7 | 15.3 | 0.08 | 97.9 | 6.0 |
| 30 | 626.0 | 13.6 | 16.6 | 0.13 | 82.3 | 664.9 | 24.6 | 21.7 | 0.22 | 149.4 | 9.1 |
| 37 | 245.5 | 10.4 | 23.2 | 0.34 | 82.3 | 419.4 | 27.0 | 28.6 | 0.51 | 213.9 | 11.3 |
| 44 | 121.4 | 8.6 | 30.0 | 0.68 | 82.3 | 298.0 | 28.4 | 34.8 | 0.91 | 271.5 | 12.7 |
| 51 | 71.0 | 6.7 | 34.8 | 1.02 | 72.6 | 227.0 | 29.1 | 40.4 | 1.40 | 318.4 | 13.3 |
| 58 | 39.2 | 4.8 | 39.6 | 1.45 | 56.9 | 187.8 | 30.1 | 45.2 | 1.91 | 358.0 | 13.4 |
| 65 | 21.8 | 3.2 | 43.5 | 1.85 | 40.3 | 166.0 | 31.1 | 48.9 | 2.36 | 391.5 | 13.1 |
| 72 | 15.5 | 2.6 | 46.6 | 2.22 | 34.4 | 150.5 | 31.9 | 52.0 | 2.78 | 418.7 | 12.7 |
| 79 | 150.5 | 34.6 | 54.1 | 3.12 | 470.0 | - | - | - | - | - | 12.2 |

a MAI = Mean Annual Increment (Edwards and Christie, 1981; Rollinson, 1985).

**Table 12** M1 model output for the first cohort in scenario SS4 adjusted for partial fellings at ages 65 and 86.

| Age | Thinning/felling yields (per ha) | | | | | Stand after thinning and mortality (per ha) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | No. of stems | Basal area ($m^2$) | Mean dbh (cm) | Mean volume ($m^3$) | Total volume ($m^3$) | No. of stems | Basal area ($m^2$) | Mean dbh (cm) | Mean volume ($m^3$) | Total volume ($m^3$) |
| 15 | - | - | - | - | - | 2311.0 | 15.3 | 9.2 | 0.01 | 29.3 |
| 23 | 385.2 | 5.9 | 13.9 | 0.06 | 23.2 | 1925.8 | 29.3 | 13.9 | 0.06 | 115.9 |
| 30 | 949.2 | 16.9 | 15.0 | 0.10 | 96.0 | 976.6 | 27.0 | 18.8 | 0.16 | 153.7 |
| 37 | 428.1 | 12.7 | 19.4 | 0.22 | 96.0 | 548.6 | 27.1 | 25.1 | 0.37 | 205.0 |
| 44 | 171.5 | 8.9 | 25.7 | 0.48 | 82.3 | 377.0 | 28.0 | 30.7 | 0.69 | 259.7 |
| 51 | 95.7 | 6.9 | 30.4 | 0.76 | 72.6 | 281.3 | 28.2 | 35.8 | 1.07 | 302.2 |
| 58 | 52.3 | 4.9 | 34.7 | 1.09 | 56.9 | 229.1 | 28.8 | 40.0 | 1.47 | 336.8 |
| 65 | 68.9 | 9.2 | 41.3 | 1.65 | 113.5 | 160.2 | 23.6 | 43.4 | 1.83 | 292.7 |
| 72 | 16.3 | 2.2 | 41.0 | 1.69 | 27.5 | 143.8 | 24.1 | 46.2 | 2.16 | 311.3 |
| 79 | 11.1 | 1.8 | 45.3 | 2.16 | 24.0 | 132.7 | 24.3 | 48.3 | 2.45 | 325.4 |
| 86 | 39.8 | 7.6 | 49.3 | 2.63 | 104.9 | 92.9 | 18.2 | 50.0 | 2.70 | 251.0 |
| 93 | 5.3 | 1.0 | 48.6 | 2.61 | 13.8 | 87.6 | 18.2 | 51.4 | 2.92 | 255.9 |
| 100 | 4.4 | 0.8 | 49.9 | 2.80 | 12.2 | 83.3 | 18.0 | 52.5 | 3.11 | 259.1 |
| 107 | 83.3 | 18.6 | 53.4 | 3.26 | 271.6 | - | - | - | - | - |

Post-harvesting number of stems, basal area and total volume are multiplied by 0.8 at ages 65-85 and by 0.6 at ages 86-106. Thinning/clearfell yield number of stems, basal area and total volume are multiplied by 0.8 at ages 72-86 and by 0.6 at ages 97-107. Additional yield from 20 % fellings calculated by multiplying post-harvest number of stems, basal area and total volume by 0.2 at ages 65 and 86. Number of stems, basal area and total volume summed with those from thinning yields, mean dbh calculated from number of stems and basal area, and mean volume calculated from number of stems and total volume.

**Table 13** M1 model output for the second and subsequent cohorts in scenario SS4 adjusted for area occupied.

| Age | Thinning/felling yields (per ha) | | | | | Stand after thinning and mortality (per ha) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | No. of stems | Basal area ($m^2$) | Mean dbh (cm) | Mean volume ($m^3$) | Total volume ($m^3$) | No. of stems | Basal area ($m^2$) | Mean dbh (cm) | Mean volume ($m^3$) | Total volume ($m^3$) |
| 15 | - | - | - | - | - | 924.4 | 6.1 | 9.2 | 0.01 | 11.7 |
| 23 | 408.0 | 4.6 | 12.0 | 0.04 | 16.5 | 516.4 | 9.5 | 15.3 | 0.08 | 39.2 |
| 30 | 250.4 | 5.4 | 16.6 | 0.13 | 32.9 | 266.0 | 9.8 | 21.7 | 0.22 | 59.8 |
| 37 | 98.2 | 4.2 | 23.2 | 0.34 | 32.9 | 167.8 | 10.8 | 28.6 | 0.51 | 85.5 |
| 44 | 48.6 | 3.4 | 30.0 | 0.68 | 32.9 | 119.2 | 11.3 | 34.8 | 0.91 | 108.6 |
| 51 | 28.4 | 2.7 | 34.8 | 1.02 | 29.0 | 90.8 | 11.6 | 40.4 | 1.40 | 127.4 |
| 58 | 15.7 | 1.9 | 39.6 | 1.45 | 22.8 | 75.1 | 12.0 | 45.2 | 1.91 | 143.2 |
| 65 | 8.7 | 1.3 | 43.5 | 1.85 | 16.1 | 66.4 | 12.5 | 48.9 | 2.36 | 156.6 |
| 72 | 6.2 | 1.1 | 46.6 | 2.22 | 13.8 | 60.2 | 12.8 | 52.0 | 2.78 | 167.5 |
| 79 | 60.2 | 13.8 | 54.1 | 3.12 | 188.0 | - | - | - | - | - |

Number of stems, basal area and total volume of all thinning/clearfell yields and post-harvest growing stock multiplied by 0.4.

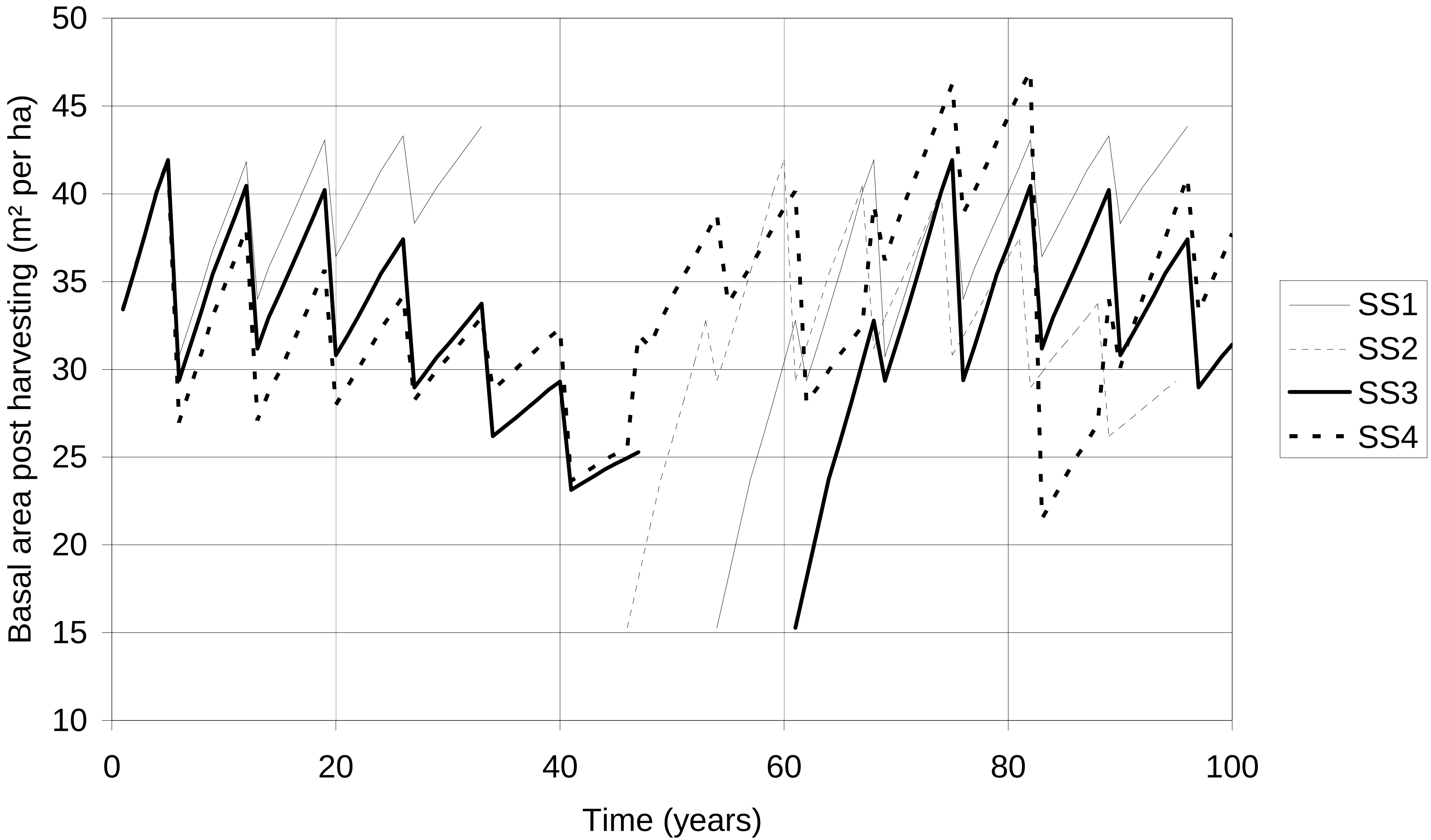


**Figure 1** Stand basal area development over the first 100 years of all four scenarios.

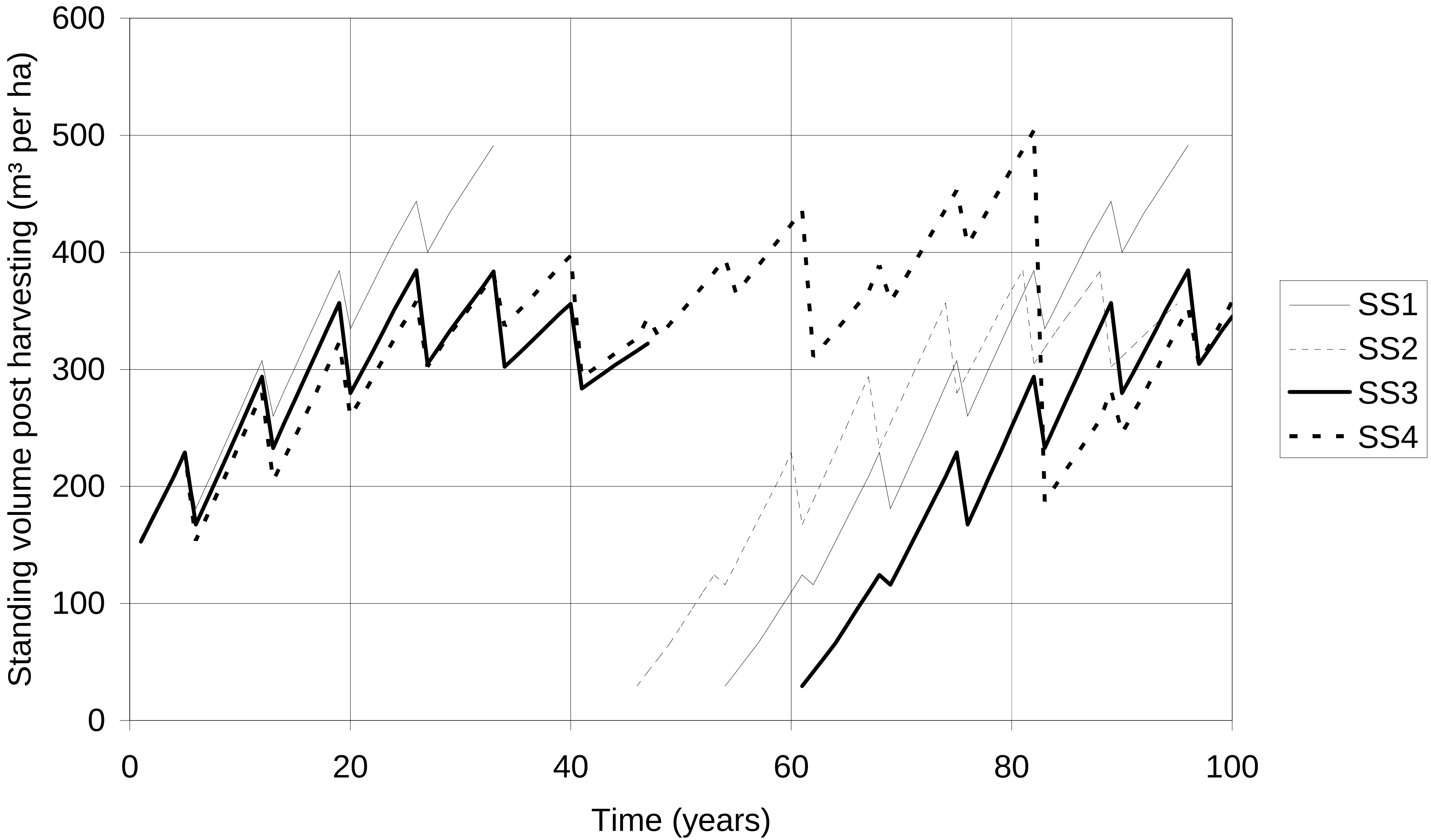


**Figure 2** Stand standing volume development over the first 100 years of all four scenarios.

## 2.3 Cost data

Costs in this analysis are broken down into four main groups; those associated with monitoring, establishment and harvesting, and those costs not attached explicitly to specific operations but treated as annual overheads. These groupings are used in the analysis spreadsheet, and the assumptions and sources which determine the cost figures used are discussed by group in the following sections.

Wherever possible in calculating costs, preference has been given to data arising from formal work study, largely from Forest Research's Technical Development Branch but also from a study of harvester and forwarder productivity at Coed Trallwm in mid Wales (Price, 2007). Where such data are not available, the standard costs agreed by the English Woodland Grant Scheme (EWGS) working group have been used (Forestry Commission England, 2010), and where standard costs are not available this study relies on anecdotal evidence from forest managers, referenced in this document as personal communications (pers. comm.). It should be noted that even work study data must be treated with caution as they are often based on only a single case study and may not be truly representative.

### 2.3.1 Monitoring and tariffing costs

Three main types of monitoring and tariffing costs are included in the scenarios; abbreviated tariffing of stands of simple structure (Matthews and Mackie, 2006), monitoring of natural regeneration in simple stands and of both regeneration and the overstorey in complex stands as per *Forestry Commission Information Note 45* (FCIN45, Kerr *et al*., 2002), and monitoring of planted crops, including underplanting, as per FC *Operational Guidance Booklet 4* (OGB4, Forestry Commission, 2010). Monitoring operations are named below as in the scenario summary tables and the analysis spreadsheet.

#### 2.3.1.1 B6 abbreviated tariff

In this study it is assumed that the only formal assessment made of the growing stock in more or less uniform stands is a B6 abbreviated tariff (Matthews and Mackie, 2006, p. 93, Table 4.4) carried out shortly before final felling. Thinning control prior to the tariff is assumed to be based on simple basal area sweeps by the forest manager. The cost of a B6 tariff has been estimated as £0.50 per $m^3$ of standing timber (Gareth Hopkins, pers. comm.); given that tariffing is only carried out in scenarios with relatively uniform overstoreys, this cost is assumed not to vary between scenarios.

#### 2.3.1.2 FCIN45 abbreviated and full

Guidance for monitoring in stands undergoing transformation to continuous cover forestry has been presented by Kerr *et al*. (2002), and the system can be applied flexibly (Forestry Commission, 2008). The only data available on the cost of applying this method come from a study in the North York Moors (Kerr *et al*., 2005). This work showed that the cost of monitoring depended on the size of the stand and therefore the intensity of sampling, and on what exactly was monitored, whether all seedlings, saplings and trees in the stand or just the regeneration. Cost also depended on the frequency of assessments, but in the present study the exact timing of assessments is specified in each scenario. For the purposes of quantifying costs in each scenario, therefore, assumptions must be made concerning the intensity and nature of monitoring.

Costs per hectare for each scenario are calculated on the assumption that each stand is 10 ha in area and would contain 27 sample plots, or 2.7 per ha (Kerr *et al*., 2002, 2005). Two levels of FCIN45 monitoring are recognised; full monitoring, represented by the cost of £16 per plot (Kerr *et al*., 2005), and abbreviated monitoring, either of regeneration only or of a smaller number of plots, both represented by the equivalent cost of £11.20 per plot (Kerr *et al*., 2005). Full monitoring is assumed to be necessary in stands managed to develop and maintain a complex structure (scenario SS4) whereas abbreviated monitoring is assumed to be adequate to monitor the success (or lack thereof) of regeneration in simple stands (scenarios SS2 and SS3). The costs presented by Kerr *et al*. (2005) included additional costs of data entry and interpretation of approximately 10 %. The cost of a single full monitoring assessment is taken to be £47.50 per ha (2.7 plots × £16 per plot = £43.20 fieldwork costs plus approx. £4.30 data entry and interpretation costs). The cost of an abbreviated assessment is taken to be £33.25 per ha (2.7 plots × £11.20 per plot = £30.24 fieldwork costs plus approx. £3.01 data entry and interpretation costs).

#### 2.3.1.3 OGB4 initial and final

Forestry Commission practice, as outlined in *Operational Guidance Booklet 4*, requires that stocking density be assessed initially one growing season after planting and finally four to five growing seasons after planting or when plants reach 1.5 m in height, whichever comes soonest (Forestry Commission, 2010, p. 15). For the purposes of this study the final assessment is assumed to take place four growing seasons after planting. The cost per plot is estimated at £6 to £8 (Steve Mather, pers. comm.). Assuming a stand area of 10 ha, OGB4 requires 23 plots or 2.3 per ha (Forestry Commission, 2010, p. 18). At an average cost of £7 per plot, the cost per hectare per assessment is therefore £16.10 (2.3 × £7).

### 2.3.2 Establishment costs

The assumptions and costs associated with the establishment of planted crops, attempts to encourage natural regeneration and the early tending of all young crops are described in the following sections, which are named as per the operations in the scenario summary tables and the analysis spreadsheet. It is assumed that there is no requirement for the creation or maintenance of drains. It has been noted previously that the five year fallow period in scenario SS1 is assumed to render any direct control of *Hylobius abietis* unnecessary. The results of a study in Wales have suggested that *Hylobius* damage to young Sitka spruce is negligible in stands under continuous cover management relative to that on conventional restock sites (Mason *et al*., 2004), and so it is assumed that no control costs are incurred in scenarios SS2-4.

### 2.3.2.1 Cultivate, plant

Conventional restocking costs are taken to be made up of cultivation, plant and planting costs. The cultivation cost of £320 per ha is based on the cost of hinge mounding on a mechanically harvested restock site by a Daewoo DX 180LC tracked excavator (Saunders, 2009). Plant and planting costs are taken from EWGS standard costs (Forestry Commission England, 2010), conifer plants costing £200 per 1,000 and planting costing £240 per 1,000 plants. On the assumption that planting is at a density of 2,500 plants per hectare, the cost per hectare of plants is £500 (2.5 × £200), the cost of planting is £600 (2.5 × £240) and the total cost including mounding is £1,420 per ha.

### 2.3.2.2 Cultivate, underplant

Very little data could be found on the costs of cultivation associated with underplanting. Recent experience in the Glentress CCF trial area has shown that mounding at approximately 1.5 m spacing under mature crops cost approximately £1,000 per ha, compared with a local cost of £450 per ha for conventional restock sites (Stewart Mackie, pers. comm.). In the absence of any other information, it is assumed in this study that cultivation for underplanting costs twice as much per hectare as has been assumed for mounding prior to conventional restocking, i.e. £640 per ha. As with conventional restocking, plants are assumed to cost £200 per 1,000 (Forestry Commission England, 2010). A comparison at Coed Trallwm in mid Wales showed that the time and therefore cost per plant of manual underplanting was approximately 126 % of manual planting on a clearfell (Martin Price, pers. comm.). The cost of planting is therefore taken to be 125 % of the EWGS cost, i.e. £300 per 1,000 plants. The total cost per hectare is therefore £1,890 (£640 + 2.5 × £200 + 2.5 × £300).

Although parts of the stand would not be underplanted, particularly racks still in use and felling zones, it is assumed that the density of plants in underplanted areas is increased so that the overall average stocking remains 2,500 plants per ha. Losses are assumed to be made good by low levels of natural regeneration in unplanted areas.

### 2.3.2.3 Beat up

The calculation of beat up costs assumes 5 % failure of the planted crop, i.e. the loss of 125 of the 2,500 plants per hectare. The cost of plants is therefore £25 per ha (0.125 × £200). Planting costs per plant are assumed to be 500 % of the standard EWGS cost to account for greater travel time between planting positions and the need to inspect plants, i.e. £1,200 per 1,000 plants. With 125 plants replaced the cost per hectare of planting is £150 (0.125 × £1,200) and the total cost including plants is £175 per ha.

### 2.3.2.4 Scarify

Mechanical disturbance of ground vegetation and litter is assumed to be employed to improve seed bed conditions when natural regeneration is inadequate. Information on the cost of such operations is limited. Excavator scrapes under an overstorey of larch in the Wykeham CCF trial area were found to cost £270 per ha (Graham Jackson, pers.

comm.). Work study by Technical Development suggests that in good conditions scarification by a Bracke T26a disc scarifier costs £300 per ha (Murgatroyd, 2010); assuming less than ideal conditions for manoeuvring but a smaller area per hectare to scarify (excluding racks and space occupied by overstorey trees), this cost could perhaps be applied directly to the required circumstances. In the absence of any more robust data, a cost of £300 per ha for scarification to encourage natural regeneration is assumed.

#### 2.3.2.5 Overall herbicide

The cost of manual overall spraying has been estimated, on the basis of the experience of Forestry Commission Scotland staff, at £200 per ha (Duncan Ireland, pers. comm.).

#### 2.3.2.6 Spot herbicide

Spot spraying costs are based on the EWGS standard cost of £0.08 per spot (Forestry Commission England, 2010), giving a cost per hectare, with 2,500 plants, of £200 (2,500 × £0.08).

#### 2.3.2.7 Clean

Experience among FC Scotland staff has suggested that cleaning costs can vary from £250 to £500 per ha (Duncan Ireland, pers. comm.). A value in the middle of this range, £375 per ha, is used in this study on the assumption that there would be moderate growth of undesirable saplings on a yield class 14 Sitka spruce site.

#### 2.3.2.8 Respace regeneration

The cost of motor manual respacing of natural regeneration to 2 m spacing is taken to be £700 per ha on the basis of work study in Wales (Ireland, in press), rather than £1000 per ha as assumed in EWGS (Forestry Commission England, 2010). No interventions in natural regeneration are assumed to be necessary prior to this selective respacing, on the basis that machine access during thinning operations will keep racks sufficiently open for stand inspection by crushing any young regeneration into the brash mat. In the complex transformation scenario, where each new cohort is assumed to occupy 40 % of each hectare of the stand, the respacing cost per hectare is reduced by 50 % to account for the smaller number of stems to respace but greater travel times between areas of regeneration.

### 2.3.3 Harvesting costs

Harvesting costs are based on the assumption that operations will, as far as possible, be carried out by harvester and forwarder. They are calculated on the basis of machine productivity varying according to the mean tree size felled or handled and, in the case of forwarding, the total volume extracted per hectare. It is assumed that operations involving the felling of trees amongst far smaller trees, which must be protected from damage or which limit visibility or operating space, will attract a productivity penalty and therefore a cost penalty. Such penalties apply in operations late in the rotation of a stand with a simple structure or in the felling of trees greater than 45 cm dbh in a stand with a complex structure.

Some studies have used separate harvesting costs for thinning and clearfelling (e.g. Price and Price, 2006; Tahvonen *et al*., 2010). It can be argued, however, that these operations represent different points on a continuum of intensity of volume removal (Martin Price, pers. comm.). It is for this reason that, rather than costing thinning and clearfelling differently, machine productivities have been evaluated not only in terms of mean tree size but also in terms of the total volume harvested per hectare. An alternative is to consider the proportion of the crop removed (e.g. Kluender *et al*., 1998), but this suggestion has been rejected because harvesting the same proportion of different crops may involve very different total volume removals per hectare and therefore very different working intensities per unit area.

#### 2.3.3.1 Harvester productivity

Work study data used to model harvester productivity are shown in Table 14. All of the data are from studies in Sitka spruce stands, and despite the fact that the studies cover both thinnings and clearfells and a wide range of tree sizes the machines used are all relatively similar (Timberjack 1270C, John Deere 1270D, and Silvatec 82665TH Sleipner). Two further studies on harvester productivity in Sitka spruce (Spencer, 1998b; Saunders, 2007) were consulted but not included as the derivation of productivity data was unclear. A similar study in pine (Price, 2009) was also not included to avoid introducing further variables.

Using data on both mean tree volume and total volume felled per hectare, the latter not available for Webster (2008), in a multiple linear regression as for forwarder productivity (see section 2.3.3.2) showed that the total volume term did not significantly improve model fit ($p$ = 0.277). Therefore the figures in Table 14 were simply used to fit a power function between mean tree size and productivity in $m^3$ per standard hour in Microsoft Excel (Figure 3). This gave an $R^2$ value of 0.97 and the following fitted equation:

$$\text{Harvester productivity } (m^3/\text{shr}) = 25.741 \times v^{0.8517} \qquad \text{(Eq. 1)}$$

where $v$ = mean tree volume harvested ($m^3$)

The power function was chosen not only because of its high explanatory power but also because it fitted closely to points at the extremes of available data, particularly for the smallest mean tree size observed. The current curve is superficially similar to those presented by Spencer (1998a) for smaller size classes. In the absence of any information on productivity with trees larger than 1.5 $m^3$, it is considered safer to assume that productivity stabilises rather than increasing indefinitely. Ultimately, trees can become too big to be felled by harvesters, and before this point they may be difficult to handle or cause excessive strain on the machine (Martin Price, pers. comm.). It is assumed that the maximum mean tree sizes achieved in this study (3.26 $m^3$, Table 10, or 54.1 cm dbh, Table 11) are largely within the realistic capacity of modern harvesters, but that harvester productivity cannot exceed the maximum observed in Table 14 (33.54 m³ per standard hour) and some motor manual assistance may be required with particularly large trees (see section 2.3.3.4).

**Table 14** Harvester productivity data.

| Operation | Mean tree volume ($m^3$) | Harvester productivity [a] | | Source |
|---|---|---|---|---|
| | | ($m^3$ per productive machine hour) | ($m^3$ per standard hour) | |
| Thin | 0.07 | - | 2.44 | Webster (2008) [b] |
| Clearfell | 0.34 | - | 12.80 | Webster and Price (2007) [c] |
| Thin | 0.50 | 20.85 | 14.72 | Price (2007) [d] |
| Thin | 0.61 | 24.33 | 17.18 | |
| Thin | 0.65 | 29.98 | 21.17 | |
| Thin | 0.85 | 32.79 | 23.16 | |
| Thin | 0.88 | 29.84 | 21.07 | |
| Thin | 0.89 | 30.42 | 21.48 | |
| Thin | 0.90 | 28.59 | 20.19 | |
| Clearfell | 1.05 | 39.68 | 28.02 | |
| Thin | 1.47 | - | 33.54 | Ireland (2008) [e] |

a Price (2007, p. 234, Table 7.1) presented productivity figures in terms of m³ per productive machine hours; these were converted to m³ per standard hour by dividing by 1.416 (Price, 2007, p. 241, Table 7.4; Martin Price, pers. comm.). Other authors gave productivity figures in m³ per standard hour. Standard hours include allowances for maintenance and rest.

b Webster (2008, p. 3, Table 3) presented productivity figures for cutting a 'standard' product assortment and an assortment which included woodfuel; the figure used in this table is that for the standard product assortment. Mean tree volume is pre-thinning (Webster, 2008, p. 2, Table 1).

c Webster and Price (2007, p. 8, Table 5) presented productivity figures for two species, lodgepole pine (*Pinus contorta* Douglas ex Loudon) and Sitka spruce, and two product assortments, fuelwood and conventional; the figure used in this table is that for Sitka spruce and the conventional assortment. Mean tree volume is taken from Table 2 (p. 5). This was a clearfell of an unthinned stand.

d The derivation of productivity figures from Price (2007, p. 234, Table 7.1) is detailed above in (a). Mean tree volumes are taken from Table 3.5 (p. 70).

e Ireland's (2008) productivity figure is taken from Table 8 (p. 7). Mean tree volume was derived by calculating the total volume and number of stems harvested from pre- and post-thinning figures in Table 2 (p. 2). This was a thinning amongst regeneration up to 3 m in height.

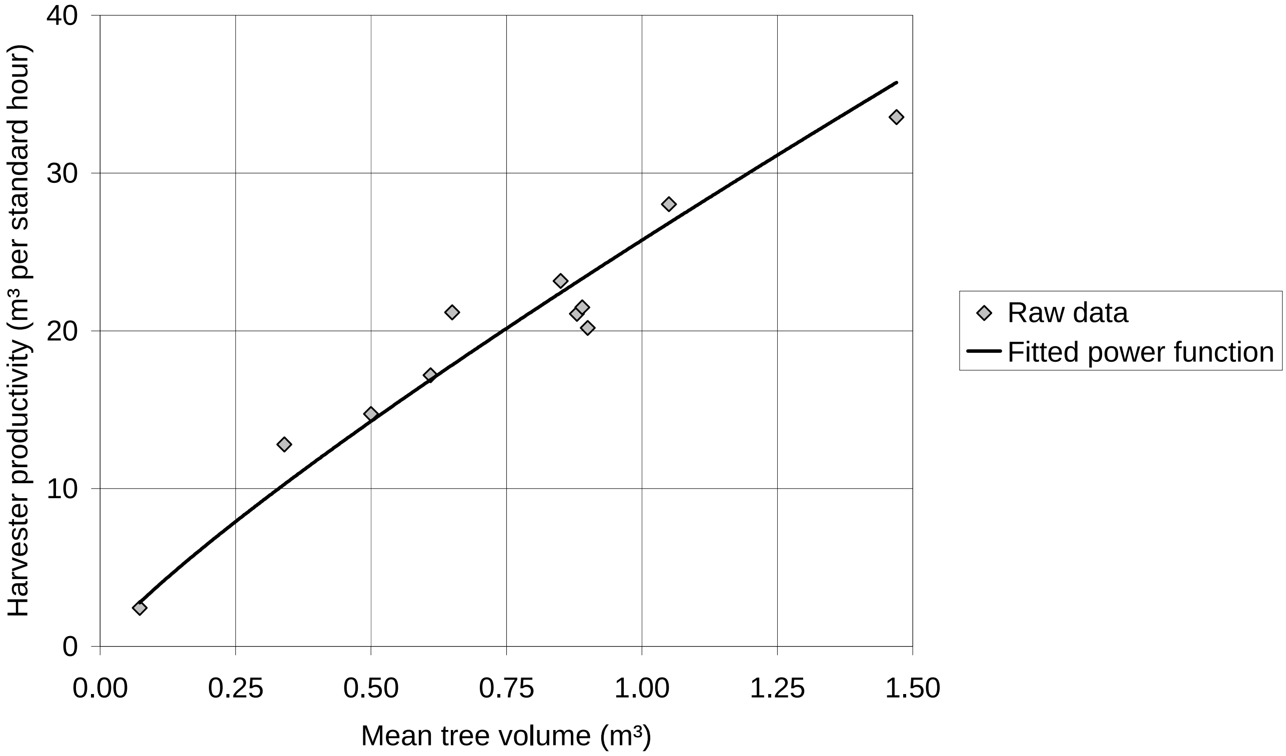


**Figure 3** Relationship between mean tree volume and harvester productivity.

#### 2.3.3.2 Forwarder productivity

Forwarder productivity is more complex than harvester productivity, being affected by factors including in-wood extraction distance, grapple capacity, bunk size, the number of products cut and whether mixed loads are carried (Shrimpton, 1988; Price, 2007). The model used in this study is a considerable simplification, based only on mean tree size, as an indication of the size of products cut, and the total volume harvested, as an indication of the concentration of produce within the forest. The raw data used are shown in Table 15. The sources are similar to those for harvester productivity, except that the study of Webster (2008) was omitted because of the lack of total volume data. This unfortunately removes the data point for the smallest mean tree size. A further study was consulted (Spencer, 1995) but not used because crop data were too imprecise. The machines used are more varied than in the harvester data, including a Rottne SNV Rapid, a Timberjack 810B and a John Deere 1110D, and whereas the productivity data of Webster and Price (2007) and Ireland (2008) are standardised for an extraction distance of 100 m, those of Price (2007) are not.

A multiple linear regression was fitted using the statistical software GenStat 11.1 (Payne *et al.*, 2008). This actually showed that the total volume term was not significant ($p$ = 0.092), but it was retained as mean volume alone was subjectively judged to give a poor fit to the data. The fitted model is as follows:

Forwarder productivity ($m^3$/shr) = 2.6492 + $v$ × 11.5027 + $V$ × 0.0076 (Eq. 2)

where $v$ = mean tree volume harvested ($m^3$)
$V$ = total volume harvested ($m^3$ per ha)

**Table 15** Forwarder productivity data.

| Operation | Mean tree volume ($m^3$) | Total volume harvested ($m^3$ per ha) | Forwarder productivity [a] | | Source |
|---|---|---|---|---|---|
| | | | ($m^3$ per productive machine hour) | ($m^3$ per standard hour) | |
| Clearfell | 0.34 | 546.0 | - | 12.91 | Webster and Price (2007) [b] |
| Thin | 0.50 | 102.2 | 12.21 | 9.07 | Price (2007) [c] |
| Thin | 0.61 | 88.0 | 14.18 | 10.53 | |
| Thin | 0.65 | 90.7 | 14.92 | 11.08 | |
| Thin | 0.85 | 100.6 | 14.78 | 10.98 | |
| Thin | 0.88 | 79.9 | 19.67 | 14.61 | |
| Thin | 0.89 | 92.1 | 16.50 | 12.26 | |
| Thin | 0.90 | 73.5 | 18.41 | 13.68 | |
| Clearfell | 1.05 | 520.3 | 20.68 | 15.36 | |
| Thin | 1.47 | 250.6 | - | 24.46 | Ireland (2008) [d] |

a Price (2007, p. 237, Table 7.3) presented productivity figures in terms of $m^3$ per productive machine hours; these were converted to $m^3$ per standard hour by dividing by 1.346 (Price, 2007, p. 241, Table 7.4; Martin Price, pers. comm.). Other authors gave productivity figures in $m^3$ per standard hour. Standard hours include allowances for maintenance and rest.

b Webster and Price (2007, p. 9, Table 7) presented productivity figures for two species, lodgepole pine and Sitka spruce, and two product assortments, fuelwood and conventional; the figure used in this table is that for Sitka spruce and the conventional assortment. Mean tree volume is taken from Table 2 (p. 5). This was a clearfell of an unthinned stand.

c The derivation of productivity figures from Price (2007, p. 237, Table 7.3) is detailed above. Mean tree volumes and total volumes are taken from Table 3.5 (p. 70).

d Ireland's (2008) productivity figure is taken from Table 10 (p. 8). Mean tree volume was derived by calculating the total volume and number of stems harvested from pre- and post-thinning figures in Table 2 (p. 2). This was a thinning amongst regeneration up to 3 m in height.

Productivity increases both with mean tree size (and therefore the average size of produce handled) and the total volume harvested, which is associated with greater concentrations of produce in the forest. As with harvester productivity, it was considered prudent to assume that productivity cannot exceed the maximum observed value (24.46 m³ per standard hour). Modelled forwarder productivity, including this constraint on maximum productivity, is illustrated in Figure 4.

It should be noted that the dependence of forwarding productivity on the total volume extracted has implications for the costing of operations in scenario SS4. Productivities, and therefore costs, have been calculated separately for each canopy layer; the total volume harvested from each hectare of the stand is naturally much higher than is indicated for each canopy layer, as once the steady state is reached three canopy layers are thinned or felled in every intervention. The summed forwarding costs for all cohorts are therefore slightly higher than if the volumes to be extracted were summed and forwarding costs calculated accordingly. In practice the difference is proportionally very small, and the artificially raised costs are used here to reflect the potentially more dispersed produce in each product category which might be expected to reduce productivity.

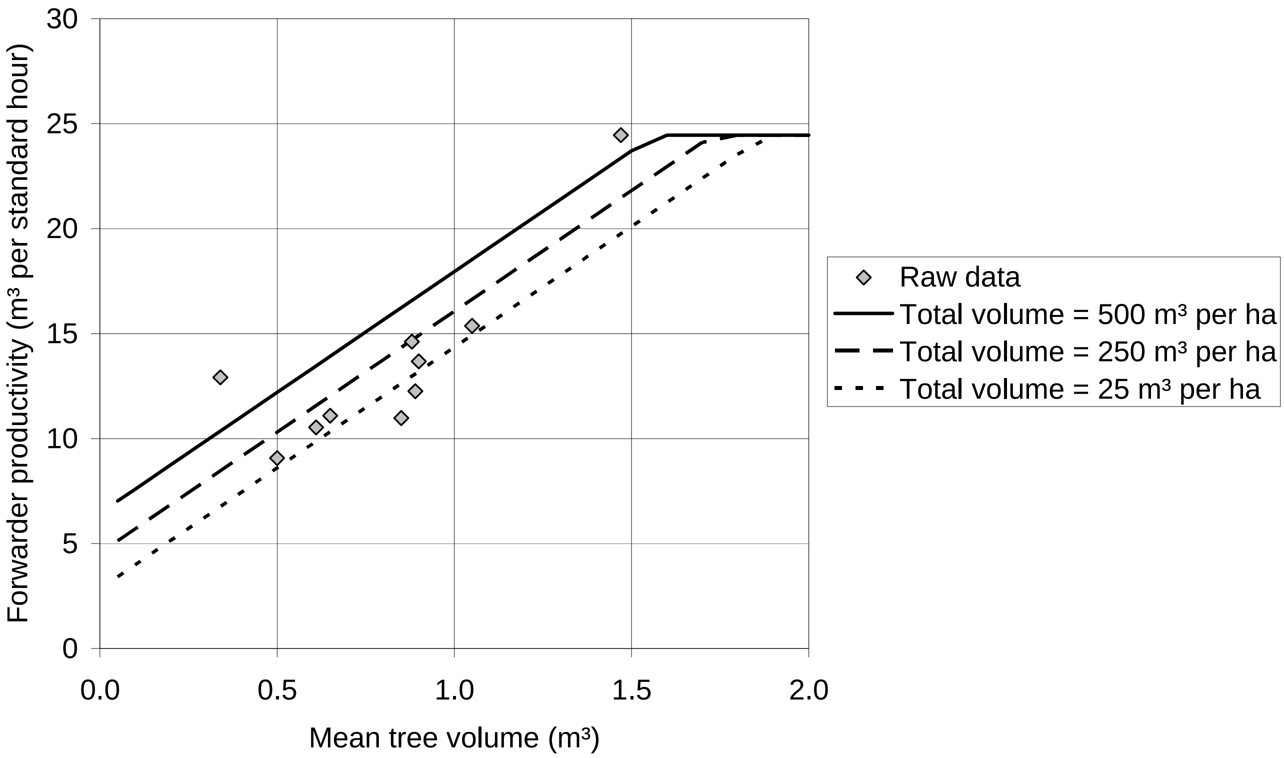


**Figure 4** Relationship between mean tree volume, total volume and forwarder productivity.

#### 2.3.3.3 Productivity modifiers

The only objective basis available for quantifying the effect of the presence of regeneration on harvesting productivity may be derived from the work of Ireland (2008, 2009), whose case studies measured harvester and forwarder productivity in operations involving machines of the same model felling and extracting trees of similar mean volume (1.47 and 1.60 $m^3$, calculated from pre- and post-thinning stand data) but with regeneration of either ≤ 3 m or ≤ 5 m height. If the latter is taken to represent the more difficult conditions expected late in transformation to a simple structure, as was in fact the case in Ireland (2009), or in complex stands, the relative harvester productivity (30.15 $m^3$ per standard hour; Ireland, 2009) was 90 % of that in more favourable conditions with smaller regeneration (33.54 $m^3$ per standard hour; Ireland, 2008). Similarly, forwarder productivity (18.63 $m^3$ per standard hour per 100 m; Ireland, 2009) was 76 % of that in more favourable conditions (24.46 $m^3$ per standard hour per 100 m; Ireland, 2008). The reduced harvester productivity may therefore be calculated by multiplying the productivity derived from equation (1) by 0.90, or the increased cost may be calculated directly by dividing the normal cost by 0.90. Reduced forwarder productivities may be calculated by multiplying the results of equation (2) by 0.76, or the cost may be divided by 0.76.

An alternative approach to productivity modifiers is to attach additional costs to operations under certain circumstances (Price and Price, 2006).

#### 2.3.3.4 Motor manual requirements and productivity

The only information found on motor manual felling and processing requirements in CCF was that presented by Ireland (2009). This related to the final felling of the overstorey in a uniform shelterwood in Sitka spruce, in which some debuttressing, felling, snedding and cross-cutting was beyond the capacity of the harvester used (a John Deere 1270D) and had to be carried out motor-manually. The volume harvested per hectare was calculated as 267.9 $m^3$ on the basis of pre- and post-thinning stem numbers and mean tree volumes (Ireland, 2009, Table 2, p. 3), and the total volume harvested was calculated by multiplying by the stand area of 1.22 ha (Ireland, 2009, Table 1, p. 3) to give 326.8 $m^3$. The total volume in the stand requiring motor manual felling and partial processing was 48.3 $m^3$, comprising 30 trees averaging 1.61 $m^3$ (Ireland, 2009, p. 15). The ratio of 48.3 $m^3$ to 326.8 $m^3$ shows that 15 % of the volume harvested required motor manual input.

In terms of gauging when this motor manual input is required, Ireland (2009) noted that the mean size of trees felled manually was 1.61 $m^3$ and also that trees larger than 55 cm dbh were involved (larger than the maximum dbh of 54.1 cm in this study). Given that the shelterwood thinning recorded by Ireland (2008) did not require any motor manual felling and that the mean tree size harvested (calculated from pre- and post-thinning figures in Table 2, p. 2) was 1.47 $m^3$, the threshold for motor manual felling is taken to fall between the mean tree sizes of 1.47 and 1.61 $m^3$. In this study it is therefore assumed that an element of motor manual felling is required when mean tree volume exceeds 1.5 m³, and it is further assumed on the basis of the work of Ireland (2009) that 15 % of the volume felled incurs this additional cost. The proportion of harvested volume requiring chainsaw felling or processing may increase further with tree size, but on the basis of one study it is impossible to quantify this effect.

Motor manual productivity is taken to be 8.50 m³ per standard hour (Ireland, 2009, Table 9, p. 8). The additional harvesting cost of motor manual felling is therefore calculated as 15 % of the total volume harvested multiplied by the cost per hour (see section 2.3.3.5) and divided by 8.50.

#### 2.3.3.5 Costs

The cost per hour of a John Deere 1270D harvester was given by Ireland (2008, p. 4, Table 5) as £70.62, very similar to the figure of £69.37 per hour presented by Ireland (2009, p. 16) for a machine of the same model. A figure of £70 per hour was therefore used to convert harvester productivity to cost per m³ harvested by dividing cost per hour by the productivity in m³ per standard hour.

The cost per hour of a John Deere 1110D forwarder was given by Ireland (2008, p. 4, Table 5) as £52.64 and by Ireland (2009, p. 16) as £53.61. A figure of £53 per hour was used in this study to calculate forwarding costs.

The cost per hour for motor manual felling was given by Ireland (2009, p. 16) as £26.12. A figure of £26 per hour was used in this study.

As an example of harvesting costs, the following calculations are for thinning and partial felling in year 41 of scenario SS4. This involves the harvesting of 113.5 m³ of timber per hectare, with a mean tree volume of 1.65 m³. Productivity penalties apply, and because the mean tree size is greater than 1.5 m³ there is a need for motor manual felling.

Harvester productivity (Eq. 1) = $25.741 \times 1.65\ \text{m}^{3\ 0.8517}$ (max. 33.54) = 33.54 m³/shr
With productivity penalty = 33.54 m³/shr × 0.90 = 30.186 m³/shr
Cost per m³ = £70/shr ÷ 30.186 m³/shr = £2.32/m³
Total cost = £2.32/m³ × 113.5 m³/ha = £263.20/ha

Forwarder productivity (Eq. 2) = 2.6492 + 11.5072 × 1.65 m³ + 0.0076 × 113.5 m³/ha (max. 24.46) = 22.49 m³/shr
With productivity penalty = 22.49 m³/shr × 0.76 = 17.09 m³/shr
Cost per m³ = £53/shr ÷ 17.09 m³/shr = £3.10/m³
Total cost = £3.10/m³ × 113.5 m³/ha = £351.92/ha

Volume requiring motor manual felling = 113.5 m³/ha × 0.15 = 17.025 m³/ha
Cost per m³ = £26/shr ÷ 8.50 m³/shr = £3.06/m³
Total cost = £3.06/m³ × 17.025 m³/ha = £52.08/ha

Grand total cost = £263.20/ha + £351.92/ha + £52.08/ha = £667.20/ha

This differs slightly (~0.06 %) from the figure of £667.62 in the analysis spreadsheet because of rounding in yield data. Note that the motor manual cost is in addition to rather than in place of the harvester cost for the 15 % of volume felled by chainsaw, as further processing by the harvester is still required.

### 2.3.4 Annual costs

Some costs which cannot easily be assigned to specific operations are treated as annual costs and are described in the following sections. Knoke *et al*. (2001) similarly assumed costs including administration and forest roading to be constant over time.

#### 2.3.4.1 Management overheads

As monitoring costs are accounted for elsewhere, management overheads are assumed to account for the planning of interventions in the light of monitoring data, and the management and supervision of operations. This is quantified in abstract terms as a time commitment from pay band 5(op) and 6a Forestry Commission staff. Note that this accounts only for costs directly associated with the management of an individual stand, and does not take account of the cost of higher level or administrative staff (cf. Mohr and Schori, 1999). It must also be recognised that this is not a genuine annual cost; in reality the time commitment would vary from year to year with the cycle of planning and executing operations. Other studies have considered management input in terms of a cost per cubic metre of timber harvested (Hubert *et al*., 2000) or a cost per harvesting operation (Andreassen and Øyen, 2002).

The time commitment is approximated as 0.3 pb5(op) and 0.6 pb6a hours per hectare per year. Before the thinning of each cohort begins there are management and supervisory requirements associated with artificial and natural regeneration. Assuming a 10 ha stand and taking into account the seven year thinning cycle in all scenarios, the time commitment is roughly equivalent to 21 pb5(op) and 42 pb6a hours per stand per thinning cycle. The pb5(op) time commitment is expected to cover planning and management and the pb6a time to allow for planning and site supervision.

Costs are taken from Forest Research 2010/11 daily charge out rates which include salary and overheads as shown in Table 16. The total management overhead cost per hectare per year derived using hourly cost figures is £29.75 (0.3 × £38.64 + 0.6 × £30.27).

**Table 16** Staff costs.

| Pay band | Daily costs | | | Hourly costs |
|---|---|---|---|---|
| | Salary | Overhead | Total | |
| 5(op) | £183 | £157 | £340 | ÷ 8.8 = £38.64 |
| 6a | £124 | £100 | £224 | ÷ 7.4 = £30.27 |

It is assumed that transformation to a simple structure will incur 150 % of this cost and that transformation to a complex structure will incur costs at 200 %, due to increased demands for planning, supervision and training for staff who are unfamiliar with CCF. It should be noted that even if these relative costs are realistic the differences will decline over time as experience of CCF systems increases.

#### 2.3.4.2 Mammal control

Although for an individual stand there may be periods relating to artificial or natural regeneration when mammal control is particularly crucial, it is assumed that a relatively constant level of control is required to keep pest populations in check. The cost per hectare is taken from the EWGS standard cost C7 for deer control at the landscape scale of £6 (Forestry Commission England, 2010). To account for the potentially greater difficulty of protecting regeneration established under a canopy (Ireland, 2006), the cost in the SS2 and SS3 scenarios is increased to 150 % (£9 per ha). As regeneration events are more frequent and more dispersed in the transformation to a complex structure, and as the resulting stand structure may be less amenable to deer control, the cost is increased to 200 % (£12 per ha).

#### 2.3.4.3 Road maintenance

The cost of road maintenance has been crudely estimated on the assumption that each hectare is served by 100 m of cat. 1a road maintained on a ten-year cycle at a cost of £1 per metre (Forestry Commission England, 2010), giving an annual cost of £10. Conditions are generally assumed to be highly suitable for machine access so that there are no requirements for ramps or other facilities, and it is assumed that it is possible to keep harvesting machinery off forest roads so that the need for specific remedial work after harvesting operations is negligible. No cost differential between scenarios is assumed.

## 2.4 Revenue data

For the purposes of estimating harvesting revenues, the volume yield is assigned to three product categories, namely sawlogs, bars and chip/pulp. The derivation of prices and the calculation of product assortments are described below.

### 2.4.1 Product specifications and assortments

Sawlogs are assumed to have a minimum top diameter overbark of 18 cm and a minimum length of 3 m. Bars are assumed to have a minimum top diameter overbark of 14 cm and a minimum length of 2 m. Chipwood and pulpwood account for the remaining volume to 7 cm top diameter overbark.

Assortments were calculated using tables 33 and 34 of Matthews and Mackie (2006, pp. 217-218). The scenario spreadsheet incorporates tables 32-35 (pp. 216-219) so that assortments may be calculated for minimum product lengths of 1, 2, 3 or 4 m. The percentage by volume of sawlogs arising from a harvesting operation was derived from the rounded down mean diameter of the felled timber cross-referenced against the minimum top diameter of 18 cm in table 34. The percentage of volume to 14 cm top height with a minimum length of 2 m was derived in a similar fashion from table 33, and the sawlog percentage was subtracted to estimate the bar percentage. The sawlog and bar percentages were subtracted from 100 to give the remaining chip/pulp percentage.

The scenario spreadsheet allows users to specify their own products. The functions referencing the volume assortment tables have been set up so that user specified minimum top diameters are rounded up to the nearest 2 cm, unless equal to or less than 7 cm in which case they are treated as 7 cm (and encompass 100 % of stand volume) or greater than 40 cm (which causes the calculations to fail). User specified minimum lengths are rounded up to the nearest metre with a maximum of 4 m.

### 2.4.2 Roadside product prices

Approximate average product prices for recent roadside sales in Wales (Roger Nock, pers. comm., October 2010) are £35.25 per tonne for short logs (1.9-3.7 m length, 18 cm minimum top diameter), £31.00 per tonne for bars (1.9-3.7 m length, 14 cm minimum top diameter), and £16.00 per tonne for chip and pulp. To be used in this study, these figures must be converted to prices per cubic metre. The relationship between weight and volume depends on product mid diameter and the delay between felling and weighing (Matthews and Mackie, 2006, pp. 134-136). It is assumed that harvesting occurs in the winter and that uplift of timber is prompt so that the effect of drying on the relationship is negligible. Assuming average mid diameters of 25, 17 and 11 cm, conversion factors of 1.135, 1.047 and 0.981 $m^3$ per tonne may be derived for logs, bars and chip/pulp respectively according to the method of Matthews and Mackie (2006). Prices per cubic metre may be calculated by dividing prices per tonne by these conversion factors, giving £35.25 ÷ 1.135 = £31.06 per $m^3$ for logs, £31.00 ÷ 1.047 = £29.61 per $m^3$ for bars, and £16.00 ÷ 0.981 = £16.31 per $m^3$ for chip/pulp. On this basis the roadside prices per cubic metre used in this study are £31.00 for logs, £29.50 for bars and £16.25 for chip/pulp.

### 2.4.3 Revenue calculations

Once product assortments were known, harvesting revenues were calculated by multiplying, for each product, the total volume harvested by the product percentage and then by the product price, and summing the results. For example, harvesting 60.5 $m^3$ per ha of which 76 % was log, 15 % was bar and 9 % was chip/pulp gave: (60.5 × 0.76 × £31.00) + (60.5 × 0.15 × £29.50) + (60.5 × 0.09 × £16.25) = £1,781.57.

## 2.5 Financial comparisons

All financial comparisons between scenarios are on the basis of net present values (NPVs), i.e. the sum of discounted revenues minus the sum of discounted costs (Price, 1989). Factors which directly affect the calculations of discounted cash flows are the start point for comparisons, the timescale over which cash flows are compared, and the discount rate.

### 2.5.1 Start point for comparisons

In the description of scenarios (section 2.1) it was stated that the detailed scheduling of operations in each began when the initial stand was 25 years old, as up to age 23 management was assumed not to differ. The financial comparison of scenarios uses the same start point, so that year 1 for discounting purposes is year 25 of the initial stand. Hanewinkel (2001) similarly started comparisons of diverging management regimes in Norway spruce with stands 30 years old. Given that cash flows up to this point are assumed to be identical in all scenarios, starting financial comparisons earlier in the rotation of the initial stand would affect only absolute and not relative NPVs for infinite series of rotations, i.e. the ranking of scenarios would not change, because all future cash flows would still be taken into account and would be shifted uniformly into the future. It is important to recognise that changing the start point could change the relative ranking of scenarios when considered over finite time horizons, however, as doing so may alter which cash flows are included in or excluded from calculations. For example, starting comparisons four years earlier would exclude a set of final felling costs and revenues from scenario SS1 for a 100 year time horizon (currently at year 97, Table 2) but would still include final felling cash flows in scenario SS2 (currently at year 96, Table 3). The choice of the exact start point for comparisons is essentially arbitrary, and this must be borne in mind when interpreting results.

### 2.5.2 Timescales for comparisons

The start point has been shown to interact closely with the length of finite time horizons for comparisons. Like the choice of start point, the choice of length of a finite period for comparing cash flows is arbitrary and the effect of excluding cash flows beyond the time horizon must be considered when interpreting results. Despite this disadvantage in comparison with considering cash flows in perpetuity, the use of finite time horizons is not without precedent (e.g. Knoke and Plusczyk, 2001) and does have advantages. Although the use of discounting may partly be justified in terms of time preference and the greater importance attached to benefits accruing or costs arising closer in time (Price, 1989), the information needs of the decision making processes of some stakeholders may be better supplied by considering a short timescale (e.g. ten years in the study of Emmingham *et al*., 2002) than by applying a high discount rate. Indeed the original brief for this study as communicated to Forest Research staff was to consider the cost implications of transformation and CCF over the next 100 years. A short time horizon is particularly pertinent in the face of government spending reviews in Britain, which may severely curtail the financial resources available for the management of publicly owned forests and potentially, if grant aid is affected, of privately owned forests. Future benefits, however great, cannot be achieved if short-term costs are too great to be borne.

Having established that finite time horizons for financial comparisons are arbitrary and require careful interpretation, two were chosen for this study. The 100 year horizon of the original study conception has been retained, which is twice the length of the time period stated to be covered by forestry strategies such as *Woodlands for Wales* (Welsh Assembly Government, 2009). This might be considered a medium-term assessment in a forestry context. A 20 year time horizon is also included, equivalent to the period covered by the 2005 UK softwood production forecast (Halsall *et al*., 2006), to provide an indication of short-term consequences.

A consideration of cash flows in perpetuity, assuming an indefinite series of identical rotations or, in the case of scenario SS4, an indefinite continuation of the steady-state cycle of cohorts, forms the basis of the third timescale for comparisons. This avoids the artificial exclusion of cash flows beyond finite time horizons and allows comparisons to be made with similar studies.

### 2.5.3 Discount rate

The choice of discount rate can profoundly affect financial comparisons by altering the weight attached to cash flows at different points in time; the higher the discount rate, the greater the effect of any delay in realising cash flows in diminishing their contribution to net present value. As this study is set in the context of the British state forestry service, the discount rate recommended in the Treasury *Green Book* (H.M. Treasury, 2003) has been adopted. The *Green Book* specifies that a declining rate is appropriate when considering long-term investments, justifying this in terms of uncertainty about the future (H.M. Treasury, 2003, p. 98); the rates applied according to the time period under consideration are given in Table 17.

**Table 17** Declining discount rate according to time period.

| **Time period (years)** | 0-30 | 31-75 | 76-125 | 126-200 | 201-300 | 301+ |
|---|---|---|---|---|---|---|
| **Discount rate (%)** | 3.5 | 3.0 | 2.5 | 2.0 | 1.5 | 1.0 |

While this schedule of declining discount rate is used by default in analyses, the analysis spreadsheet gives the user the options of specifying the starting discount rate and of choosing whether or not to use a declining rate. If the option to use a declining rate is enabled and the starting rate is greater than 1.0 %, the rate declines in 0.5 % steps in the same time periods as in Table 17 to a minimum of 1.0 %. If the option to use a declining rate is disabled or the chosen starting rate is 1.0 % or less, the starting rate is applied in all time periods.

### 2.5.4 Calculations

Discounted cash flows are calculated using the equations given by Price (1989). For the first 300 years of each scenario discounted cash flows are calculated individually because of the complicating effect of the declining discount rate. All such discounted present values (PVs) are calculated as:

PV of cash flow £X = £X / $(1 + r)^{t}$ (Eq. 3)

where $r$ = decimal discount rate (i.e. % discount rate divided by 100)
$t$ = time (years) until cash flow occurs

For example, a respacing cost of -£700 per ha occurring in year 43 of scenario SS2 is discounted at a rate of 3.0 % to give a PV of -£196.38 (-£700 / $(1.03)^{43}$).

From year 301 onwards, when there is no further decrease in the discount rate, the present values of ongoing annual costs are calculated as:

PV of annual cost £X in perpetuity = $PV_{301} \times (1 + r) / r$ (Eq. 4)

where $PV_{301}$ = PV of annual cost £X at year 301

For example, the annual mammal control cost of -£9.00 per ha in scenario SS3 is discounted for each individual year up to 300, then from year 301 to the indefinite future, at a discount rate of 1.0 %, is calculated as -£9.00 / $1.01^{301} \times 1.01 / 0.01$ = -£45.48.

For all other cash flows, the present value from year 301 to the indefinite future is calculated using their present value at their first occurrence after year 300 and the following equation:

PV of cash flow £X in perpetuity = $PV_{t} \times (1 + r)^{T} / ((1 + r)^{T} - 1)$ (Eq. 5)

where $PV_{t}$ = PV of cash flow £X at year $t$, being the first occurrence after year 300

For example, in scenario SS4 the final felling of a cohort first occurs after year 300 at year 321, yielding revenues of £5,794.20 per ha. As a new cohort arises every 21 years, the final felling of a cohort also occurs every 21 years. The present value of these revenues from year 301 to the indefinite future, at a discount rate of 1.0 %, is therefore calculated as £5,794.20 / $1.01^{321} \times 1.01^{21} / (1.01^{21} - 1)$ = £1,259.97.

Net present values for the three timescales are calculated simply by summing present values of all costs and revenues from years 1-20 ($NPV_{20}$), years 1-100 ($NPV_{100}$), and years 1-300 plus PVs from year 301 to the indefinite future ($NPV_{\infty}$).

## 2.6 Factors not accounted for

It has already been noted that this is a strictly financial cost-benefit analysis, dealing only with the direct tangible costs and revenues of forest operations. No attempt has been made to quantify the effects of the different scenarios on the provision of wider ecosystem services, and the financial comparisons must be interpreted in this light.

Other species could have been considered and other scenarios formulated, some of which are considered in the discussion of results. Within the context of the current series of scenarios, however, other issues could have been addressed, and some major points to consider when comparing the scenarios are briefly discussed below.

### 2.6.1 Genetic changes

Given the very substantial commitments which have been made to selective breeding of Sitka spruce (Rook, 1992), scenarios SS1 and SS3 could be reformulated using genetically improved stock for replanting or underplanting. The use of improved stock may lead to substantial increases in volume production (Lee and Matthews, 2004) without any apparent decrease in timber quality (Mochan *et al.*, 2008). Tree nursery catalogues show that there is an increased cost associated with genetically improved plants, particularly if the highest quality vegetatively propagated stock is used (e.g. Christie Elite Nurseries field grown conifers catalogue, http://www.christie-elite.co.uk/Field-Conifers.html, accessed 13/10/2010); thus in the short term restocking and underplanting costs are increased. However, the more rapid growth of the resulting stand, which has been represented in the past by an increase in yield class (Lee, 1992), has the effect of both increasing and bringing forward in time all future harvesting revenues. Unless a high discount rate has the effect of unduly increasing the significance of the early costs at the expense of the more distant revenues, the planting of improved Sitka spruce is highly likely to increase the net present value of scenarios SS1 and SS3.

It has been suggested that dysgenic effects of selective felling during the transformation process may have a negative effect on the growth and yield of future cohorts (Price, 2003; Price and Price, 2006). This assumes the early removal of the most vigorous trees in single tree selection systems, thereby eliminating them as future potential parent trees. However, in the transformation scenarios presented in this study, early crown thinnings are intended to favour the best formed and most vigorous trees (Mason and Kerr, 2004; Davies *et al*., 2008; Kerr and Haufe, 2011) rather than remove them. Although these trees do represent the ultimate crop trees in each scenario, they are expected to persist long enough to contribute seed to natural regeneration. By removing exceptionally coarse trees or those most lacking in vigour, early thinnings should improve the overall genetic quality of successor crops.

### 2.6.2 Timber quality, products and prices

No attempt is made in this study to quantify the effects of management on timber quality in the different scenarios, although understanding of the effects of silviculture on timber quality continues to increase (Macdonald and Hubert, 2002; Moore *et al*., 2009;

Macdonald *et al*., 2010). Explicitly modelling the effects on quality might facilitate more sophisticated modelling of product assortments and therefore revenues. The current approach to product assortments is basic, and is designed simply to optimise the proportion of logs. This will obviously lead to sub-optimal financial results if other products command higher prices, as is currently the case with small dimension fencing material in Wales (Roger Nock, pers. comm.).

Timber prices may vary considerably over time (Knoke *et al*., 2001) and there is currently much uncertainty about the future value of large dimension Sitka spruce logs in Britain. No attempt is made in this study to predict future trends in timber prices, any more than an attempt is made to predict future trends in costs, but it must be recognised that this is a major uncertainty with a very great influence on financial comparisons of silvicultural scenarios.

The maximum mean stem diameter removed in final fellings of stands or cohorts increases from scenario SS1 to SS4 from 33.8 to 54.1 cm, with a corresponding increase in the proportion of log material under the assumptions given in section 2.4.1 from 89 to 97 %. Any change in log prices is therefore likely to have a greater effect on scenario SS4 than SS1, for instance. As the interaction of product assortments and prices is a major source of uncertainty in financial comparisons, these factors are included in a sensitivity analysis (see section 2.7).

### 2.6.3 Risk and stochastic events

Uncertainty extends beyond product prices to rising fuel costs, changes in harvesting technology, policy limitations on practices, the effects of climate change, the depredations of insects, wind damage and other such largely unpredictable factors. These factors have not been taken into account in this study, and no attempt has been made to model stochastic events such as disease outbreaks or windthrow. Knoke *et al*. (2001) contended that the failure to take into account risk is acceptable only if the risks are equal among alternatives, and that if they are not equal comparisons of alternatives may be misleading. This must be borne in mind when interpreting results, as not only are the risk factors themselves unpredictable, but in addition the relative susceptibility of stands under different management are largely unknown.

Major disease and pest outbreaks in British forests are topical issues at present, with *Phytophthora ramorum* severely affecting Japanese larch (*Larix kaempferi* (Lindl.) Carrière) in the southwest (Brasier and Webber, 2010) and a breeding population of the pine-tree lappet moth *Dendrolimus pini* having recently been found in Scotland (Green, 2009). Of potential significance for the future of Sitka spruce is the recent expansion of the range of the great spruce bark beetle *Dendroctonus micans* (Green, 2010). It has been suggested that the risk of such outbreaks may be increased by climate change (Broadmeadow *et al*., 2009), and the potential economic effects are substantial (Price, 2010). Crucially for this study, however, there is very little evidence to indicate how the management of monocultures may influence the risk of damage. The limited information on the effects of different regeneration strategies on the susceptibility of seedlings to damage by *Hylobius abietis* has already been taken into account in formulating the scenarios (sections 2.1.1 and 2.3.2). Research findings suggest that the green spruce aphid *Elatobium abietinum* infests spruce seedlings more densely when they are grown in shade rather than in the open (Bertin, 2009), which may have implications for the success of natural or artificial regeneration under a canopy. The consequences of continuous cover forestry for infection by *Heterobasidion annosum* butt rot are unclear. While it is currently extremely difficult to quantify these risks, they must be considered when comparing silvicultural alternatives.

The potential for wind damage is a risk which must be borne in all forests. Even if site conditions are assumed to be such that endemic windthrow is minimal, the threat of catastrophic windthrow remains (Miller, 1985). However, it appears that there is little difference in windthrow risk between regular and irregular Sitka spruce stands on relatively sheltered sites (Mason, 2002). Guidance on the selection of sites suitable for continuous cover forestry is generally to avoid areas of high wind risk (Mason and Kerr, 2004). Therefore, while it is unrealistic to assume that there is no wind risk, there may at least be some basis for assuming that there are no substantial differences between scenarios in the susceptibility of the stands to wind damage if they are assumed to occupy sheltered sites. The effects of climate change on wind risk are still uncertain, though the risk seems likely to increase (Broadmeadow *et al*., 2009), but given the assumption of a relatively sheltered site there does not appear to be any reason to expect a greater increase in risk for any scenario in particular.

While changes in the suitability of the local climate for Sitka spruce, for example in terms of moisture deficit (Broadmeadow *et al*., 2009) might be expected to affect all scenarios equally, there is a suggestion that the more equable climate within stands managed under continuous cover, particularly in terms of humidity, may be advantageous (Kirby *et al*., 2009).

## 2.7 Sensitivity analysis

Calculating the net present values for all four scenarios using the assumptions outlined above simply results in 12 figures; one value of $NPV_{20}$, $NPV_{100}$ and $NPV_{\infty}$ for each scenario. This is meaningful only in terms of comparing these exact scenarios. In order to draw any more general meaning from the results there must be some indication of which factors most strongly influence the relative profitability of different silvicultural approaches. An impression of this may be achieved via a sensitivity analysis.

Sensitivity analysis in this study is complicated by the fact that, even if the schedules of operations, yield data and basic harvesting productivity relationships are kept constant, there are 51 inputs which may be individually adjusted by the user in the analysis spreadsheet, encompassing costs, revenues and discounting variables. Attempting to analyse the simultaneous adjustment of all these inputs is unlikely to yield comprehensible results. For this reason, only the inputs discussed below are considered, with each varied in isolation.

### 2.7.1 Management overheads

Of all the cost data in this study, the figures for management overheads have the weakest objective basis. The figure for scenario SS1 has some basis in current experience but the relative figures for the other scenarios are more speculative. It therefore seems prudent to consider how sensitive the results are to these overheads. Published figures give little indication of what the range of management costs might be. Andreassen and Øyen (2002) assumed a 50 euro administration cost for each harvesting operation. Hubert *et al*. (2000) assumed management costs of £50-90 per ha for respacing and considered costs of £2-3 per $m^3$ for harvesting, but did not attach management costs to other operations. Knoke *et al*. (2001) did not itemise overhead costs, which included taxes, buildings, and roads in addition to management staff costs.

With such a limited evidence base the range of value explored is relatively arbitrary. In addition to the default value of £29.75 per ha per year, costs of approximately 50 % (£15.00) and 150 % (£45.00) are tested, giving three base cost situations:

1. Reduced overhead of £15.00 per ha per year.
2. The baseline cost of £29.75 per ha per year.
3. Increased overhead of £45.00 per ha per year.

In addition to these different overhead costs, different relative costs for the four scenarios are tested at the default baseline cost of £29.75, as follows:

1. Relative costs SS1-4 100 %.
2. Relative costs SS1 100 %, SS2 150 %, SS3 150 %, SS4 200 % (baseline assumptions).
3. Relative costs SS1 100 %, SS2 200 %, SS3 200 %, SS4 400 %.

### 2.7.2 Product prices

The range and value of products cut, which along with the actual volumes harvested are the sole determinants of revenues in the scenarios, necessarily have a profound influence on the financial comparison of alternatives. Some of the deficiencies in the treatment of product assortments in this study have already been highlighted. To investigate potential effects on financial comparisons, three product price variations are considered, namely:

1. An increased value of £20.00 per $m^3$ for chip/pulp, potentially representing increased demand for biofuel.
2. Product prices as per baseline assumptions.
3. A high sawlog premium price of £40.00 per $m^3$.

### 2.7.3 Discount rate

The discount rate used may also exercise a considerable influence over comparisons by adjusting the relative importance attached to cash flows more or less distant in time. The following rates are investigated:

1. 1.0 %, constant.
2. 3.5 %, declining (baseline assumptions).
3. 3.5 %, constant.
4. 6.0 %, declining.
5. 6.0 %, constant.

The higher the discount rate, the greater the effect of distance in time in diminishing the contribution of cash flows to net present value.

# 3 Results

## 3.1 Net present values using baseline assumptions

The net present values derived using the baseline assumptions detailed in sections 2.1 to 2.5 are shown in Table 18. Immediately evident is the fact that none of the scenarios breaks even over the first 20 years. The management in scenarios SS2 and SS3 does not differ over this period so their NPVs are identical; they are also the least costly scenarios over this time period. For longer time horizons all scenarios have positive values, but the ranking changes over 100 years with SS1 showing the highest net present value. Considering cash flows in perpetuity alters the ranking once again, with scenario SS2 showing the highest NPV.

These figures are reproduced in Table 19 in relative form. For each timescale, relative net present values are calculated using the NPV for scenario SS1, representing current standard practice, as 100 %. This demonstrates that scenario SS4 is 10 % less costly than scenario SS1 over 20 years while scenarios SS2 and SS3 are 17 % less costly. While scenarios SS3 and SS4 are less than half as valuable as SS1 over 100 years, scenario SS2 is only 5 % less valuable. When cash flows into the indefinite future are considered, scenario SS2 is 20 % more valuable than SS1. Scenario SS4 becomes considerably more valuable over this timescale, but SS3 retains a relatively low value.

**Table 18** Net present values using baseline assumptions.

| Scenario | Net present value per hectare considering cash flows... | | |
|---|---|---|---|
| | to 20 years | to 100 years | in perpetuity |
| SS1 | -£724 | £3,790 | £4,689 |
| SS2 | -£600 | £3,611 | £5,621 |
| SS3 | -£600 | £1,653 | £2,802 |
| SS4 | -£651 | £1,465 | £4,293 |

**Table 19** Relative net present values using baseline assumptions.

| Scenario | Relative net present value per hectare considering cash flows... | | |
|---|---|---|---|
| | to 20 years | to 100 years | in perpetuity |
| SS1 | -100.0 % | 100.0 % | 100.0 % |
| SS2 | -82.9 % | 95.3 % | 119.9 % |
| SS3 | -82.9 % | 43.6 % | 59.8 % |
| SS4 | -89.9 % | 38.7 % | 91.6 % |

On the basis of these net present values, scenario SS2, transformation to a simple structure with successful natural regeneration, is the least costly option in the short term, roughly equally as valuable as current standard practice over the medium term, and the most valuable option in the long term. Scenario SS4, transformation to a complex structure, yields the lowest net returns over the medium term, but is only slightly less valuable than standard practice in the long term; this diminution in value should be considered in the light of any increase in ecosystem service provision which might be attributed to this management type.

## 3.2 Volume outturn using baseline assumptions

The total volume outturn for each scenario is set by the growth and yield data described in section 2.2. The breakdown of that volume into individual products, however, depends on the product specifications set by the user. Tables 20 and 21 show the volume outturn over the first 20 and 100 years respectively of each scenario on the basis of the product specifications given in section 2.4.1. In the short term (Table 20), scenario SS4 yields the greatest volume of timber and the highest proportion of log material because of initial heavy crown thinnings. The intermediate thinnings at marginal intensity in scenario SS1 yield the smallest total volume, the lowest proportion of log material and the highest proportion of chip and pulp. In the medium term (Table 21), the ongoing transformation to a complex structure in scenario SS4 yields a relatively low total volume but the highest proportion of logs. Scenario SS2, transformation to a simple structure with successful natural regeneration, yields both the greatest average annual volume outturn and the greatest volume of log material.

**Table 20** Volume outturn over 20 years using baseline assumptions.

| Scenario | Mean annual volume outturn ($m^3$ per ha per year) | | | |
|---|---|---|---|---|
| | Sawlogs | Bars | Chip / pulp | Total |
| SS1 | 2.8 (27.3 %) | 3.3 (32.3 %) | 4.2 (40.3 %) | 10.3 |
| SS2 | 4.0 (31.1 %) | 4.0 (30.6 %) | 5.0 (38.3 %) | 13.0 |
| SS3 | 4.0 (31.1 %) | 4.0 (30.6 %) | 5.0 (38.3 %) | 13.0 |
| SS4 | 4.8 (35.3 %) | 4.2 (31.0 %) | 4.6 (33.8 %) | 13.7 |

**Table 21** Volume outturn over 100 years using baseline assumptions.

| Scenario | Mean annual volume outturn ($m^3$ per ha per year) | | | |
|---|---|---|---|---|
| | Sawlogs | Bars | Chip / pulp | Total |
| SS1 | 11.1 (70.5 %) | 2.3 (14.4 %) | 2.4 (15.0 %) | 15.7 |
| SS2 | 11.8 (71.3 %) | 2.2 (13.3 %) | 2.5 (15.3 %) | 16.6 |
| SS3 | 8.0 (64.1 %) | 2.0 (16.3 %) | 2.4 (19.7 %) | 12.4 |
| SS4 | 9.2 (71.9 %) | 1.6 (12.4 %) | 2.0 (15.8 %) | 12.9 |

## 3.3 Sensitivity analysis

In reporting the results of the sensitivity analysis, it is assumed that it is any change in the relative performance of the four scenarios that is of interest. Changes in the absolute performance of scenarios are noted only when they involve a change from a positive to a negative net present value.

### 3.3.1 Management overheads

Net present values in perpetuity for all four scenarios at the three management overhead base costs tested are illustrated in Figure 5. It may be noted that for all three costs scenario SS2 has the highest NPV and scenario SS3 the lowest. The relative performance of scenarios changes only at the lower cost of £15.00 per hectare per year, when scenario SS4 moves from having the third highest value to having the second highest value. The lower cost also favours scenario SS4 over shorter time horizons (data not shown), particularly over the first 20 years when the rank of the scenario improves from second most costly to least costly. The higher cost of £45.00 worsens the performance of SS4 from second most costly to most costly over 20 years, but does not affect the ranking of scenarios over 100 years.

Changes in relative management cost (Figure 6) primarily affect the relative performance of scenario SS4, with scenario SS1 remaining the most valuable in all cases and SS3 generally the least valuable. When relative costs are equal for all scenarios, the performance of SS4 improves so that it becomes the second most valuable scenario. Conversely, when relative costs for transformation scenarios are increased, SS4 performs poorly, having the lowest NPV, while the difference in performance between SS1 and SS2 decreases substantially. Over shorter time horizons (data not shown), equal relative costs favour scenario SS4, increasing its rank from second most costly to least costly over 20 years, while higher costs for transformation scenarios naturally favour scenario SS1, increasing its NPV from most costly to least costly over 20 years.

### 3.3.2 Product prices

Changes to product prices, even a very substantial premium on sawlogs, do not affect the ranking of scenarios by NPV in perpetuity (Figure 7). Nor do they affect the ranking of scenarios over 100 years, and over 20 years the only effect of the log premium is to greatly improve the performance of scenario SS4, which becomes the least costly option in the short term (data not shown).

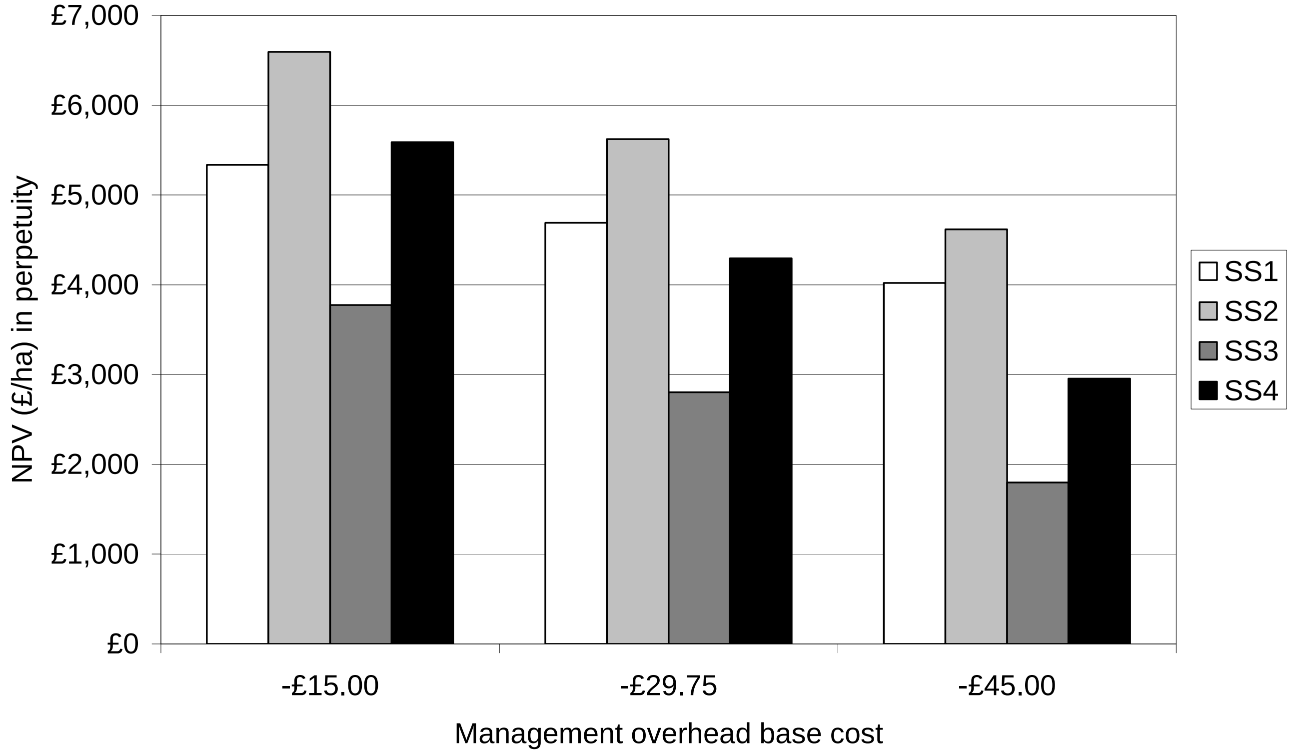


**Figure 5** Changes in net present value of scenarios with different management overhead base costs.

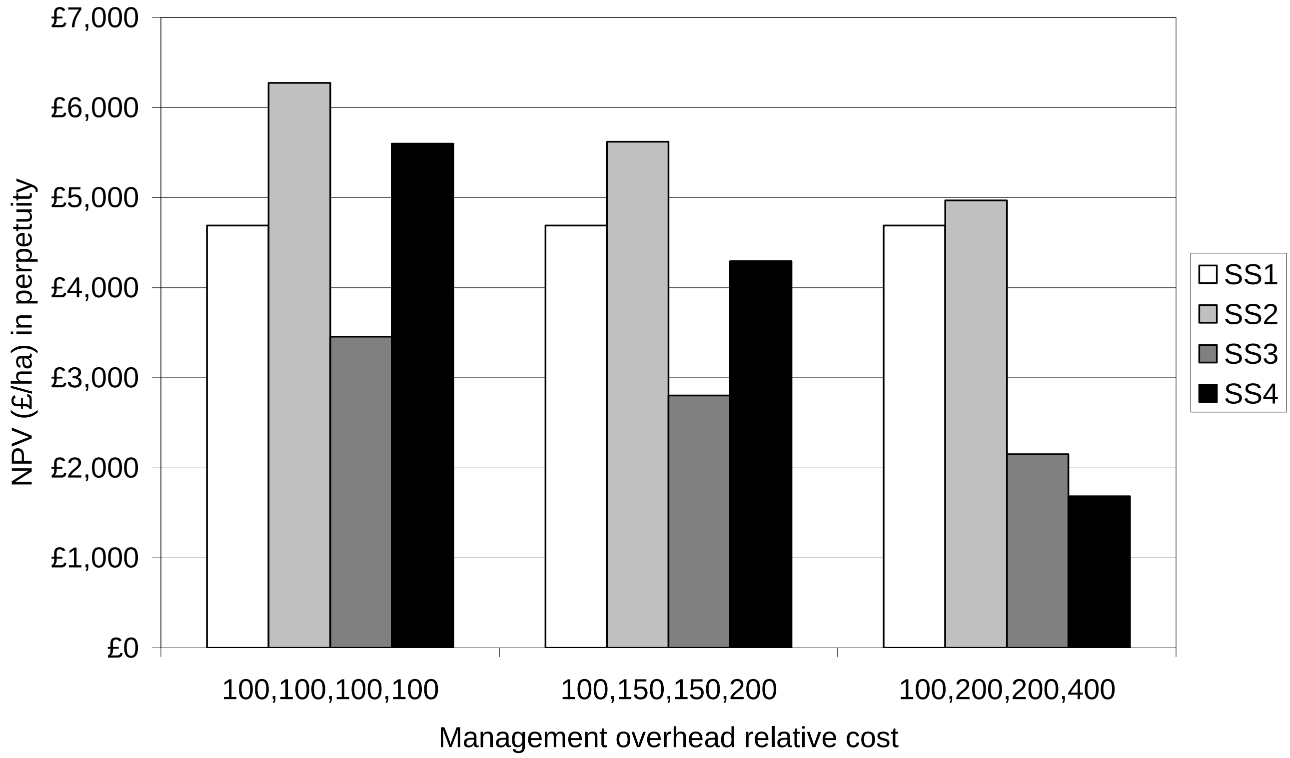


**Figure 6** Changes in net present value of scenarios with different management overhead relative costs.

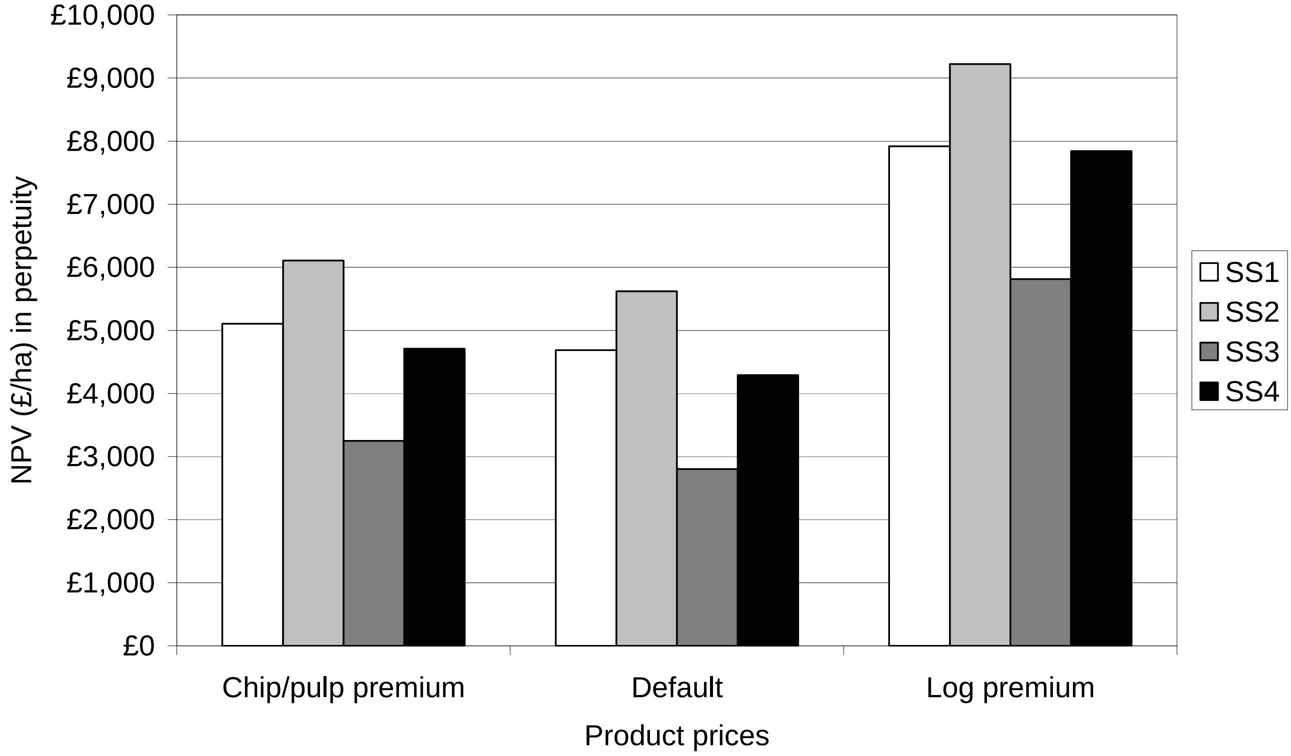


**Figure 7** Changes in net present value of scenarios with different product prices.

### 3.3.3 Discount rate

The effects of different discount rates on net present values are shown in Figure 8. Compared to the default 3.5 % declining rate, a 1.0 % rate improves the relative performance of scenario SS4, making it the second most valuable option. A constant 3.5 % rate or a rate of 6.0 %, however, greatly diminishes the relative values of scenarios SS2 and SS4 so that SS1, clearfelling and replanting, becomes the most valuable option and, in the case of a 6.0 % rate, SS4 fails to achieve a positive NPV. Overall, SS2 performs best at low rates, SS1 rises from second to first place in terms of NPV at higher rates, and SS3 performs relatively poorly throughout.

Over shorter time horizons (data not shown), a change in discount rate has a smaller effect. The ranking of scenarios at 100 years only changes from that for baseline assumptions (where SS1 gives the highest NPV and SS4 the lowest) at a 1.0 % rate, when SS2 becomes the most valuable and SS3 the least valuable. Over 20 years, scenarios SS2 and SS3 always give the lowest overall cost and only the relative ranking of SS1 and SS4 changes; at 1.0 % or 3.5 % SS1 is the most costly, and at 6.0 % SS4 is the most costly.

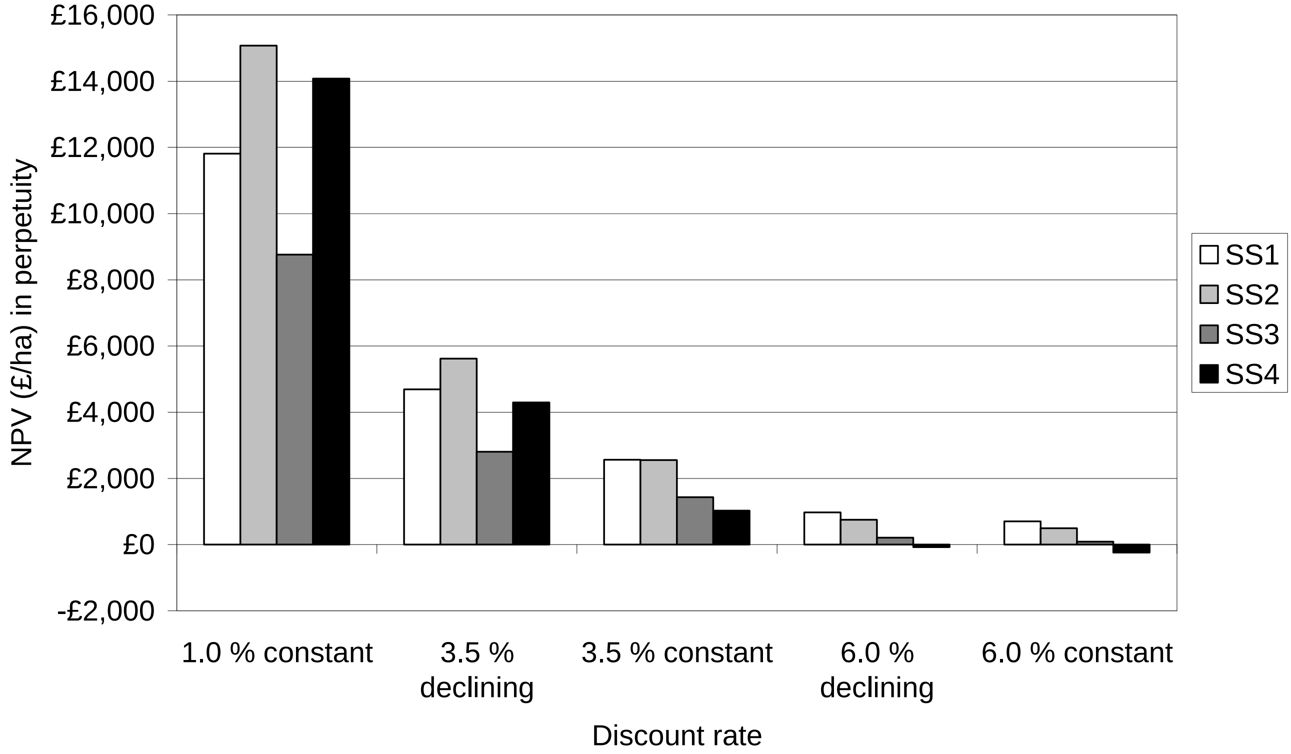


**Figure 8** Changes in net present value of scenarios with different discount rates.

# 4 Discussion

## 4.1 Scope of study

Before discussing the results of this study, it is important to understand its scope and limitations. The study is not a comprehensive assessment of the cost and revenue streams arising from continuous cover forest management in comparison with conventional practice. The actual costs incurred and revenues accrued following a large-scale change in management practice cannot be meaningfully predicted, given the variability of the public forest estate in terms of factors such as crop and site conditions, potential silvicultural approaches, local markets and costs, and unforecastable events such as windthrow or disease outbreaks. It is also unlikely that the exact schedules of operations or cash flows described for the four scenarios would ever be achieved in practice. While it is hoped that the scenarios are realistic, they are idealised in as much as operations follow a very rigid timetable, yields are exactly according to models, and there is no stochastic disruption to the orderly development of each stand. The results are indicative, and simply compare the relative performance in terms of net present value of the four specific scenarios described. The generalisation and extrapolation of results must be approached with a great deal of caution, given the many variables involved.

A key aim of this study is to clarify the sorts of operations which may be involved in transformation and CCF management and to quantify the costs of those operations. This, at least, may be useful as a broad guide to assessing the costs likely to be incurred in real stands.

The growth and yield data in this study certainly should not be used as yield models for real life transformation scenarios. Considerable uncertainties remain about the growth of stands of complex structure – the treatment of which in this study is necessarily abstract and simplified – and these uncertainties will only be definitively resolved on the basis of long-term field measurements under a wide range of circumstances. Actual practice should be responsive to the development of individual stands with, for example, thinning practice being modified according to the relative success of regeneration.

## 4.2 Comparison of scenarios

The comparison of net present values using baseline assumptions (Tables 18 and 19) shows that, in the short term (over the first 20 years), transformation need not be costly relative to conventional clearfelling management. In fact, in all of the transformation scenarios modelled the higher efficiencies and greater yields of heavy early thinnings lead to lower net costs over the first twenty years. Thus there appears to be a short-term financial argument for a change in thinning practice even if there is no intention to transform to CCF; the economic benefits of thinning from above have also been noted by Tahvonen *et al*. (2010). Over the short term, volume yields are higher for all transformation scenarios than for conventional management, and over the medium term successful transformation to a simple structure (scenario SS2) yields a greater total volume and a greater log volume per hectare per year than conventional management. That thinning at greater than marginal intensity should increase total volume yields is not entirely consistent with the concept of marginal thinning intensity (given that thinning at MTI supposedly optimises volume production over a rotation), but may be at least partly explained by the overlap of rotations that occurs in CCF compared with their separation by a fallow period in conventional practice. However, thinning from above in Norway spruce stands in Sweden has been found to give consistently higher volume increment than thinning from below (Lundqvist *et al*., 2007), an effect not necessarily reflected in current M1 model output, so it is possible that CCF volume yields may be higher than the figures in this study (Tables 8-13) suggest.

In the medium to long term (100 years and beyond), in terms of NPV, scenario SS2 is comparable with or even better than the conventional management reflected by scenario SS1. Even assuming relatively high management costs, transformation to a complex structure, scenario SS4, achieves an NPV in perpetuity which is 91.6 % of that for conventional management, so that, if substantial ecosystem service benefits are expected to arise from this stand structure they need to be balanced against a possible relative decrease in value of only 8.4 %. A Swiss study (Mohr and Schori, 1999) found that selection systems were on average more profitable than shelterwood systems, the opposite of the relationship between SS2 and SS4 found in the current work, but the authors noted that increased mechanisation, which is reflected in this work, would disadvantage selection systems. A study on beech silviculture in Denmark (Tarp *et al*., 2000) gave similar results to the present work, in that even-aged management (simple structure) with natural regeneration was more profitable than even-aged management with artificial regeneration and uneven-aged management (complex structure) with natural regeneration. Andreassen and Øyen (2002) found that the net present value of clearfelling was consistently higher over a range of assumptions than for group felling or single tree selection, both of which may be closer to SS4 than SS2 in this study, in which case the results of this study are similar.

The effects of the timescale of comparison, the silvicultural approach and the relative success of regeneration are evident. Scenario SS2 performs robustly over all timescales, but does depend on successful regeneration. Scenario SS3, without successful natural regeneration, performs poorly in longer timescales because of additional costly operations and delayed future rotations. The relative performance of scenario SS4 does depend very much on the timescale considered. Transformation practice in reality must be based on a consideration of the current state of a stand, and it may be financially optimal to clearfell and replant a mature stand with a view to transforming the successor crop (Tahvonen *et al*., 2010).

Changes to the details of costs and revenues, however, show that NPVs in perpetuity are relatively insensitive to variation in the assumptions tested in the sensitivity analysis (section 3.3). Scenario SS2 remains the most valuable and scenario SS3 the least valuable with changes to the base management overhead cost (Figure 5), and in most cases with changes to relative cost (Figure 6) unless scenario SS4 is severely disadvantaged. If relative costs are assumed to be equal for all scenarios, which might eventually be the case when CCF management is firmly embedded in corporate practice, transformation to and management of a complex structure actually becomes more profitable than standard clearfelling practice. The greater effects of base and relative management costs on SS4 are not surprising, as changes in base cost are magnified by default relative costs, and changes in relative cost (from 200 to 100, or 200 to 400) are greater than for scenarios SS2-3 (from 150 to 100, or 150 to 200).

The different product prices investigated do not alter the ranking of scenarios by NPV at all (Figure 7). It is notable that changes to product prices do not affect rankings, given that these are the only sources of income, though Knoke and Plusczyk (2001) also found that stumpage had a minimal effect on economic comparisons. It appears that the details of yield data are more critical to the performance of scenarios. Interestingly, Knoke *et al*. (2001) have suggested that in reality stumpage values are far more variable than management costs, which is encouraging in terms of the insensitivity of results to the potentially more variable factor.

Discount rate can have a pronounced effect (Figure 8), particularly on scenario SS4, but unless the rate is very high scenario SS2 remains the most valuable. Generally, relative indifference of decision makers to time (low discount rate) favours SS2 and SS4, while pronounced time preference (high discount rate) favours SS1. This effect of time preference presumably occurs because a higher discount rate gives proportionally greater weight to the relatively early clearfell revenues in scenario SS1 than to substantial revenues delayed to a greater or lesser extent in other scenarios, although other work has shown that higher rates favour transformation because of higher early thinning revenues (Hanewinkel, 2001).

As noted previously, in all discussion of the sensitivity of results to variations in inputs it has been assumed that it is only the relative performance of scenarios which matters, not the absolute NPVs achieved. Hubert *et al*. (2000) noted that the potential variability within the scenarios they investigated was greater than the differences between them, and this can be seen to be the case in this study, too. For example, the NPV in perpetuity of individual scenarios varies by up to around £14,000 per ha at discount rates between 1 % and 6 % (Figure 8), whereas the maximum difference between scenarios using the default assumptions is only around £2,800 (Table 18). The fact that scenario rankings remain relatively constant, however, is taken to indicate that the comparison of scenarios is robust, even if absolute NPVs must be treated with caution.

Overall, the comparison of scenarios in terms of both net present values and volume outturns strongly favours scenario SS2. Crucially, no increase in cost is incurred in the short term by pursuing transformation, which may actually be less costly than standard management. This scenario does assume complete success of regeneration. If sites and crops are correctly selected as being suitable for transformation, at least some regeneration should be a reasonable assumption. If regeneration does not occur uniformly across a site, some beating up may be required, or pruning of stems established at wider than standard spacings, which would increase costs. Alternatively, the silvicultural approach could be modified to accept a more irregular successor crop, which would probably have the effect of extending the rotation and deferring future cash flows, thus decreasing NPV in perpetuity. In reality, therefore, the NPV of a stand transformed to a simple structure is likely to be lower than that indicated for scenario SS2, but almost certainly not as low as that for SS3. As scenario SS4 does not depend on uniform regeneration it is hoped that the proposed transformation trajectory is realistic, but as noted above there remains much uncertainty about the growth and yield of complex stands. As an alternative to the conventional management represented by scenario SS1, early costs could be avoided by adopting a no-thin regime. This is likely to result in earlier clearfelling, bringing revenues for the first and all subsequent rotations forward, but a smaller mean tree size, leading to lower harvesting productivity and log outturn. The consequences of this approach in terms of non-market benefits should be considered, however.

The financial consequences of transformation to CCF management must of course be balanced against any perceived benefits or disbenefits in terms of ecosystem services provided by the transformed stands. Such effects of transformation remain largely unquantified. The reader is directed to sources such as Price and Price (2008) for a discussion of the potential consequences of transformation. One particular economic benefit which has been claimed for CCF, namely the potential for continuous yield at a stand level (Knoke and Plusczyk, 2001) which may minimise the risks associated with volatile markets (Knoke *et al*., 2001), may be relevant only for smaller forest holdings; in large forest estates, the development of a normal age structure managed under a clearfelling system is potentially equally robust.

## 4.3 Potential modifications of the method

Several refinements or modifications to this study may be suggested. Most obviously, there is a very wide range of potential scenarios which could be investigated, encompassing, for example, differences in tree species and yield, terrain, working methods, silvicultural approaches and the success of regeneration. Regeneration success, along with the risk of windthrow or pest outbreak, could be modelled stochastically. Many of these developments would stretch our knowledge of the processes and costs involved to the limits. The current approach is considered justified as a first step in realistically scheduling and quantifying cash flows. Successful further development of the method used in this study will depend on a steady increase in our knowledge, particularly in terms of work study for many of the operations involved and of the growth of complex stands.

Various aspects of the financial comparison could be adjusted. While the scenarios defined in this study are based on current practice or guidance on best practice for transformation, they have not been economically optimised, and it could be argued that an economic comparison is therefore illogical. Other studies have considered scenarios in which rotation lengths are financially optimal, for instance (e.g. Tarp *et al*., 2000; Price and Price, 2006; Tahvonen, 2009). Methods of valuation could also be modified. For the finite time horizons, for instance, liquidation values could be calculated so that costs and revenues can be balanced against the value of the standing crop, an approach used by Hanewinkel (2001) who noted some of the drawbacks of the method.

# 5 Conclusions

Transformation to continuous cover forestry management need not be more costly than conventional clearfelling and replanting. Under the assumptions in this study, increased early thinning revenues and the overlap of rotations may offset increased management overhead costs and harvesting costs in transformation to a simple structure assuming successful natural regeneration. In the short term this approach to management appears less costly than conventional management, and in the long term it is more valuable. Even assuming management costs twice as high as those for conventional management, the long term value of transformation to a complex structure is very close to that for conventional management. The outcomes of this study are relatively insensitive to changes in input values.

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