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Estimating and valuing the carbon sequestered in softwood and hardwood trees, timber products and forest soils in Wales

I. J. Bateman[†‡*] and A. A. Lovett[†‡]

Models of carbon storage in softwood and hardwood trees and forest soils and its emission from timber products and waste are developed and integrated with data on storage benefits to yield estimates of the value of the net carbon flux generated by afforestation. The long-term nature of the processes under consideration and the impact of varying the discount rate are explicitly incorporated within the model. A geographical information system (GIS) is used to apply carbon sequestration models to data on tree growth and soil type distribution for a large study area (the entire country of Wales). The major findings are: (1) all three elements under analysis (carbon sequestration in livewood, release from different products and waste, and storage or emission from soils) play a vital role in determining overall carbon flux; (2) woodland management has a substantial impact upon carbon storage in livewood however the choice of discount rate exerts the largest overall influence upon estimated carbon flux values; (3) timber growth rates (yield class) also have a major impact upon values; (4) tree species does affect storage values, however this is less important than the other factors listed above; (5) non-peat soils generally sequester relatively low levels of carbon. Planting upon peat soils can result in very substantial emissions of carbon which exceed the level of storage in livewood.

The GIS is used to produce valuation maps which can be readily incorporated within cost-benefit analyses regarding optimal locations for conversion of land into forestry.

Keywords: carbon, valuation, livewood, timber, soil, GIS, Wales.

Introduction

The global process of industrialisation over the past 2 centuries has, in more recent years, led to detectable increases in the concentration of insulating greenhouse gases (GHGs). This situation has coincided with increases in global temperatures which are expected to continue rising with GHG emissions for the foreseeable future. Best estimates suggest that global surface air temperature will rise by more than 1°C between 1990 and 2050 and by 2°C in less than a century from the present day (IPCC, 1996a; Hulme and Jenkins, 1998). The consequences of such climatic change are uncertain but potentially highly adverse (IPCC, 1996b; Parry *et al.*, 1999).

The advent of the global warming issue has raised interest in the potential for using forestry as a way of reducing atmospheric concentrations of carbon dioxide (Sedjo *et al.*, 1995; Cannell *et al.*, 1999), the gas which in absolute terms provides the largest contribution to global insulation.[1] This paper attempts to model and value changes in carbon storage induced by the afforestation of previously unplanted land. In doing so, we model carbon storage in trees and forest soils and its emission from timber products and waste (and certain soils). Species effects are considered by examining a representative softwood (Sitka spruce; *Picea sitchesis* (Bong.) Carr.) and hardwood (beech; *Fagus sylvatica* L.) species.

In order to fully capture the temporal nature of the process under consideration, the analysis is extended to cover a long

Email of corresponding author: i.bateman@uea.ac.uk

[1] It should be stressed that this can only be a marginal stopgap measure. Afforestation alone would be a grossly inadequate response to global warming (Nowak, 1993).

* Corresponding author

† School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK

‡ Centre for Social and Economic Research on the Global Environment (CSERGE), University of East Anglia and University College London

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time horizon (1000 years), with post-felling replanting being assumed. Furthermore, so as to be compatible with the economic analyses used by relevant decision makers (e.g. IPCC, 1996b), the 'net carbon flux' (i.e. the net change in carbon storage) assessment produced by our model is monetised using estimates of the value of sequestered carbon. This monetisation also permits us to consider the impact of discounting upon estimated values of net carbon flux.

Finally, the paper adopts a novel methodology in that sequestration value models are applied to data concerning spatial variations in tree growth and soil type distribution held within a geographical information system (GIS). The GIS is then used to produce maps of the value of predicted carbon sequestration (taking into account variations in tree growth rates and soil carbon uptake and allowing for eventual carbon liberation from timber products) for a large case-study area (the entire country of Wales). The resultant valuation maps can be readily incorporated within cost-benefit decisions regarding optimal locations for conversion of land into forestry such as the map-based approach to the identification of sites for new woodlands announced by the Countryside and Forestry Commissions (1996).

The paper begins with a review of existing literature. This considers, in brief, the valuation of sequestered carbon before assessing work on the storage of carbon in trees or soils and its eventual liberation from timber products. Next we present a brief overview of our research methodology. This is implemented to model carbon flux in both Sitka spruce and beech trees and their products. We then consider the impacts of afforestation upon soil carbon levels and synthesise our various analyses. In addition, we apply GIS techniques to produce carbon sequestration potential maps and corresponding monetary value maps. Finally, we present conclusions and consider the wider implications of our findings for land-use policy-making.

Literature review

The value of carbon emissions and sequestration

The pioneering work on the economic value of carbon emission and sequestration is that of Nordhaus (1991, 1992) who developed a model of optimal economic growth under climate change which yields implicit estimates of carbon storage value. These models have provoked a number of critical responses (Daily *et al*, 1991; Cline, 1992) focusing upon the structure and assumptions made. A more sophisticated non-linear, stochastic model was developed by Fankhauser (1994, 1995). This model consists of components examining: future emissions; atmospheric concentration; radiative forcing; temperature rise; annual damage; costs of sea-level rise protection; and discounting.

Such a complex model yields carbon sequestration values for a variety of scenarios. However, Fankhauser's best estimate of these values rises from \$20·3/*t*C in 1991, to \$22·8, \$25·3 and \$27·8/*t*C in the subsequent three decades to 2021 so reflecting the predicted increase in greenhouse damages during that period.

Other carbon sequestration estimates can be found in the literature and clearly different unit values will produce contrasting overall totals. However, the Fankhauser model is extensively relied upon in the report by the Intergovernmental Panel on Climate Change into the socio-economic impacts of the greenhouse effect (IPCC, 1996b). Accordingly, we feel justified in adopting the above values for use in this study. However, as our analysis extends long beyond the 2021 horizon considered by Fankhauser, an assumption had to be made regarding carbon sequestration values beyond that point. From a review of the literature it became apparent that simply extending the trend of Fankhauser's estimates would be incorrect as this would ignore any greenhouse abatement measures. Given the lack of any firm evidence it was decided to treat the final (2021) carbon value as an equilibrium level extending throughout the remainder of our analysis. While this is clearly a key assumption it was felt that no other course of action was justified given the uncertainty that exists within the literature.[2]

[2] It should be noted that the process of discounting very greatly diminishes the impact of this assumption. In effect it is the initial period (for which we have published valuation estimates) which is of paramount importance.

Carbon storage in trees

Calculating carbon storage

Existing timber yield models provide information on the merchantable volume (MV) of trees throughout a rotation (Edwards and Christie, 1981). MV only concerns the saleable volume of a tree but may be related to total woody volume (TWV) by allowing for branchwood, roots, etc. (Corbyn *et al.*, 1988; Matthews, 1991). This in turn is correlated with the trees dry weight (DW) via its specific gravity (SG). SG varies substantially across species, being about 0·33 for Sitka spruce and 0·56 for beech (Lavers, 1969). However, the proportion of DW which is carbon is roughly constant at about 49% (Matthews, G., 1993).

While timber yield and species effect carbon storage, forestry management also has a major impact. The move from unmanaged woodland to managed plantation results in a significant increase in MV yield (Bateman, 1996). However, profit maximisation results in smaller stems being periodically removed (thinned) so as to promote the growth of a reduced number of larger, high value, trees. This alone causes a substantial reduction in potential carbon storage (Matthews, 1992). Furthermore, the practice of discounting leads both to high-yield stands being felled on a shorter rotation than those in slower growing areas, and to all trees being cut before they attain their maximum carbon carrying capacity.

Figure 1 illustrates the impact of management upon three stands of Sitka spruce growing at yield classes (*YC*) 8, 16 and 24 (where *YC*8 denotes a stand producing on average 8 m^3/year/ha over an optimal rotation). Yield class models (Edwards and Christie, 1981) are combined with data on carbon storage in Sitka spruce (Cannell and Cape, 1991, Matthews, R. W., 1993) to plot out carbon storage curves for both thinned and unthinned (denoted t*YC* and u*YC*, respectively) stands.[3] Unthinned stands produce a characteristic S-shaped carbon storage curve. Thinned stands follow this curve until the date of first thinning (*TD*1), which arrives sooner for faster growing stands (as does the date of felling; *F*).[4] Following *TD*1 the t*YC* curve becomes much more shallow than its u*YC* counterpart. Furthermore, the relatively early *F* terminates the former curve considerably before that for unmanaged crops. Therefore, while plantation forests may represent a new carbon sequestration gain over previous land uses, thinned stands sequester less carbon than unthinned crops.

Carbon liberation from wood products

Once a tree is felled its fixed carbon store begins to be liberated back to the atmosphere as CO_2. This liberation may occur quite quickly if the wood is used as fuel, left to decompose (e.g. small trimmings), or used for short term purposes (e.g. paper). The carbon liberation rates resulting from these various end-uses can vary substantially.[5]

An examination of the impact of end use upon carbon liberation is given in Thompson and Matthews (1989a,b) and Matthews (1995) who show that end use is the major non-soil determinant of the speed of liberation. In order to incorporate this within a general carbon flux model information regarding the proportion of wood allocated to each end use is required. Data gathered from a variety of sources are summarised in Table 1 which provides a breakdown of 1991/1992 UK domestic production data divided into softwood and hardwood species.

[3] Note that a number of studies have considered a possible feedback loop between the greenhouse effect and tree growth whereby higher atmospheric CO_2 concentrations lead to enhanced timber yield (Eamus and Jarvis, 1989; D'Arrigo *et al*, 1987; Cannell and Cape, 1991). Although there is no clear consensus regarding effects in our study area this debate suggests that our model may produce lower bound estimates of carbon sequestration.

[4] Figure 1 and underlying calculations use a 5% discount rate to determine TD1 and F. As the discount rate is increased so TD1 and F decrease. For a full sensitivity analysis see Bateman (1996).

[5] Matthews (1992, 1993) also considers the carbon emissions which can accrue in the course of forest management (e.g. emissions from vehicles and machinery) and product manufacturing (where emissions may be substantial for capital intensive products such as paper) while he and Marland and Marland (1992) note that where timber is used as fuel and substitutes for existing high-carbon fossil fuels, a further net benefit will accrue. For discussion of these issues in relation to our analysis see Bateman (1996).

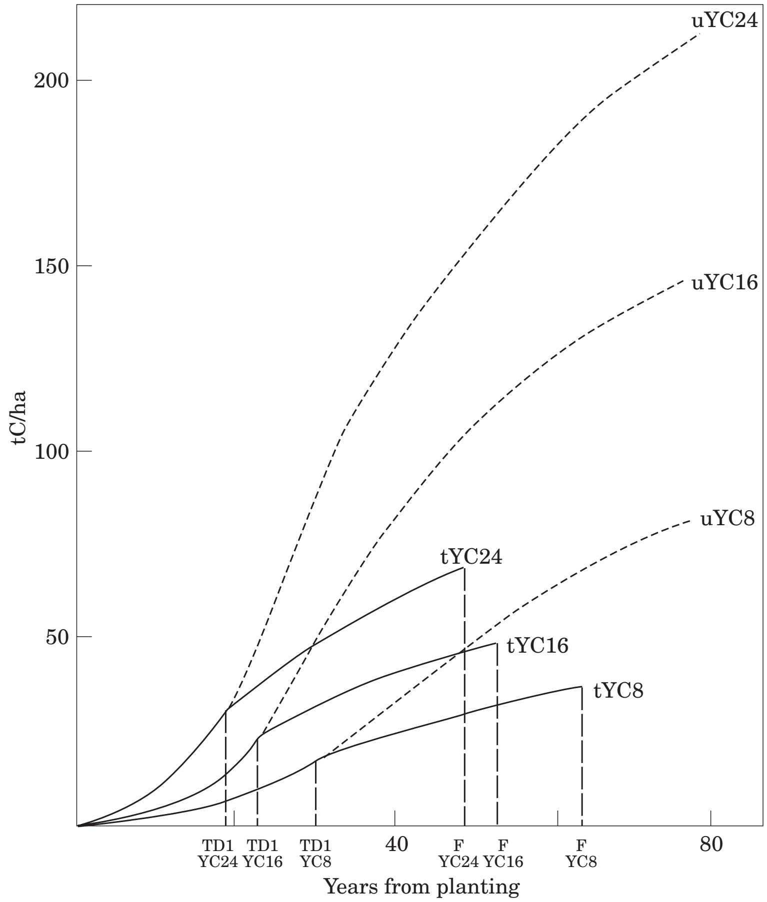

Figure 1. Total carbon storage curves for unthinned and thinned Sitka spruce (discount rate=5%). TD1=date of first thinning (∴TD1 YC24=date of first thinning for yield class 24 Sitka spruce). Dashed line (and solid line prior to TD1) =total carbon stored in unthinned live wood (uTWCS). Solid line (after TD1) =total carbon stored in thinned live wood (tTWCS). ∴uYC24=uTWCS for YC24 Sitka spruce. ∴tYC24=tTWCS for YC24 Sitka spruce.

Table 1. Softwood and hardwood end uses for UK domestic production

Product	Softwood				Hardwood			
	′000 m^3	% of total	Modal liberation year (from felling)	95% carbon liberation (years from felling)	′000 m^3	% of total	Modal liberation year (from felling)	95% carbon liberation (years from felling)
Sawn logs	2925	49·292	70	150	558	49·512	150	300
Board	1154	19·447	15	40[a]	87	7·720	15	40
Paper	936	15·774	1	5	138	12·245	1	5
Mining	23	0·004	40	200	0	0·000	40	200
Fuel[b]	142	2·393	1	5	114	10·115	1	5
Other[b]	142	2·393	15	30	114	10·115	40	80
Bark	612	10·313	1	5	116	10·292	1	5
Total	5934	100	—	—	1127	100	—	—

[a] Based on this being almost exclusively particleboard as per statistics given in Forestry Commission (1992).
[b] Based on assumption that roughly 50% of ‘Other Industrial Wood’ (FICGB, 1992) is fuelwood, as per statistics given in Forestry Commission (1992).
Sources: Carbon liberation data from Cannell and Cape (1991) and Thompson and Matthews (1989a,b). Production data from FICGB (1992) and Forestry Commission (1992); Whiteman (1993) pers. comm.

Carbon flux in soils

Determinants of soil carbon levels

All soils contain a certain natural level of carbon. This generally consists of decaying soil organic matter (SOM) although a small amount (usually less than 5%) is held as soil organisms (Jenkinson, 1988). On uncultivated soils a number of natural factors influence soil carbon content including: soil texture; moisture; temperature; and the lignin content of the natural plant cover (Parton *et al*., 1987). In lowland areas the quantity and type of organic material returned to the soil as dead plant tissue is, in the long run, balanced by the decomposition of SOM and release of CO_2 and water (Jenkinson, 1988). Such soils are therefore in carbon balance. However, soils which are poorly drained and frequently waterlogged (typically in upland areas) exhibit very slow decomposition rates (Edwards, 1975; Harrison *et al*., 1995). Where organic deposition exceeds decomposition peat is formed (Askew *et al*., 1985). Such soils have no predetermined upper limit for SOM levels (although average levels can be calculated) and consequently, may have very high carbon contents (Adger *et al*., 1992).

On cultivated soils a variety of additional factors may influence soil carbon levels including: tillage regime; crop selection; addition of fertiliser and organic matter; irrigation; stubble burning; etc. (Parton *et al*., 1987). The transition from uncultivated to intensive arable land, particularly where bare fallow rotation systems are used, is commonly associated with significant losses in SOM (Tiessen *et al*., 1982; Jenkinson, 1988) and has substantially contributed to increases in stratospheric CO_2 concentrations (Post *et al*., 1990).

Afforestation and soil carbon

The major determinants of soil carbon change under afforestation are soil type and prior usage, from which we can estimate present carbon levels and predict long term equilibrium levels under afforestation. Adger *et al*. (1992) report equilibrium soil carbon levels for a variety of soils and land uses. This work was combined with the views of subject experts to produce the estimates in Table 2 of the range of carbon storage changes that could occur through afforestation of various soil types in upland and lowland areas.

Table 2 indicates that afforestation is generally synonymous with long term rises in soil carbon storage levels and that these increases are liable to be somewhat larger in lowland sites due to a variety of factors including the prevalence of more intensive prior agricultural land uses (Cannell and Dewar, 1995; Cannell *et al*., 1999). The one clear exception to this trend arises where planting occurs on previously unplanted peat soils. Here, the extremely high prior levels of soil carbon are substantially reduced by the planting and tree growth processes (Braekke, 1987; Cannell *et al*., 1993; Harrison *et al*., 1995; Davidson and Grieve, 1995; Cannell *et al*., 1999). Indeed Adger *et al*. (1992) calculate that a mixture of planting upon peat soils and the replacement of old growth broadleaf woodlands with conifer plantations

Table 2. Post-afforestation changes in equilibrium soil carbon storage levels for various soils previously under grass (*t*C/ha): upland and lowland sites

Soil type	Upland sites			Lowland sites		
	Under grass	Under trees	Change	Under grass	Under trees	Change
Peat	1200	450	(750)	n/a	n/a	n/a
Humic gley	180–400	250–450	50–70	180–350	180–450	0–100
Podzol	200–400	250–450	50	100–200	100–450	0–250
Brown earths	n/a	n/a	n/a	100–120	100–250	0–130
Humic stagno podzol	180–400	250–450	50–70	120–350	120–450	0–100
Stagnogley	170–400	170–450	0–50	100–120	100–450	0–330

Use prior to afforestation is assumed to be long established agricultural pasture (dairy, cattle or sheep). Brackets indicate negative amounts.

We are grateful to Professor David Jenkinson (Rothamsted), Professor Steven McGrath (Rothamsted) and Dr Robert Sheil (University of Newcastle upon Tyne) for conversations regarding the formulation of these estimates.

n/a, not applicable as soil type not common at this altitude.

has resulted in post-war forestry being a net emitter of carbon.

Given the impact of discounting upon subsequent valuations of carbon flows, the shape of the soil carbon flux function is clearly important. The general consensus is that marginal soil carbon flux is relatively high in the years following initial planting and declines smoothly to reach equilibrium over an extended period (Cannell and Milne, 1995). Robert Shiel (1994, pers. comm.) suggests that roughly 95% of the net change in soil carbon will occur within 200 years of planting. Both Matthews, R. W. (1993) and Dewar and Cannell (1992) present total soil carbon storage curves which have negative exponential shapes. Combining these pieces of information allows us to model both total and marginal soil carbon storage curves.

Methodology

Functional relationships were estimated for three model elements: (1) carbon storage in live wood; (2) carbon emission from thinnings and wood products; (3) carbon storage or release (as appropriate) from afforested soils. Functions for both Sitka spruce and beech were estimated on a per hectare per annum basis.

To allow for: the long time periods involved in these various functions (e.g. rotations of more than 100 years); the overlapping of functions (e.g. the wood product liberation curve from an initial rotation will not have run to zero before the second rotation is felled and a second such curve commences); and the impact of discounting (e.g. low discount rates will produce significant non-zero discount factors far into the future), it was decided that the analysis should be extended to cover a 1000-year time period with replanting assumed to follow within a year of felling throughout this period. This allows the calculation of full equilibrium carbon flux effects (although the subsequent process of discounting places more emphasis upon short-term impacts).

Once functions have been estimated the per hectare net carbon storage (or emissions) for a selected species in any given year were calculated as follows: (1) The carbon storage function for live trees of a given species and yield class was applied from planting to felling date (*F*). This function was restarted after each F to simulate replanting. (2) Emissions from thinnings and products deriving from prior rotations were summed and subtracted from (1). Note that the emissions functions from any given rotation may extend beyond the lifespan of the next rotation, i.e. such functions overlap so that in any given year there may be emissions from more than one previous rotation. However, it was assumed that there were no emissions prior to first thinning of the initial rotation. (3) The net soil carbon flux function is applied from the date of first planting. Predicted sequestration (or emission) is added (subtracted) from the sum of (1) and (2) to yield the marginal net annual change in carbon storage.

The above calculations were performed for each year in our 1000-year analysis. The process was then repeated for both species (and all *YC*s) under consideration. Valuation of the marginal net annual change in carbon storage was achieved by reference to the relevant unit values for each year given by Fankhauser (1994). We thereby derived a stream of marginal carbon storage values for each species, and within that each *YC*, under consideration. These were undiscounted values to which any desired discount rate could be applied to calculate net present value (*NPV*) or annuity equivalents as required (for examples of such calculations, see Gittinger, 1982).

As a final step a geographical information system (GIS) was used to apply these various valuations to existing maps of predicted *YC* for the two species under consideration (Bateman and Lovett, 1998, 2000a). These maps showed estimated *YC* for a large study area, the entirety of Wales, where forestry is a viable alternative to agricultural land uses. In doing so, maps of livewood carbon storage value were produced. The GIS was also used to relate our soil carbon values to a soil-type map of the same area so producing a soil carbon-flux values map. By overlaying these a joint live wood and soil carbon sequestration value map was obtained. Finally, by subtracting the thinnings and wood product emissions levels for the relevant species, a map of the overall net carbon-flux value for a given species for all locations in our case-study area was generated. Such a map permits ready identification of those areas which, if afforested, would yield optimal carbon storage values.

Modelling carbon storage in trees

Carbon storage in sitka spruce live wood

As discussed above, carbon sequestration in an unthinned standing crop follows a roughly S-shaped time trend. Figure 1 illustrated that in thinned crops the total carbon storage curve is non-linear, following the unthinned S-shaped growth curve up to $TD1$ after which a significantly shallower path is followed until the rotation ends at F. However, both $TD1$ and F can be shown to be functions of yield class and discount rate (Bateman, 1996; remember that the discount rate is held constant in Figure 1). Carbon-storage modelling therefore needs to reflect this complex interaction of diverse factors.

While a simple approach to this problem would be to use long term equilibrium storage levels (such as those reported by Dewar and Cannell, 1992) this would ignore the low levels of carbon storage occurring in the early years after initial planting. Given that storage values are to be discounted, this overstatement of early sequestration could result in a substantial upward bias in benefit estimates. A superior approach is suggested by Pearce (1991, 1994) who adopted a negative exponential total carbon storage function. While clearly better than a simple average, this approach still results in some overstatement of early storage rates as the marginal storage curve implied by the differential of a negative exponential shows annual net storage being highest during the initial planting year and declining thereafter.

To avoid these problems explicit consideration was given to the S-shaped curve which is total carbon storage in unthinned live wood (u$TWCS$). This can be modelled as the cubic given in Equation (1):

$$\mathrm{u}TWCS_{\mathrm{iYC}} = \beta_{1\mathrm{iYC}} + \beta_{2\mathrm{iYC}}t + \beta_{3\mathrm{iYC}}t^2 + \beta_{4\mathrm{iYC}}t^3 \quad (1)$$

where:

i = species (for Sitka spruce i = SS; for beech i = BE)

YC = (for i = 1) 4, 6, 8 . . . 26

t = years from planting (t = 0, 1, 2 . . . F)

A priori one would expect $\beta_1 = 0$; $\beta_2 > 0$; $\beta_3 > 0$; and $\beta_4 < 0$. In order to estimate Equation (1) data regarding UTWCS for YC12 Sitka spruce were taken from Matthews, R. W. (1992, 1993). Initial investigations confirmed that an optimal statistical model based on Equation (1) gave estimates of β_1 which were not significantly different from zero (as per expectations) and so this element was dropped from our final model which is reported as Equation (2) (figures in brackets in this and subsequent equations are t-statistics).

$$\begin{aligned} \mathrm{u}TWCS_{\mathrm{SS,12}} &= \underset{(4{\cdot}40)}{0{\cdot}43727t} + \underset{(28{\cdot}09)}{0{\cdot}10747t^2} \\ &\quad \underset{(-29{\cdot}21)}{-0{\cdot}0010267t^3} \qquad (2) \\ R^2 &= 99{\cdot}9\% \qquad N = 81 \end{aligned}$$

It is not surprising that given the predictability of tree growth patterns, the model reported in Equation (2) fits the data extremely well. All parameter estimates are statistically significant[6] and coefficients have expected signs and magnitudes.

Cannell and Cape (1991) show that, within a given species, carbon storage varies linearly across YC. We can therefore derive a species specific YC adjustment factor A_{iYC} which allows us to adjust from the YC of our baseline data ($YC12$) to any other Sitka spruce YC. Using the data given in Cannell and Cape (1991) the adjustment factor given in Equation (3) was derived:

$$A_{\mathrm{SS,YC}} = 0{\cdot}08333\ YC \quad (3)$$

A generalised function for u$TWCS_{\mathrm{iYC}}$ for i = SS and any YC can then be derived as per Equation (4):

$$\mathrm{u}TWCS_{\mathrm{SS,YC}} = A_{\mathrm{SS,YC}} {}^{*} \mathrm{u}TWCS_{\mathrm{SS,12}} \quad (4)$$

The value of these functions will continue to rise until $t = F$. However, as noted, F is

[6] By convention we use a significance level of $P = 0{\cdot}05$ throughout. For further details of precise significance levels see Bateman and Lovett (2000b).

a complex and species specific function of both the discount rate (r) and YC. This relationship was investigated using YC/discount rate analysis of optimal felling dates which is summarised in the Appendix to this paper. Using these data, our resultant best fit model for Sitka spruce was as shown in Equation (5) where the discount rate (r) is expressed as a decimal:

$$F_{\mathrm{SS,YC}} = \underset{(32{\cdot}67)}{114{\cdot}43} \; \underset{(-6{\cdot}25)}{-997{\cdot}3r} \; \underset{(3{\cdot}62)}{+7167r^2} \; \underset{(-9{\cdot}21)}{-2{\cdot}8657YC} \; \underset{(5{\cdot}79)}{+0{\cdot}05919YC^2} \quad (5)$$

$R^2 = 96{\cdot}6\%$ $\quad N = 39$

Equation (5) fits the data extremely well and all parameters are statistically significant. It shows that F declines with r and YC, although the significance of the quadratic terms indicates that this is not a simple straight-line relationship.

To move from unthinned to thinned crops one first needs to estimate $TD1$. The yield models reported in Edwards and Christie (1981) show a clear relationship between $TD1$, F and YC. Table 3 summarises data for the relevant thinned Sitka spruce models and indicates that $TD1$ declines as YC increases and F falls.

One simple method of representing this relationship is to model the ratio $TD1:F$ as a function of YC as shown in Equation (6):

$$\mathrm{RATIO}TD1_{\mathrm{SS,YC}} = \underset{(32{\cdot}21)}{0{\cdot}48149} - \underset{(-5{\cdot}27)}{0{\cdot}0049061YC} \quad (6)$$

Table 3. Date of first thinning (TD1) for Sitka spruce yield models

Yield class (YC)	Year of first thinning[a] (TD1)	Optimal felling year[b] (F)	Ratio (TD1/F)
6	33	68	0·485
8	29	67	0·433
10	26	64	0·406
12	24	58	0·414
14	22	54	0·407
16	21	51	0·412
18	20	50	0·400
20	19	50	0·380
22	18	49	0·367
24	18	48	0·375

2 m spacing: no delay in thinning; $r = 0{\cdot}05$ throughout.
[a]Source: Edwards and Christie (1981).
[b]Source: Bateman (1996); see Appendix for summary.

where:

$$\mathrm{RATIO}TD1 = \text{Ratio of } TD1 \text{ to } F$$

$R^2 = 77{\cdot}7\%$ $\quad N = 9$

While the number of observations used in Equation (6) is small, individual t-statistics are significant. Collection of further data would clearly be highly desirable and should be considered a research priority. However, in the absence of such data the model represents our best estimate of this relationship and $TD1$ can then be calculated for any given YC by manipulation of Equation (6) as shown in Equation (7):

$$TD1_{\mathrm{SS,YC}} = [0{\cdot}4815 - (0{\cdot}004906^{*}YC)]^{*}F_{\mathrm{SS,YC}} \quad (7)$$

Once thinning commences total tree carbon storage falls progressively below that predicted by the uTWCS function. Using data from Matthews, R. W. (1991, 1992, 1993) this proportion can be measured as the Thinning Factor (TF) listed in the final column of Table 4.

Statistical investigation showed that TF_{SS} could be well predicted by the natural log of t^* where $t^* = t - TD1$. Equation (8) takes the data given in Table 4 to give our best fitting model of $\mathrm{TF}_{\mathrm{SS}}$ (note that where $t^* < 0$ (i.e. before $t = TD1$) TF is constrained to equal 1):

$$TF_{\mathrm{SS}} = \underset{(37{\cdot}90)}{1{\cdot}000} - \underset{(-13{\cdot}41)}{0{\cdot}1158} \ln(t^*) \quad (8)$$

$R^2 = 96{\cdot}3\%$ $\quad N = 8$

Total live wood tree carbon storage for thinned stands of Sitka spruce ($tTWCS_{\mathrm{SS,YC}}$) can then be calculated as per Equation (9):

$$tTWCS_{\mathrm{SS,YC}} = uTWCS_{\mathrm{SS,YC}}{}^{*}TF_{\mathrm{SS}} \quad (9)$$

The total carbon storage value from Equation (9) increases each year from planting until felling after which replanting is assumed to follow within one year and the level returns to zero and restarts its growth path. Given that this model is discontinuous it cannot readily be differentiated. As a consequence marginal carbon storage was calculated by solving Equation (9) iteratively for each year in our time series and calculating the annual addition as storage.[7]

[7] Care was taken to ensure that restarting of the growth path following felling was not recorded as a fall in tree carbon storage. All carbon liberation is captured by the function relating to felling waste and timber products.

Table 4. Thinning factor (TF) for Sitka spruce YC12

Years after date of first thinning ($t^*=t-\mathrm{TD1}$)	Total unthinned tree carbon storage (*t*C/ha) ($\mathrm{uTWCS_t}$)	Total thinned tree carbon storage (*t*C/ha) ($\mathrm{tTWCS_t}$)	Reduction in total potential tree carbon storage arising from thinning (*t*C/ha)	Thinning factor ($\mathrm{TF_{SS}}$) $\left[\mathrm{TF}=\frac{\mathrm{TWCS_t}}{\mathrm{uTWCS_t}}\right]$
0	50	50	0	1·00
5	67	55	12	0·83
10	84	61	23	0·73
15	109	71	38	0·65
20	133	82	51	0·62
30	169	95	74	0·56
40	192	107	86	0·56
50	206	116	90	0·56
60	211	120	91	0·56

Source: based on data by Matthews, R. W. (1991, 1992, 1993).

Carbon storage in beech live wood

The modelling of carbon storage in beech live wood followed the same principles as used for Sitka spruce and therefore will only be described in brief. Beech was chosen as the hardwood for which data were most available in the underlying yield class models (Bateman and Lovett, 1998, 2000a). However, information regarding carbon sequestration in beech is somewhat sparser than for its coniferous cousin, such that our analysis is based upon the estimates for oak (*YC*4) given in Dewar and Cannell (1992) adjusted by consulting the *YC*4 model for beech given in Edwards and Christie (1981). This exercise reinforced the findings of Matthews, G. (1993) who suggested that, within *YC* bands, carbon storage for oak and beech are similar. Using this approach, observations on the S-shaped unthinned carbon storage curve $\mathrm{u}TWCS_{\mathrm{BE},4}$ were recorded for use in the estimated model which is reported in Equation (10):

$$\begin{aligned}\mathrm{u}TWCS_{\mathrm{BE},4} = {} & \underset{(2{\cdot}17)}{0{\cdot}2414t} + \underset{(13{\cdot}73)}{0{\cdot}030752t^2} \\ & \underset{(-13{\cdot}24)}{-0{\cdot}00014252t^3} \end{aligned} \qquad (10)$$

$$R^2=99{\cdot}9\% \qquad N=26$$

As with Sitka spruce, the model of total carbon storage in unthinned beech live wood fits the data very well. All parameter estimates are significant and coefficients have expected signs and magnitudes (the latter differing logically from those of the Sitka spruce model).

Following our methodology as before, a beech adjustment factor ($A_{\mathrm{BE,YC}}$) can be calculated so as to allow comparison between *YC* as per Equation (11) (note that when $YC=4$ then $A_{\mathrm{BE,4}}=1{\cdot}0$).

$$A_{\mathrm{BE,YC}}=0{\cdot}25YC \qquad (11)$$

A generalised function for $\mathrm{u}TWCS_{\mathrm{i,YC}}$ for $i=BE$ and any *YC* can then be derived as per Equation (12):

$$\mathrm{u}TWCS_{\mathrm{BE,YC}}=A_{\mathrm{BE,YC}}{}^*\mathrm{u}TWCS_{\mathrm{BE,4}} \qquad (12)$$

The felling date, *F*, for beech is then estimated as a function of *r* and *YC* using the data for beech summarised in the Appendix to this paper to produce the model reported in Equation (13).

$$\begin{aligned}F_{\mathrm{BE,YC}} = {} & \underset{(20{\cdot}78)}{173{\cdot}89} - \underset{(-18{\cdot}07)}{1901{\cdot}4r} + \underset{(11{\cdot}99)}{8870{\cdot}8r^2} \\ & \underset{(-2{\cdot}25)}{-5{\cdot}387YC} + \underset{(1{\cdot}47)}{0{\cdot}2500YC^2} \end{aligned} \qquad (13)$$

$$R^2=97{\cdot}8\% \qquad N=31$$

Equation (13) fits the data very well and reconfirms the relationships noted with the Sitka spruce data. All estimates are statistically significant with the exception of the YC^2 term which has $P=0{\cdot}152$. While this is in itself insignificant the term is retained both for comparison with our Sitka spruce model and because it yields a slight improvement in adjusted model fit.

The year of first thinning (*TD*1) is also estimated as before. Table 5 presents the data for this analysis. As can be seen, the lack of

Table 5. Date of first thinning for beech yield models

Yield class (YC)	Year of first thinning[a] (TD1)	Optimal felling year[b] (F)	Ratio (TD1/F)
4	35	81	0·432
6	30	75	0·400
8	25	71	0·352
10	25	69	0·362

1·2 m spacing, no delay in thinning, $r=0{\cdot}05$ throughout.
[a]Source: Edwards and Christie (1981).
[b]Source: Bateman (1996); see Appendix for summary.

variation in *YC* for British beech considerably reduces the number of observations available.

The data given in Table 5 is then used to estimate $\mathrm{RATIO}TD1_{\mathrm{BE,YC}}$ as per Equation (14):

$$\mathrm{RATIO}TD1_{\mathrm{BE,YC}}=\underset{(15{\cdot}29)}{0{\cdot}47666}\;\underset{(-3{\cdot}03)}{-0{\cdot}012861YC} \qquad (14)$$

$$R^2=82{\cdot}1\% \qquad N=4$$

The small number of observations underpinning Equation (14) contributes to the fact that our single explanatory variable is only significant at $P<0{\cdot}10$ and again the collection of data can be seen as a priority. Nevertheless the overall fit is satisfactory and $TD1$ can be calculated for any given *YC* as per Equation (15):

$$TD1_{\mathrm{BE,YC}}=[0{\cdot}47666-(0{\cdot}012861^*YC)]^*F_{\mathrm{SS,YC}} \qquad (15)$$

Dewar and Cannell (1992) do not report any information from which a thinning factor (TF_{BE}) might be estimated. However, an estimate for this can be obtained by examining the beech yield models of Edwards and Christie (1981). These show that TF_{BE} is very similar to TF_{SS} as listed in Table 4 in that both follow a roughly logarithmic pattern, falling rapidly once thinning commences and then tending towards some fairly stable constant after about 30 years. One can therefore assume an approximate equality between these relationships as detailed in Equation (16):

$$TF_{\mathrm{BE}}=TF_{\mathrm{SS}}=1-0{\cdot}1158\ln(t^*) \qquad (16)$$

where:

$$t^*=t-TD1$$

and

$$TF_{\mathrm{BE}}=1 \text{ for all } t^*<0$$

Total live wood tree carbon storage for thinned stands of beech ($\mathrm{t}TWCS_{\mathrm{BE,YC}}$) can then be calculated as per Equation (17):

$$TWCS_{\mathrm{BE,YC}}=\mathrm{u}TWCS_{\mathrm{BE,YC}}{}^*TF_{\mathrm{BE}} \qquad (17)$$

Modelling carbon liberation from felling waste and timber products

Carbon liberation from felling waste and timber products was modelled using the same methodology for both Sitka spruce and beech. End use has a major impact upon overall carbon flux and Table 1 indicates that, for all but the shortest lifespan products and felling wastes, carbon liberation appears to follow a roughly normal distribution. Conversely, short-lifetime products (where virtually all carbon is liberated within 5 years of felling) have their highest liberation rates during the year of felling after which rates fall swiftly over time. Assuming a downward sloping linear trend for the latter and a normal distribution centred upon the modes listed in Table 1 for all other products, we obtain the product specific carbon liberation schedules illustrated in Figure 2 for Sitka spruce and Figure 3 for beech. These are expressed as a proportion of the total amount of carbon stored by 1 ha of live wood during the course of a full rotation.

Figure 2(a)–(e) shows carbon liberation distributions for Sitka spruce products and waste categorised according to longevity. Figure 2(f) sums all these to produce an overall liberation distribution which shows that emissions are highest in the felling year and then fall rapidly to some low positive amount which then gradually declines over an extended period. A number of statistical models were fitted to these data including exponential and logarithmic functional forms. The optimal model is reported in Equation (18) with predictions being illustrated in Figure 2(g).

$$SUMLIBSS=\underset{(6{\cdot}30)}{0{\cdot}0017146}\;\underset{(36{\cdot}53)}{+0{\cdot}110363ETRENDSS} \qquad (18)$$

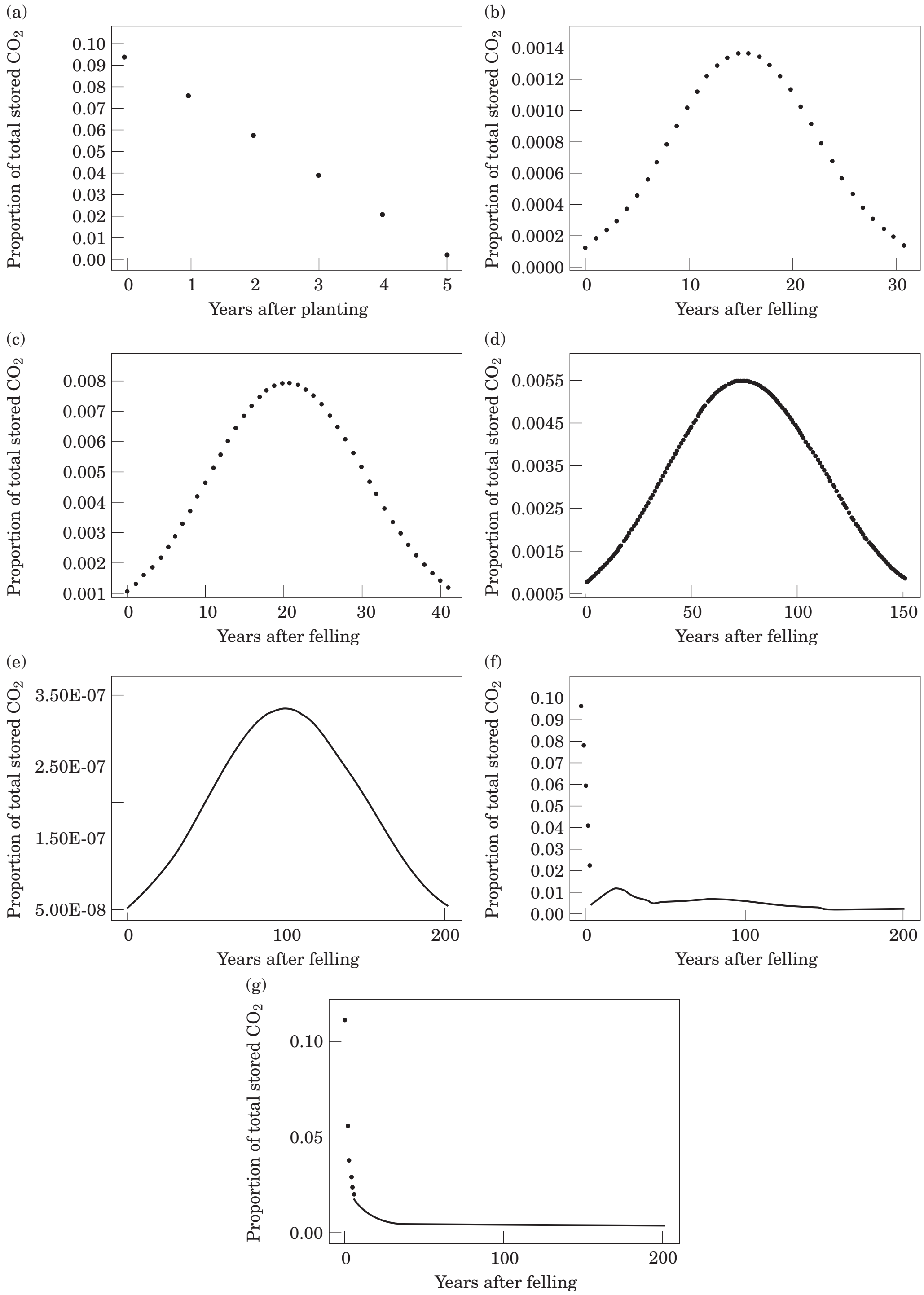

Figure 2. Annual carbon liberation distributions for products and waste expressed as a proportion of total carbon sequestration in wood from one rotation of Sitka spruce. (a) Annual CO_2 liberation from short lifetime (5 year) products (paper, fuel) and waste as proportion of total liberation from 1 ha Sitka spruce. (b) Annual CO_2 liberation from medium lifespan (30 year) products (non-fuel other industrial) as a proportion of total liberation from 1 ha Sitka spruce. (c) Annual CO_2 liberation from medium lifespan (40 year) products (board) as a proportion of total liberation from 1 ha Sitka spruce. (d) Annual CO_2 liberation from long lifespan (150 year) products (sawn wood) as a proportion of total liberation from 1 ha Sitka spruce. (e) Annual CO_2 liberation from very long lifespan (200 year) products (mining) as a proportion of total liberation from 1 ha Sitka spruce. (f) Annual CO_2 liberation from all products and waste as a proportion of total liberation from 1 ha Sitka spruce. (g) Predicted annual CO_2 liberation from all products and waste as a proportion of total liberation from 1 ha of Sitka spruce.

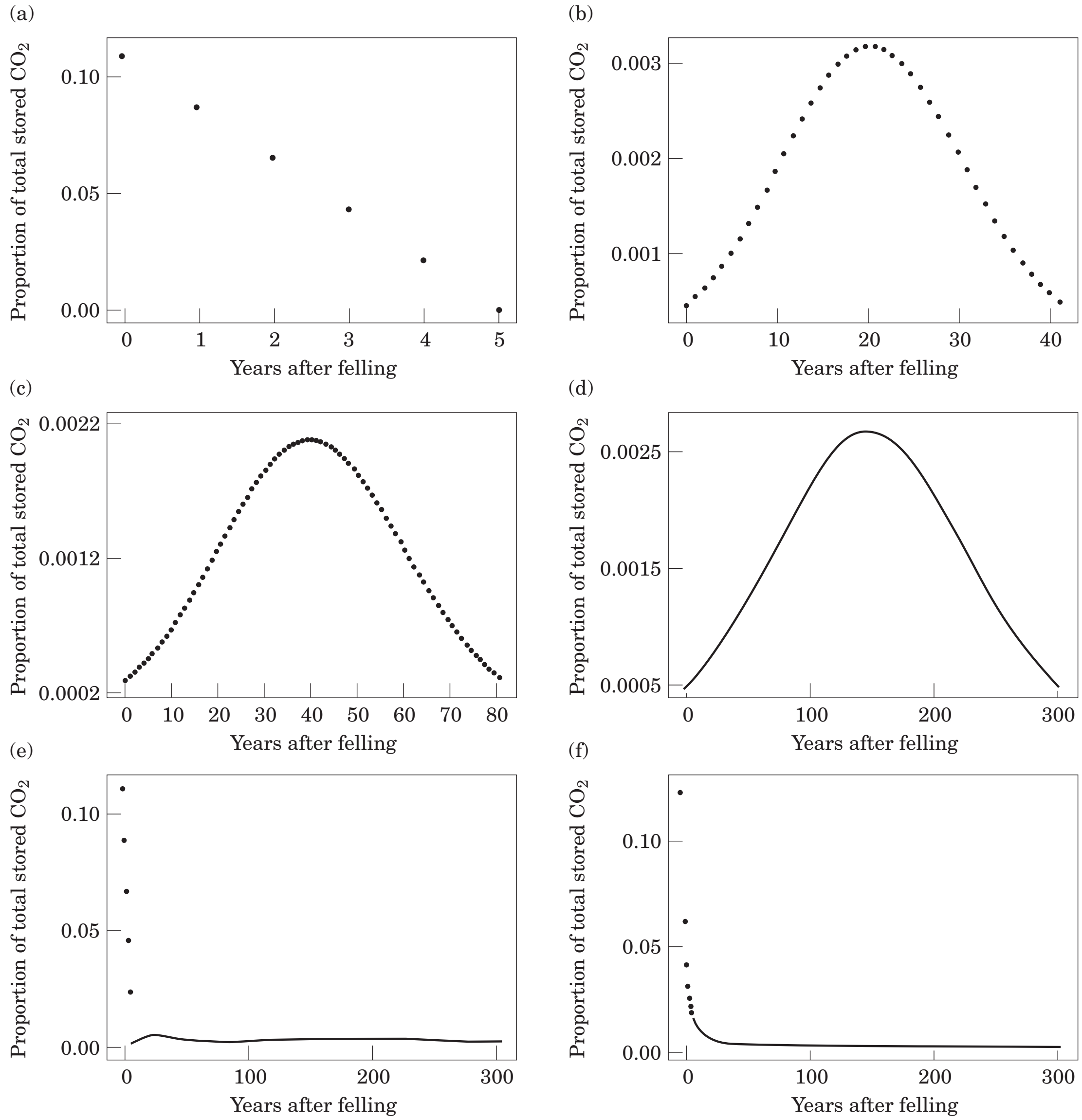

Figure 3. Annual carbon liberation distributions for products and waste expressed as a proportion of total carbon sequestration in wood from one rotation of beech. (a) Annual CO_2 liberation from short lifespan (5 year) products (paper fuel) and waste as proportion of total liberation from 1 ha beech. (b) Annual CO_2 liberation from medium lifespan lifespan (40 year) products (board) as a proportion of total liberation from 1 ha beech. (c) Annual CO_2 liberation from long lifespan (80 year) products (non-fuel other industrial) as a proportion of total liberation from 1 ha beech. (d) Annual CO_2 liberation from very long lifespan (300 year) products (sawn wood) as a proportion of total liberation from 1 ha beech. (e) Annual CO_2 liberation from all products and waste as a proportion of total liberation from 1 ha beech. (f) Predicted annual CO_2 liberation from all products and waste as a proportion of total liberation from 1 ha beech.

where:

SUMLIBSS = sum of annual carbon liberation from all products and waste as a proportion of total carbon sequestration in wood from one rotation of Sitka spruce

ETRENDSS $=1/(1+t')$ where

$t'=0$ at felling and

maximum $t'=200$

$R^2=87{\cdot}0\%$ $\quad N=201$

Our *ETRENDSS* variable provides a good fit to the carbon liberation data as illustrated by the similarity between actual and predicted sum liberation shown in Figure 2(f) and (g), respectively. Equation (18) implies that all carbon stored by a Sitka spruce rotation will be liberated by $t'=200$, after which *SUMLIBSS* is constrained to zero.

Turning to Figure 3(a)–(d), these show individual product carbon liberation distributions for beech, while Figure 3(e) illustrates their sum. Again this was modelled using a variety of functional forms with the best model being reported in Equation (19):

$$\begin{aligned} SUMLIBBE = {} & \underset{(4{\cdot}01)}{0{\cdot}0007818} \\ & + \underset{(45{\cdot}97)}{0{\cdot}121461}\, ETRENDBE \end{aligned} \tag{19}$$

where:

$SUMLIBBE$ = sum of annual carbon liberation from all products and waste as a proportion of total carbon sequestration in wood from one rotation of beech

$ETRENDBE = 1/(1+t')$ where $t'=0$ at felling and maximum $t'=300$

$R^2 = 87{\cdot}6\%$ $\quad N=301$

Equation (19) for beech adopts an identical form as used for Sitka spruce in Equation (18). A similar high degree of fit is achieved, illustrated by comparing actual and predicted liberation in Figure 3(e) and (f), respectively. Equation (19) implies that all carbon stored by a rotation of beech will be liberated by $t'=300$ after which *SUMLIBBE* is constrained to zero.

Modelling carbon storage and loss from soils

Given the trends in Table 2 it is tempting to model individual soil category carbon changes by taking some account of altitude. Indeed the integrative and analytical capabilities afforded by GIS invite such an approach. However, we are aware of the paucity of data that underpins Table 2 and of the numerous complications (such as the implications of replanting) which have yet to be quantified (this is an area of considerable ongoing international research). A simplified and conservative approach to modelling soil carbon flux was therefore adopted along the lines of Sampson (1992), Dewar and Cannell (1992) and Matthews, R. W. (1993) all of whom assume a constant, smooth and marginally diminishing carbon flux path for all soils.

Erring on the conservative side, Table 2 supports a net long term increase in equilibrium soil carbon levels for non-peat soils at a range of altitudes of about 50 *t*C/ha, while for peat soils a net long term loss of some 750 *t*C/ha seems defensible (for further discussion see Bateman, 1996). A literature review (Bateman, 1996) indicates that for both peat and non-peat soils the rate of carbon flux will be highest immediately after felling and decline such that 95% of soil carbon change will have been achieved after roughly 200 years.

Equation (20) calculates the proportion of the total change in soil carbon ($PROPT\Delta SC_t$) which will have been achieved in any year t where $t=0$ at planting. Notice that $PROPT\Delta SC_t = 1{\cdot}00$ when $t=263$ (after which it is constrained to equal 1·00 throughout the remainder of the period under analysis).

$$PROPT\Delta SC_t = 0{\cdot}1793022 \ln TIME1 \tag{20}$$

where:

$TIME1 = t+1$ where $t=0$ at planting.

Equation (20) implies a diminishing marginal rate of soil carbon change (as required), values for which can be obtained by simple, one-period differencing. Multiplying these annual rates of change by the total change (50 *t*C/ha for non-peat soils and −750 *t*C/ha for peat soils) gives the annual soil carbon gains and losses.

Results

Net carbon storage in live wood, products and waste

Setting aside soil carbon impacts for the moment, the carbon storage and liberation equations reported for Sitka spruce and beech were operationalised through a custom written Fortran program (Bateman, 1996). This program yielded estimates of carbon sequestration value by species for a range of *YC* and discount rates. For each discount rate/*YC* combination, three net carbon flux values were calculated: (1) the NPV of the initial optimal rotation; (2) the NPV of a perpetual series of optimal rotations, and; (3) the annuity equivalent of the latter. Bateman (1996) describes full results of all these analyses. In brief, we report just the first of these measures for Sitka spruce (see Table 6) and beech (see Table 7).

From Tables 6 and 7 it can be seen that both yield class and discount rate have highly significant impacts upon net carbon-flux values. The data reported in these tables allow us to estimate, for each tree species, a series of linear regression equations where, for each specified discount rate, the net present value of sequestration is related to yield class. All these regression models are reported in Bateman (1996) while Equations (21) and (22) represent models for the 3% discount rate applied to the NPV of carbon in live wood, waste and products from an optimal rotation of Sitka spruce and beech, respectively:

$$NPV_{SS} = \underset{(9{\cdot}90)}{187{\cdot}70} + \underset{(87{\cdot}48)}{100{\cdot}46}\, YC_{SS} \quad (21)$$

$$R^2(\text{adj.}) = 99{\cdot}9\% \qquad N = 12$$

$$NPV_{BE} = \underset{(4{\cdot}92)}{148{\cdot}14} + \underset{(46{\cdot}18)}{178{\cdot}34}\, YC_{BE} \quad (22)$$

$$R^2(\text{adj.}) = 99{\cdot}8\% \qquad N = 6$$

The models reported in Equations (21) and (22) are well specified and were applied to existing maps of predicted *YC* for each species (Bateman and Lovett, 1998) using the IDRISI GIS software (Eastman, 1993) to produce maps of net carbon flux value (excluding soil carbon impacts) for the entire Welsh study area. Discounting effects can be analysed by simply selecting the equation corresponding to a desired discount rate and entering values from the YC map to generate a net carbon flux value map. As illustrations, Figure 4(a) shows the resultant NPV map for an optimal first rotation of Sitka spruce using a 3% discount rate (chosen to reflect recent debates concerning an appropriate social discount rate; Pearce and Ulph, 1998), while Figure 4(b) shows the same combination for beech.

The patterns presented in Figures 4(a) and (b) strongly reflect the underlying pattern

Table 6. NPV of net carbon flux (sequestration in live wood and liberation from products and waste) for an optimal rotation of conifer (Sitka spruce)

Discount rate (%)	YC4	YC6	YC8	YC10	YC12	YC14	YC16	YC18	YC20	YC22	YC24	YC26
1·5	811	1166	1491	1815	2122	2415	2692	3002	3308	3609	3902	4228
2	699	1007	1290	1570	1837	2089	2364	2634	2897	3151	3404	3652
3	536	774	1005	1208	1415	1629	1816	2015	2199	2391	2567	2781
5	342	496	643	785	916	1035	1160	1278	1393	1503	1626	1761
6	284	411	535	653	761	859	963	1060	1156	1253	1367	1466

Various yield classes (YC) and discount rates (£; 1990 prices).

Table 7. NPV of net carbon flux (sequestration in live wood and liberation from products and waste) for an optimal rotation of broadleaf (beech)

Discount rate (%)	YC2	YC4	YC6	YC8	YC10	YC12
1·5	886	1673	2401	3059	3690	4326
2	706	1332	1889	2421	2941	3437
3	466	875	1246	1607	1924	2262
5	242	454	649	830	1003	1178
6	186	349	497	638	775	907

Various yield classes (YC) and discount rates (£; 1990 prices).

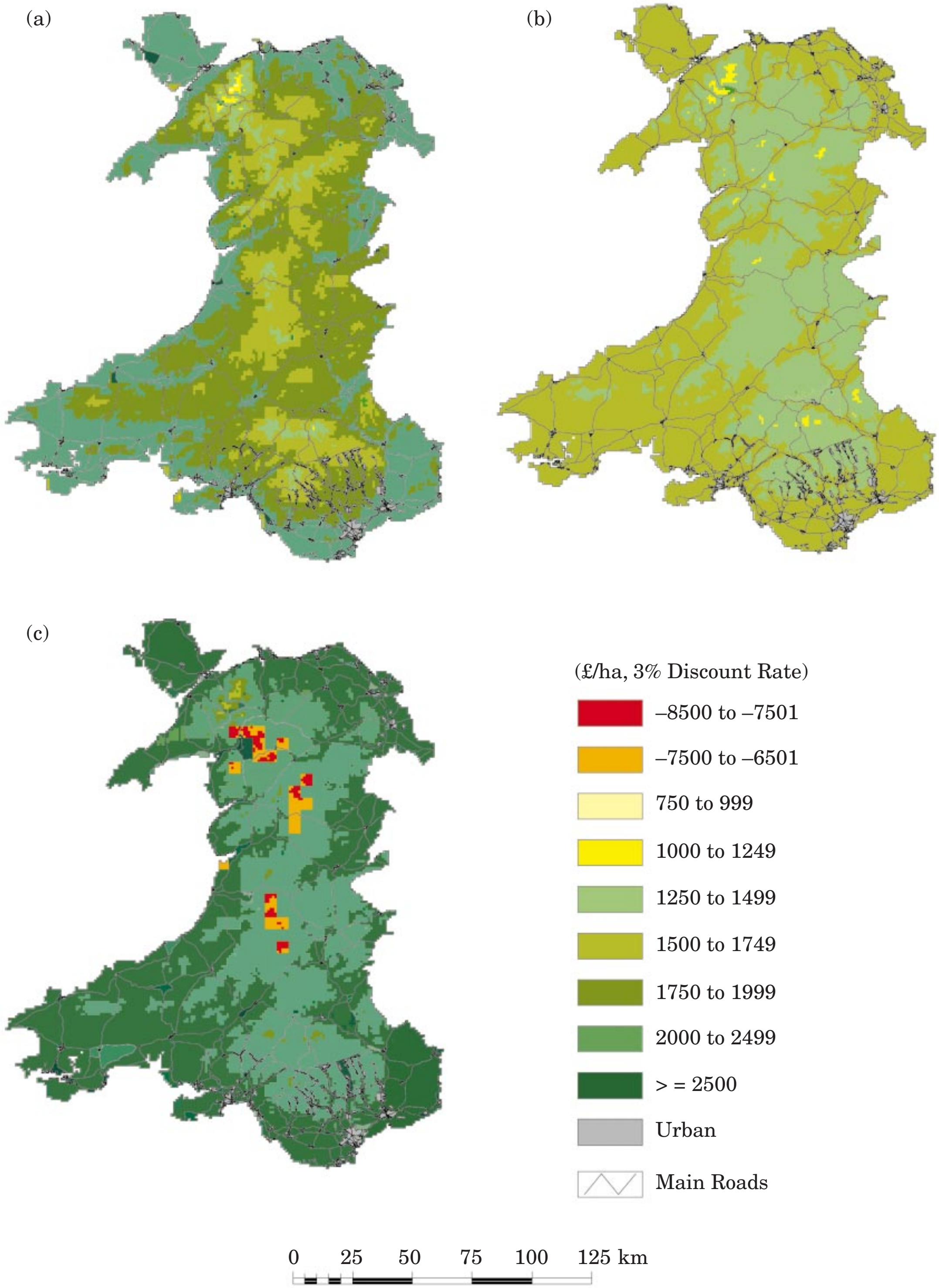

Figure 4. (a) NPV (£/ha) of net carbon flux (live wood, products and waste) for Sitka spruce (3% discount rate). (b) NPV (£/ha) of net carbon flux (live wood, products and waste) for beech (3% discount rate). (c) NPV (£/ha) of net carbon flux (live wood, products, waste and soils) for Sitka spruce (3% discount rate).

of timber yield (Bateman and Lovett, 1998) and consequently echo the determinants of such growth rates. This pattern is similar across species with lower growth rates in the upland areas running down the centre of the country and higher yields in bisecting valleys and on superior lowland soils. However, the level of carbon sequestration *NPV* sums is consistently higher for Sitka spruce than for beech. Although the timber produced by beech trees is put towards lower emission rate end uses, this carbon fixing is a slow process and resultant values are therefore heavily discounted. By contrast the superior growth rate of Sitka spruce fixes carbon more quickly and as a consequence is less affected by discounting than is beech. As in so many other instances, it is the effect of the discounting process rather than the underlying annual costs and benefits which drives this result.

There are important caveats regarding the straightforward interpretation of Figure 4(a) and (b). We have taken the conscious decision to estimate values for the entirety of the study area. However, certain areas are already afforested and may well be in carbon balance. The replanting of areas in such equilibrium will only have transitory effects upon carbon sequestration and no net value will be generated in this respect. In similar way, other areas may be unplantable, e.g. urban areas, those on rocky ground or susceptible to extreme windblow (Blakey-Smith, *et al*., 1994), etc. We could have filtered out and omitted such areas, however the deliberate decision was taken to estimate values for all areas and apply local constraints when evaluating any particular proposed planting scheme. Such an approach is more consistent with typical cost-benefit decision-making but limits the simple aggregation of values. Such aggregation would make an interesting extension to the present work although we feel that it would be more meaningful to calculate such values for specific afforestation proposals than for some overly-hypothetical blanket planting of the entire study area.

Figure 4(a) and (b) are calculated holding the discount rate constant at 3%. Table 8 relaxes this restriction and compare the NPV of net carbon flux for live wood, waste and products across a range of discount rates (annuity equivalents are reported in Bateman, 1996). The table gives frequency counts and percentages for the number of 1-km^2 cells within each value band.

Table 8 indicates that the choice of both discount rate and species have a substantial impact upon net carbon-flux values. The more elongated growth period of beech results in lower discounted values of carbon sequestration. However, as expected, this divergence of values between species declines as the discount rate falls.

Extending the analysis to include soil carbon flux

Equation (20) defined the total proportion of soil carbon flux (sequestration or liberation) achieved in any year t for any tree species. This equation was differenced to calculate the marginal proportion change in any year t. The actual marginal change in soil carbon was then obtained by multiplying the total change over the full period under analysis (50 tC/ha for non-peat soils; -750 tC/ha for peat soils) by the marginal proportion change in each year.

This annual soil carbon gain or loss was subsequently valued using the data from Fankhauser (1994) as discussed. These values were then discounted at various rates and NPV sums calculated as shown in Table 9.

Maps of soil carbon flux values were created within the IDRISI GIS by applying the values given in Table 9 to a soil map derived from the Land Information System (LandIS) database (Hallett *et al*., 1996).[8] Given the lack of detailed information concerning soil carbon flux impacts, the resultant maps contain only two values, defined by the presence or absence of peat soils (accordingly we do not reproduce this map here, see Bateman, 1996), the latter being generally confined to extreme

[8] Kindly provided by the Soil Survey and Land Research Centre (SSLRC), Cranfield. The SSLRC LandIS system provides the best source of soil type data for England and Wales. Land use data may be obtained from the ITE/NERC database. Furthermore, 5 km soil property, nutrient and elements maps are provided in McGrath and Loveland (1992) although the data supporting these maps were not available for this study. Alternative approaches include use of the CORINE land-cover database (EU, 1992) as employed by Cruikshank *et al*. (1995) while Milne and Brown (1997) and Milne *et al*. (1998) use data taken from the ITE land classification system.

Table 8. NPV of Sitka spruce and beech carbon flux for live wood, waste and products (various discount rates; r)

NPV (£/ha)	Sitka spruce						Beech					
	r=1%		r=3%		r=6%		r=1%		r=3%		r=6%	
	Freq[a]	%	Freq[a]	%	Freq[a]	%	Freq[a]	%	Freq[a]	%	Freq[a]	%
250–499	—	—	—	—	1	0·005	—	—	—	—	161	0·783
500–749	—	—	—	—	228	1·109	—	—	—	—	20 402	99·217
750–999	—	—	5	0·024	8042	39·109	—	—	—	—	—	—
1000–1249	—	—	50	0·243	12 292	59·777	—	—	159	0·773	—	—
1250–1499	5	0·024	624	3·035	—	—	—	—	7809	37·976	—	—
1500–1749	27	0·131	3621	17·609	—	—	—	—	12 595	61·251	—	—
1750–1999	71	0·345	8648	42·056	—	—	1	0·005	—	—	—	—
2000–2249	571	2·777	7615	37·033	—	—	41	0·200	—	—	—	—
2250–2499	2036	9·901	—	—	—	—	387	1·882	—	—	—	—
2500–2749	3561	17·318	—	—	—	—	4057	19·730	—	—	—	—
2750–2999	6371	30·983	—	—	—	—	8457	41·127	—	—	—	—
3000–3249	7643	37·169	—	—	—	—	7620	37·057	—	—	—	—
3250–3499	278	1·352	—	—	—	—	—	—	—	—	—	—
Mean		2859·75		1900·39		1005·36		2907·06		1518·99		608·08
SD		384·82		319·28		266·81		320·42		273·61		236·07

[a]From the total of 20 563 1 km^2 land cells which define the entirety of Wales.

Table 9. NPV sums for soil carbon flux: all tree species (£/ha)

Soil type	Discount rate (%)		
	1·5	3	6
Non-peat	742	601	476
Peat	−11144	−9018	−7141

The table reports values for full equilibrium changes over our 1000 year time horizon (annuity equivalents are given by Bateman, 1996). Given that soil carbon change is a slow process (Milne and Brown, 1997), taking many rotations to complete, calculation of conventional (timber orientated) first rotation NPV sums is of less interest than in our analysis of tree carbon fixing values.
All tree species (£/ha).

Table 10. Frequency table: NPV of net carbon flux (live wood, waste, products and soils), Sitka spruce (£/ha, 1990)

	Discount rate (%)		
NPV (£/ha)	1	3	6
−9500:−9001	33	—	—
−9000:−8501	438	—	—
−8500:−8001	5	—	—
−8000:−7501	13	177	—
−7500:−7001	—	298	—
−7000:−6501	—	14	—
−6500:−6001	—	—	489
500:999	—	—	3
1000:1499	—	1	9650
1500:1999	—	181	10 421
2000:2499	32	7907	—
2500:2999	538	11 985	—
3000:3499	5349	—	—
3500:3999	13 933	—	—
4000:4499	222	—	—

From the total of 20 563 1 km^2 land cells which define the entirety of Wales.

upland areas where carbon storage is already low due to depressed tree-growth rates.

In order to assess the full impact of planting upon carbon flux, the undiscounted marginal soil carbon storage values were added to the undiscounted annual net carbon flux values for live wood, products and waste. The resultant total annual carbon flux values were then discounted at various rates to yield the net present value for any desired period. Table 10 lists the net present value of total net carbon flux for Sitka spruce across various discount rates (values for beech are similar, but consistently below those for Sitka spruce; as a consequence, they are not reproduced here).

The most striking feature of Table 10 is the highly bipolar distribution of results. Planting upon peat soils causes very large soil carbon losses which overwhelm any values generated by storage in live wood. Elsewhere, however, the value of carbon storage is both positive and substantial. Given the nature of these distributions, mean values and variance measures are somewhat inappropriate, however the spatial distribution of values is illustrated in Figure 4(c) which shows the *NPV* values for net carbon flux generated by Sitka spruce when assessed using a 3% discount rate.

Figure 4(a) and (c) both relate to Sitka spruce and differ only in that the latter includes soil carbon flux. As can be seen, in most areas afforestation raises soil carbon such that the values shown in Figure 4(c) exceed those of Figure 4(a). However, the one clear exception is on peat soils where the large soil carbon emission associated with such afforestation results in strongly negative overall *NPV* sums. Caveats regarding already planted and unplantable land again apply.

Summary and conclusions

The objective of the research was to advance methodologies for the modelling and mapping of the value of net carbon flux induced by planting trees. In particular, we aimed to construct, for both of the tree species under investigation, models of the quantity of carbon sequestered or liberated from three sources: the growth of live wood; changes in the carbon content of woodland soils and; carbon liberation from felling waste and timber products. To allow for the long-term nature of these processes, these models were run over an extended time period. Valuation of the various carbon storage and emission flows was then achieved by reference to unit values reported in the literature. A GIS was used to apply the live-wood carbon sequestration and waste/product emission analyses to existing models of predicted tree growth rates for a large study area. In a similar way, our soil carbon flux model was related to data on soil type distribution. The GIS was then used to overlay results from these various analyses to permit the construction of a net carbon-flux valuation map for both of the species under consideration. The richness of the model developed provides a variety of results which are summarised as follows:

- most fundamentally, all three of the elements of the model, the sequestration of carbon in livewood, its release from different products and waste, and its storage or emission from soils, play a vital role in determining overall carbon flux. Omission of any one of these can result in spurious conclusions being drawn.
- Their are a number of silvicultural impacts upon carbon storage rates. We have discussed elsewhere the impact of plantation management upon growth rates (Bateman and Lovett, 1998) and here we emphasise the role of thinning upon sequestration.
- The choice of discount rate exerts one of the largest influences upon estimated carbon flux values. For example, moving from the UK Treasury 'public good' discount rate of 6% to the lower rates advocated by some for assessing greenhouse gas abatement would roughly triple the carbon flux *NPV* for most (non-peat) sites.
- Timber growth rates have, if anything, an even more marked impact upon sequestration values with NPV sums roughly quadrupling across the yield class range which encapsulates the study area.
- Changes in tree species also affects storage values however this is less important than the other factors listed above. This means that in any afforestation project the choice of species should generally not be made with reference to carbon storage alone but instead also embrace other factors, such as timber, biodiversity and recreation values (we expand upon this theme below);
- In most locations within the study area afforestation will generally lead to increases in soil carbon content although the values generated are relatively modest compared to those discussed above. However, planting upon peat soils can result in very substantial emissions of carbon overwhelming storage in livewood and producing very strongly negative *NPV* sums for overall carbon flux.

All of the above factors have to be borne in mind when assessing whether a proposed afforestation programme should be implemented and if so where the optimal location for planting might be. Such complexity underpins ongoing extensions to this work where the maps of carbon sequestration value are integrated with other valuation maps of woodland recreation (Bateman *et al*., 1999a), timber value (Bateman and Lovett, 1998, 2000a) and agriculture (the opportunity cost of afforestation in much of the study area; see Bateman *et al*., 1999b). Comparison of these values should permit land use planners to identify those areas which, on a variety of criteria, provide optimal locations for conversion from agriculture into multipurpose woodland. This approach is directly compatible with planning frameworks such as those currently under development by relevant UK forestry authorities (Countryside Commission and Forestry Commission, 1996; Forestry Commission, 1998).

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Appendix

The relationship between felling date and tree species across various discount rates and yield classes

Optimal felling age was specified through use of the Forestry Commission Forestry Investment Appraisal Package (FIAP) running at the FC head office in Edinburgh. FIAP identifies the felling age at which the net present value of a stand is maximised given a user defined tree species, yield class, and discount rate. Table A1 presents results for Sitka spruce while Table A2 details results for beech. As can be seen, as yield class and/or discount rate are increased so the optimal felling age declines. These results provide the basic data used in Equations (5) and (13) in the paper.

Table A1. Optimum felling age for various discount rates: Sitka spruce, YC6-24

Discount rate (%)	Yield class (Sitka spruce)									
	6	8	10	12	14	16	18	20	22	24
2	80	78	74	70	69	68	66	66	66	65
3	73	72	69	63	60	58	57	57	56	56
4	68	67	64	58	54	51	50	50	49	48
5	64	62	60	56	52	49	46	44	44	44
6	60	58	56	54	50	47	43	42	41	40
8	54	53	51	50	47	44	42	40	37	35
10	50	48	47	46	44	42	40	38	36	34
12	47	44	43	42	41	40	38	36	34	33

Optimal felling age maximises NPV given the relevant discount rate (*r*) and YC combination. The above figures treat the planting year as year 0. The table was calculated using FIAP running at the Forestry Commission Headquarters at Edinburgh (except for the row for $r=3\%$ which was interpolated). The author is obliged to Jane Sinclair and Roger Oakes at Edinburgh for assistance.
The table applies the following FIAP settings:
spacing, $2{\cdot}00 \times 2{\cdot}00$;
delay on first thinning, None;
successor crop NPV, Zero;
thinning price differential (£ 1992/93), £0·30 m^3;
thinning, line, MTT;
stocking, 85%;
price size curve, G.B. conifer 1992;
charge per m^3 (£ 1992/93), £3·68 m^3

Table A2. Optimum felling age for various discount rates: Beech, YC4-10

Discount rate (%)	Yield class (beech)			
	4	6	8	10
2	125	120	119	118
3	105	99	95	93
4	91	85	80	78
5	81	75	71	69
6	75	69	65	62
8	65	59	56	53
10	58	52	48	47
12	53	47	43	42

Optimal felling age maximises NPV given the relevant discount rate (*r*) and YC combination. The above figures treat the planting year as year 0. The table was calculated using FIAP running at the Forestry Commission Headquarters at Edinburgh (except for the row for $r=3\%$ which was interpolated). The author is obliged to Jane Sinclair and Roger Oakes at Edinburgh for assistance.
The table is calculated according to the following assumptions:
spacing, $1{\cdot}20 \times 1{\cdot}20$;
delay on first thinning, None;
successor crop NPV, Zero;
thinning price differential (£ 1992/93), £0·30 m^3;
thinning, Broadleaved, intermediate thin;
stocking, 85%;
price size curve, Broadleaves for 1989/90 T.R.;
charge per m^3 (£ 1992/93): £3·68 m^3.