# 7

# Modelling and valuing carbon sequestration in trees, timber products and forest soils

## Introduction

The global process of industrialisation which has grown so rapidly over the past two centuries has, in more recent years, led to detectable increases in the concentration of insulating greenhouse gases (GHGs). These have in turn resulted in increases in global temperatures, and these are expected to continue rising with GHG emissions for the foreseeable future (Houghton *et al.*, 1992; Wigley and Raper, 1992; IPCC, 1996a, 2001a, 2001b; Zecca and Brusa, 1997). The most recent report of the Intergovernmental Panel on Climate Change (IPCC) summarises the findings of contemporary research as showing:

> that the globally averaged surface temperatures have increased by 0.6 ± 0.2 °C over the 20th Century; and that, for the range of scenarios developed in the IPCC *Special Report on Emission Scenarios* (SRES), the globally averaged surface air temperature is projected by models to warm 1.4 to 5.8 °C by 2100 relative to 1990, and globally averaged sea level is projected by models to rise 0.09 to 0.88 m by 2100. (IPCC, 2001b: p. 3)

The consequences of such climatic change are uncertain but potentially highly adverse (Warr and Smith, 1993; Parry, 1993, 2000). The IPCC concludes that:

> Projected climate changes during the 21st Century have the potential to lead to future large-scale and possibly irreversible changes in Earth systems resulting in impacts at continental and global scales.... Depending on the rate of ice loss, the rate and magnitude of sea-level rise could greatly exceed the capacity of human and natural systems to adapt without substantial impacts. (IPCC, 2001b: p. 6)

Growing concern regarding climate change has raised interest in the potential for using forestry as a way of reducing atmospheric concentrations of carbon dioxide (Sedjo, 1989; Myers, 1990; Nordhaus, 1991a; Galinski and Kuppers, 1994),

This chapter extends the analysis presented in Bateman and Lovett (2000b).

the gas which in absolute terms provides the largest contribution to global insulation. Two issues of scale should be emphasised here. First, given the scale of global fossil fuel use, carbon sequestration in forests can only be a stopgap measure, providing temporary relief in advance of necessary reductions in emissions.[1] Second, stocks of carbon and the potential for future sequestration in temperate woodlands are relatively small compared to those of tropical forests, while both are dwarfed by the storage and sequestration potential of the world's oceans (IPCC, 2000; Matthews *et al*., 2000; UNDP *et al*., 2000).[2] Accepting these caveats does not diminish the value of carbon sequestration (irrespective of the biome concerned), while issues of practicality and cost highlight the fact that forest ecosystems may be considerably more amenable to initiatives to change policy than are the ocean depths.

Carbon sequestration benefits therefore constitute a separate category of forest value (Dore *et al*., 2001). Such benefits have been recognised both by economists and policy-makers internationally (IPCC, 2001b). In our study area of Wales the National Assembly's recent *Draft Document on the Future of Agriculture* (National Assembly for Wales, 2001b) explicitly recognises the need to commission research concerning ways in which both forestry and farming can contribute to cutting emissions and promoting carbon sequestration.

This chapter attempts to quantify the impact upon carbon storage of afforesting an area of previously unplanted land.[3] However, assessment of this benefit is not straightforward. An initial and daunting problem concerns the valuation of sequestered carbon. This has been a subject of heated debate within the economics literature. A number of articles have been heavily criticised for failing to grasp the complexity of the climatic processes which underlie global warming. We reviewed the literature in some detail in Bateman (1996) and defend our use of the valuation work of Sam Fankhauser as being both more sophisticated and based upon significantly more realistic climate change models than preceding work. A brief review of the debate is presented at the start of the next section.

Our review of literature also considered the physical processes of carbon sequestration in trees and forest soils, carbon storage within timber products, and eventual liberation back to the atmosphere, for carbon storage within trees is only a transitory process and total storage can only grow while the volume of timber increases. Nevertheless, the potential for expanding forest areas (heightened in the

[1] As Nowak (1993) emphasises, planting 10 million trees per annum for the next fifty years will sequester less than 1 per cent of US emissions during that period.

[2] Global carbon stocks in the vegetation and soils of tropical forests are estimated at 212 GtC (gigatonnes of carbon) and 216 GtC respectively. By comparison those for temperate forests are 59 GtC and 100 GtC. These compare to estimates for all biomes of 466 GtC in vegetation and 2,011 GtC in soils, the majority of this storage being in seas and oceans (IPCC, 2000).

[3] We do not appraise the current storage of carbon in the study area. For estimates of the latter, see Cannell and Dewar (1995).

EU by surpluses of agricultural land) means that forests do provide a vital breathing space before policy and technological change can address the root cause of global warming.

The following section presents a brief overview of our research methodology. This is then applied to the modelling of carbon sequestration in both Sitka spruce and beech trees, while the next section considers subsequent liberation of carbon from the products and felling waste of both species. The impacts of afforestation upon soil carbon levels are then considered. Results from these analyses are presented, including the monetary value maps necessary to make results compatible with the findings of previous chapters.

## Literature review[4]

This section opens by considering the ongoing debate concerning the valuation of carbon emissions and their storage. It then moves to consider three aspects of carbon sequestration by means of afforestation: the storage of carbon in trees; its post-felling liberation; and the impact of afforestation upon soil carbon flux.

### *The shadow price of carbon emissions*

While a number of studies have examined the costs of fixing carbon via afforestation, relatively few have attempted to quantify its benefits. For our purposes the most interesting of these are those adopting a damage-avoided approach to valuation. If accurate, estimates produced by such methods are shadow prices which may be directly incorporated within the cost-benefit framework which underpins our wider study.

The pioneering work on the shadow price of $CO_2$ emissions is that of Nordhaus (1991b,c). Using a very simple model and assuming a 3 per cent discount rate he calculates social costs of \$7.3/tonne of carbon (tC) emitted. This estimate has provoked a number of critical responses (Ayres and Walter, 1991;[5] Daily *et al*., 1991; Cline, 1992a; Grubb, 1992; Price, 1997b). Typical of these, Cline (1992a) highlights the simple linear structure of the underlying model, implying

[4] For a review of land use and climate change issues and policy, see the essays in Adger *et al*. (1997) and Sedjo *et al*. (1997). Other economic and physical analyses from around the world of the impacts of forests upon carbon storage are given in Maclaren and Wakelin (1991), Kauppi *et al*. (1992), Makundi *et al*. (1992), Kurz *et al*. (1992, 1994), Kolchugina and Vinson (1993), Turner *et al*. (1993, 1995), Backlund *et al*. (1995), Maclaren *et al*. (1995), Bureau of Transport and Communications Economics (1996a,b), Maclaren (1996a,b), Mauldin and Platinga (1998), Motha and Heyhoe (1998) and IPCC (2001a,b).

[5] It is somewhat ironic that Ayres and Walter criticise the Nordhaus (1991b,c) estimates as too low given that in an earlier paper they assess emissions damage costs at \$5–10/ton $CO_2$ (\$18–37/tC) (Walter and Ayres, 1990). In their subsequent critique of Nordhaus they apply different assumptions to his model to produce a damage estimate of \$30–35/tC (Ayres and Walter, 1991). However, given the problems of the simple linear Nordhaus model, such estimates must be treated with caution.

both a constant level of $CO_2$ emissions[6] and a constant shadow price through time.

In subsequent work Nordhaus (1992a,b) addresses many of these criticisms. His Dynamic Integrated Climate Economy (DICE) model uses optimal economic growth analysis in combination with a climate model which feeds climate changes back into the economy as damages. The resulting carbon shadow prices are similar to his earlier estimates ($5.3/tC in 1995 rising to $10/tC in 2025). However, Nordhaus' results have again been criticised by Cline (1992b) who suggests that the parameter values used result in an underestimation of true costs.

A similar model, utilising a more detailed economy component, is used by Peck and Teisberg (1992a,b). Their Carbon Emission Trajectory Assessment (CETA) model produces estimates of the shadow price of carbon ranging from $10/tC in 1990 to $22/tC in 2030. Given that the CETA model is structurally similar to DICE, the main reason explaining differences in the shadow price estimates produced appears to be discrepancies in assumptions regarding carbon damages.

Important contributions to the shadow pricing debate are provided by the papers of Fankhauser (1993, 1994a,b, 1995). These introduce a fully stochastic, greenhouse damages model, explicitly recognising the highly non-linear and uncertain aspects of the climate process. Uncertainty is incorporated by modelling all key parameters as random variables.[7] The model consists of modules examining: future emissions; atmospheric concentration; radiative forcing; temperature rise; annual damage; costs of sea-level rise protection; and discounting.

The issue of discounting is, arguably, the central problem in the appraisal of global warming response, and this is a focal point for much research (Howarth, 1996; Azar, 1998; Hasselmann, 1999; Pollock, 1999; Revesz, 1999; Hammitt and Harvey, 2000). Fankhauser (1994b) tackles the discounting problem in a direct, although still debatable, manner. Considering the literature on the subject, he sets the pure rate of time preference ($\rho$) as a random variable with upper and lower bounds of 0 and 3 per cent respectively and with a best guess (modal) value of 0.5 per cent. Similarly, the income elasticity of utility ($\omega$) is defined as a random variable with upper and lower bounds of 0.5 and 1.5 respectively and a best guess (modal) value of 1. This random variable discounting captures the uncertainty regarding these parameters. Furthermore, if we recall our discussion of discounting in Chapter 5, the low discount rate resulting from such a choice of parameter values seems defensible as a reflection of social preference regarding the assessment of global warming impacts. However, to allow comparability with other studies

6 Annual $CO_2$ emissions are predicted to rise from 7.4 GtC in 1990 to 9–14 GtC by 2025 (IPCC, 1992). Climate processes are clearly not first-order linear.

7 Here triangular distributions (using upper/lower bounds and the best-guess estimate) are generally assumed although where upper and lower bounds were unknown a modest range of ±10 per cent around the best guess was used.

Table 7.1. *The social costs of $CO_2$ emissions (\$/tC): comparison across studies*

| Study | Measure | 1991–2000 | 2001–2010 | 2011–2020 | 2021–2030 |
|---|---|---|---|---|---|
| Nordhaus (1991a,b)[1] | Best guess (mode) | ← | 7.3 (0.3–65.9) | | → |
| Ayres and Walter (1991)[1] | Best guess (mode) | ← | 30–35 | | → |
| Nordhaus (1992a)[1] | Best guess (mode) | 5.3 | 6.8 | 8.6[2] | 10.0 |
| Peck and Teisberg (1992b)[1] | Best guess (mode) | 10–12[2] | 12–14[2] | 14–18[2] | 18–22[2] (3.4–57.6) |
| Fankhauser (1994b)[3] | Expected (mean) | 20.3 | 22.8 | 25.3 | 27.8 |
| | 5th percentile | 6.2 | 7.4 | 8.3 | 9.2 |
| | 95th percentile | 45.2 | 52.9 | 58.4 | 64.2 |
| | standard dev. | 14.3 | 16.0 | 17.5 | 19.0 |
| | skewness | 2.5 | 2.5 | 2.5 | 2.4 |

*Notes:* Figures in brackets denote confidence intervals.
[1] Discount rate = 3 per cent for all studies except Fankhauser (1994b).
[2] Figures measured from graph as reported in Fankhauser (1994a).
[3] Random variable discounting: $\rho = (0, 0.005, 0.03)$; $\omega = (0.5, 1, 1.5)$.

Fankhauser also conducts a conventional discounting sensitivity analysis using values of $\rho = 0$ and 0.03 with $\omega = 1$ throughout.

The Fankhauser (1994b) model differs therefore from its predecessors in at least three important aspects:

(i) it models climate feedback mechanisms in a more detailed and realistic manner
(ii) it uses expected (means) rather than best guess (modal) values
(iii) it employs a discount rate sensitivity analysis.

Table 7.1 contrasts results from Fankhauser's (1994b) random variable discounting model of $CO_2$ damage costs with those discussed previously. For the latter, only a best guess (modal) value is reported. In contrast and to emphasise the importance of damage distributions, Fankhauser reports expected (mean) values as well as 5th and 95th percentiles, standard deviation and skewness. Given factors (i) to (iii) above, the discrepancy between Fankhauser's results and those of other studies are to be expected.

The Fankhauser model was adopted as a cornerstone of the report by the Intergovernmental Panel on Climate Change into the socio-economic impacts of the greenhouse effect (IPCC, 1996b).[8] Accordingly, we feel justified in adopting the

[8] These figures are slightly above the sum of \$20/tonne used by the World Bank in a retrospective appraisal of their previous funding decisions (World Bank, 1996).

above values for use in this study. However, as our analysis extends long beyond the 2021 horizon considered by Fankhauser, we have to make some assumptions regarding carbon sequestration values beyond that point. After reviewing the literature it became apparent that simply extending the trend of Fankhauser's estimates risks error if greenhouse abatement measures are implemented (although the decision, in 2001, of President George W. Bush to withdraw the United States from emission reduction obligations set under the 1997 Kyoto Climate Change Convention means that the future for global abatement policy is very uncertain). 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 we felt that no other course of action was justified given the uncertainty that exists within the literature.[9]

## *Carbon storage in trees*[10]

Much of the woody biomass of a tree is carbon; therefore, growing new trees fixes carbon over the lifetime of those trees. However, the relation between timber yield and carbon storage is not straightforward.

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. (Matthews, 1991; Rasse *et al*., 2001). The TWV/MV ratio is very high in the early life of a tree but falls rapidly as MV rises with age.[11] TWV is in turn related to the tree's 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; Thompson and Matthews, 1989a). However, the proportion of DW which is carbon is roughly similar for Sitka spruce and beech at about 49 per cent (G. Matthews, 1993).

While timber yield and species affect carbon storage, forestry management also has a major impact. The move from unmanaged woodland to managed plantation results in a significant increase in MV (Bateman and Lovett, 1997). 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).

[9] 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.

[10] This section draws upon Sedjo *et al*. (1995) and conversations during 1994 and 1995 with Robert Matthews, mensuration officer at the Forestry Commission's Research Station, Alice Holt Lodge, Farnham.

[11] This study uses the TWV/MV relationship given in Matthews (1991). As an example of how this changes with tree age, Matthews reports a ratio value of 3.0 at age 20 for YC12 Sitka spruce, falling to a value of just below 2.0 at age 40 and declining more slowly thereafter to about 1.4 at age 75.

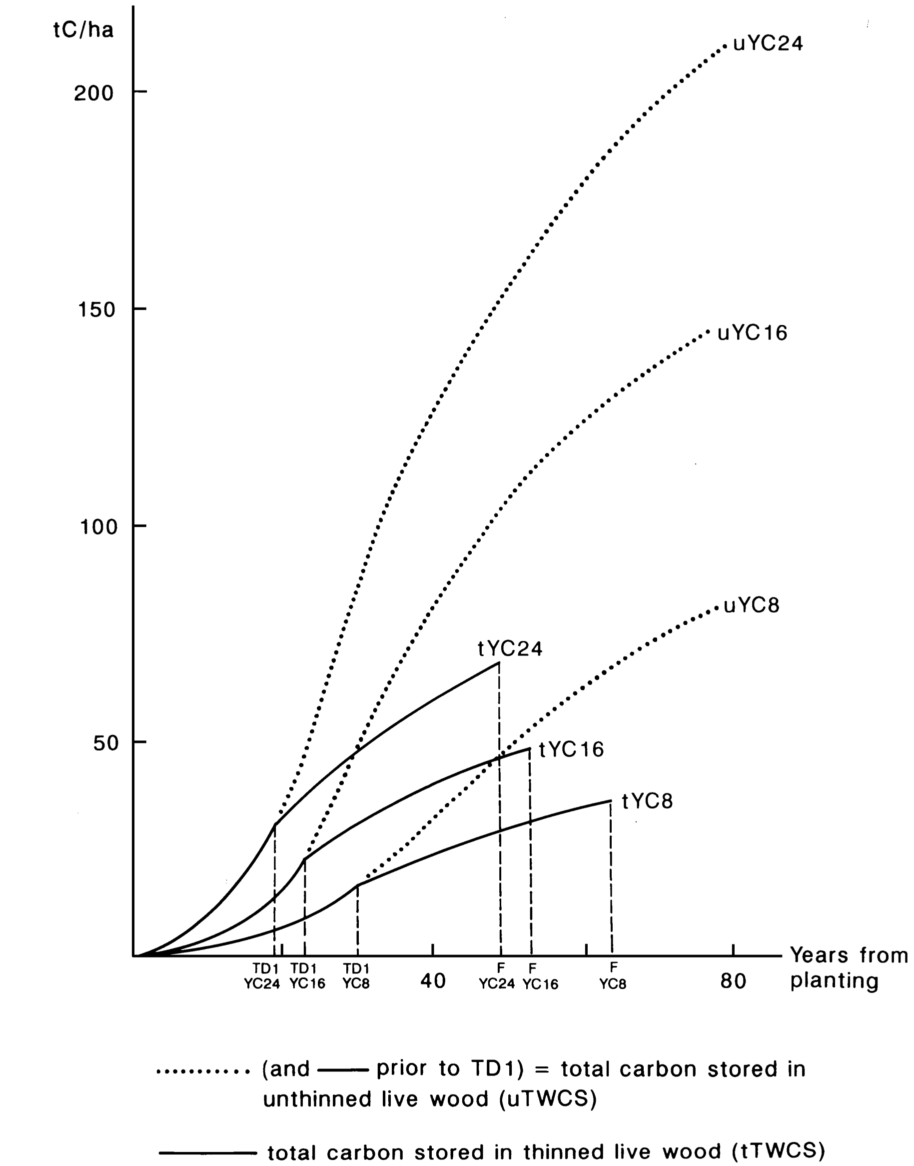


Figure 7.1. Total carbon storage curves for unthinned and thinned Sitka spruce: 5% discount rate.

Furthermore, the practice of discounting leads both to higher-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 7.1 illustrates the impact of these management decisions upon three stands of Sitka spruce growing at yield classes (YC) 8, 16 and 24 (where YC8 denotes a stand producing on average 8 $m^3$/year/ha over an optimal rotation). Here yield class models (Edwards and Christie, 1981) are combined with data on carbon storage in Sitka spruce (Cannell and Cape, 1991; R. Matthews, 1993) to plot out carbon storage curves for both thinned and unthinned (denoted tYC and uYC respectively) stands.[12] Unthinned stands produce a characteristic S-shaped carbon storage curve. Thinned stands follow this curve up to the date of first thinning (TD1), which arrives sooner for faster-growing stands (as does the date of felling; F).[13] After TD1 the tYC curve becomes much more shallow than its uYC 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 (see below), thinned stands sequester less carbon than unthinned crops.[14] Furthermore, as noted by numerous commentators (Thompson *et al.*, 1997; van Kooten and Bulte, 1999; Thornley and Cannell, 2000; Healey *et al.*, 2000), there is clearly a trade-off between managing forests for timber yield and optimising carbon storage.

### *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 may occur quite quickly if the wood is used as fuel, left to decompose (e.g. small trimmings) or used for short-term purposes. The carbon liberation rates resulting from these various end uses can differ substantially. For example, Thompson and Matthews (1989a) compare conventionally grown YC16 Corsican pine with short rotation coppice (SRC) poplar plantations, noting that the latter fixes significantly more carbon per annum than the former. However, because SRC is generally used as fuel, its long-term average sequestration rate is significantly lower than that of Corsican pine which is typically used for more durable products.[15]

[12] 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 (Waggoner, 1983; D'Arrigo *et al.*, 1987; Heath *et al.*, 1995; Murray *et al.*, 1995; Eamus and Jarvis, 1989; Cannell and Cape, 1991; Kellomaki *et al.*, 1997; Bucher-Wallin *et al.*, 2000). However, evidence also exists to indicate that some trees may reduce rates of $CO_2$ uptake within a $CO_2$-enriched atmosphere, an effect which may differ between species (Egli, *et al.*, 2001). These factors are still the subject of research and are not incorporated in our model.

[13] Figure 7.1 and underlying calculations use a 5 per cent 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).

[14] R. Matthews (1993) also considers the carbon emissions associated with felling, etc. However, these are found to be relatively minor, and substantial net carbon storage benefits are found, particularly where wood is subsequently used for biofuel as a substitute for existing high-carbon fuels such as oil or coal.

[15] Marland and Marland (1992) and R. Matthews (1993) highlight an important consequence of such examples: where timber is used as fuel and substitutes for existing high-carbon fossil fuels, a further net benefit will accrue. We have not adopted such an assumption in our analysis because of uncertainties regarding likely substitution rates. In effect we assume that capital commitments to non-timber fuelling systems mean that any conversion rate will be very low.

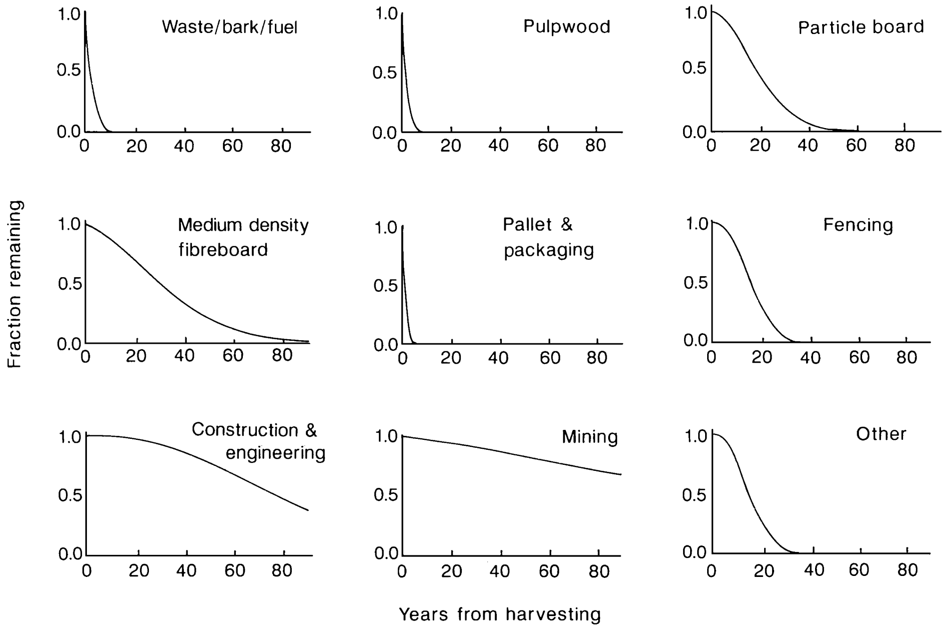


Figure 7.2. Longevity of Sitka spruce timber when put to different uses. (*Source:* Thompson and Matthews, 1989b.)

A rigorous examination of the impact of end use upon carbon fixing is given in Thompson and Matthews (1989a,b). Results are obtained for a variety of species, those for Sitka spruce being graphically summarised in Figure 7.2.

Figure 7.2 makes it clear that end use has a major influence upon plantation average carbon storage levels. Indeed, Matthews (1995) cites this as the major determinant of overall carbon storage, being significantly stronger than factors such as silvicultural management regime.[16] In order to incorporate this effect within a general carbon flux model we also require information regarding the proportion of wood allocated to each end use. Statistics gathered from a variety of sources are summarised in Table 7.2 which provides a breakdown of 1991/92 UK domestic production data divided into softwood and hardwood species.

## *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

[16] A further issue, considered by Matthews (1992), is the level of manufacturing emissions associated with differing end uses. These are relatively high for capital-intensive products such as paper and low for sawn wood, etc.

Table 7.2. *Softwood and hardwood end uses for UK domestic production 1991/92*

| | Softwood | | | | Hardwood | | | |
|---|---|---|---|---|---|---|---|---|
| Product | Production ('000 $m^3$) | % of total | Modal liberation year (from felling) | 95% carbon liberation (years from felling) | Production ('000 $m^3$) | % of total | Modal liberation year (from felling) | 95% carbon liberation (years from felling) |
| Sawn logs | 2,925 | 49.292 | 70 | 150 | 558 | 49.512 | 150 | 300 |
| Board | 1,154 | 19.447 | 15 | 40[1] | 87 | 7.720 | 15 | 40 |
| Paper | 936 | 15.774 | 1 | 5 | 138 | 12.245 | 1 | 5 |
| Mining | 23 | 0.004 | 40 | 200 | <1 | <0.001 | 40 | 200 |
| Fuel[2] | 142 | 2.393 | 1 | 5 | 114 | 10.115 | 1 | 5 |
| Other[2] | 142 | 2.393 | 15 | 30 | 114 | 10.115 | 40 | 80 |
| Bark | 612 | 10.313 | 1 | 5 | 116 | 10.292 | 1 | 5 |
| Total | 5,934 | 100.000 | — | — | 1,127 | 100.000 | — | — |

*Notes:* [1] Based on this being almost exclusively particleboard as per statistics given in Forestry Commission (1992).
[2] Based on assumption that roughly 50 per cent of 'Other Industrial Wood' (FICGB, 1992) is fuel-wood, as per statistics given in Forestry Commission (1992).
*Sources:* Carbon liberation dates from Cannell and Cape (1991) and Thompson and Matthews (1989a,b). Production data from FICGB (1992) and Forestry Commission (1992); Adrian Whiteman, pers. comm., 1993.

5 per cent) is held as soil organisms (Jenkinson, 1988). On uncultivated soils a number of natural factors influence soil carbon content. These include 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.[17] 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 and residue treatments[18] (Parton *et al.*, 1987). The transition from uncultivated to intensive arable land, particularly where bare fallow rotation systems are used, is commonly associated with very significant losses in SOM (Klimowicz and Uziak, 2001). The majority of a soil's carbon is held near the surface and repeated tillage exposes the SOM to the atmosphere, increasing decomposition rates significantly above natural levels (Jenkinson, 1988). Tiessen *et al.* (1982) reports a 35 per cent fall in carbon levels over a seventy-year period as a result of switching grassland into cropping.[19] Jenkinson (1988) reports a similar loss over roughly thirty years for an area of old established grassland switched into various arable crops, the loss being greatest where land was regularly ploughed with no crop cover being sown.

The growth of intensive agriculture world-wide during the twentieth century has led to massive depletions in soil carbon levels.[20] These depletions have provided a major source of global $CO_2$ emissions (Bridges and Batjes, 1996) which is 'second only to fossil fuel combustion in contributing to historical increases of global carbon dioxide concentrations' (Post *et al.*, 1990).

### *Afforestation and soil carbon*

The potential for forest soils to store carbon is well known (Kaiser *et al.*, 2001; Neff and Asner, 2001; Rasse *et al.*, 2001); indeed, the majority of a forest's stored

[17] Harrison *et al.* (1995) report a strong negative relation between soil moisture deficit and carbon content. See also Edwards (1975).
[18] For example, whether or not stubble is burned.
[19] Clay and silt loam soils. Use of leguminous crops reduced losses from 35 per cent to 18 per cent (Tiessen *et al.*, 1982).
[20] Although there is evidence that cultivated soils may outperform forests in consumption of carbon monoxide (King, 2000).

carbon is held in its soils rather than its vegetation (Brown, 1998; UNDP *et al.*, 2000). However, until recently, relatively little work had been done on the long-term effects of afforestation upon soil carbon levels in the UK. An important early exception was provided by the work of Jenkinson (1971, 1988) who examined two areas which had been arable for many years before being abandoned and allowed to revert to woodland for some eighty years. This natural afforestation resulted in very considerable increases in soil carbon.

R. Matthews (1993), in his model of Sitka spruce forest carbon budgets, combines the work of Jenkinson with that of Whitehead *et al.* (1975) and Wilson (1991) in formulating his soil carbon flux predictions.[21] Here soil is assumed to have previously been under intensive cropping resulting in an initial, pre-afforestation, soil carbon content of 30 tC/ha. This is assumed to rise to approximately 70 tC/ha some 200 years after planting and reach a subsequent maximum of 100 tC/ha. Similar results are reported by Sampson (1992) in a study of two US sites which exhibit long-term soil carbon equilibrium increases of about 50 tC/ha arising from afforestation.

In a study using similar soil and management conditions, Dewar and Cannell (1992) report soil carbon storage curves for hardwoods which are similar to those of R. Matthews (1993) suggesting that there is not a particularly significant species effect here. More recent research provides some, although mixed, evidence on whether or not different tree species induce different rates of soil carbon storage (Priha *et al.*, 2001). Given this uncertainty, we do not differentiate between species in this respect. However, other factors can have very substantial impacts upon soil carbon flux.

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.[22] Adger *et al.* (1992) report equilibrium soil carbon levels for a variety of soils and land uses. This work was combined with information gathered in conversations with Professor David Jenkinson (Rothamsted), Dr Robert Sheil (University of Newcastle upon Tyne) and Professor Steven McGrath (Rothamsted), to whom we are grateful, to produce estimates of the full

[21] A further assumption, that clear felling will not reduce soil carbon providing replanting occurs within one year, is also made by R. Matthews (1993) with reference to the work of Edwards and Ross-Todd (1983). However, recent work by Harrison *et al.* (1995) suggests that SOM may decline during the first fifteen years following replanting after which it begins to rise again slowly, taking anything up to sixty years to return to equilibrium. See also Adger and Brown (1994).

[22] The SSLRC LandIS system provides the best source of soil type data for England and Wales. Land cover 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 (European Union, 1992) as employed by Cruikshank *et al.* (1995). Milne and Brown (1997) use the ITE land cover data to produce 1 km resolution maps of carbon storage in vegetation and soils for the whole of Great Britain. Our own work examines potential changes rather than current storage levels.

Table 7.3. *Post-afforestation changes in equilibrium soil carbon storage levels for various soils previously under grass (tC/ha): upland and lowland sites*[1]

| | Upland sites | | | Lowland sites | | |
|---|---|---|---|---|---|---|
| Soil type | Under grass | Under trees | Change | Under grass | Under trees | Change |
| Peat | 1,200 | 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 |

*Notes:* [1] Use prior to afforestation is assumed to be long-established agricultural pasture (dairy, cattle or sheep).
n/a = not applicable; soil type not common at this altitude.
Brackets indicate negative amounts.
*Source:* See text.

range of changes which could occur through afforestation of various soil types. This analysis was extended to consider both lowland and upland areas which, because of varying rainfall and land use, may exhibit significantly different rates of soil carbon accumulation. Table 7.3 presents results from this analysis.

Inspection of Table 7.3 shows that afforestation is generally synonymous with long-term increases in soil carbon storage levels and that these increases are liable to be somewhat larger in lowland sites because of the prevalence of more intensive prior agricultural land uses.[23] 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 (Cannell *et al.*, 1993; Davidson and Grieve, 1995; Harrison *et al.*, 1995).[24] Although UK forests are at present net absorbers of atmospheric carbon,[25] in an analysis of the carbon dynamics of land use in Great Britain during the period 1947–80, Adger *et al.* (1992) calculate that the planting of coniferous trees on peatlands, combined with the widespread substitution elsewhere of old-growth

[23] Feedback links between global warming and changes in forest soil carbon sequestration are investigated by Dalias *et al.* (2001).

[24] Cannell *et al.* (1993) examine the direct carbon flux impact of planting on peatbogs and suggest that there is a threshold depth of disturbance or ploughing of peat above which the net impact of afforestation is increased emission over one rotation, but below which there was net sequestration of carbon (although this study, like our own, ignores the effect upon other greenhouse gases such as methane). Updegraff *et al.* (2001) examine the relationship between changes in temperature and water table and emission of carbon dioxide and methane from peatlands. See also Steinkamp *et al.* (2001).

[25] Cannell and Dewar (1995) estimate current sequestration due to the total UK forest estate at 2.5 million tC per annum. Adger and Subak (1996) provide estimates for agricultural land.

broadleaf forest, with high carbon storage, by new conifer plantations, has resulted in the forestry sector being a net contributor to carbon emissions, a result which reinforces the need to incorporate soil carbon flux within our analysis.

Given the impact of discounting upon our 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 some extended period (Cannell and Milne, 1995a,b). Robert Shiel (pers. comm., 1994) suggests that roughly 95 per cent of the net change in soil carbon will occur within 200 years of planting. Both R. Matthews (1993) and Dewar and Cannell (1992) illustrate 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 are estimated for our three model elements:

(i) carbon storage in live wood
(ii) carbon emission from thinnings and wood products
(iii) 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.

A number of factors were relevant to selecting the period for the analysis. These were 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). In the light of these factors, it was decided that the analysis should be extended to cover a 1,000-year time period with replanting assumed to follow within a year of felling throughout this period. This allows the calculation of equilibrium carbon flux effects (although the subsequent process of discounting exponentially favours short-term impacts).

Once functions have been estimated we can readily calculate the per hectare net carbon storage (or emissions) for a selected species in any given year as follows:

(i) The carbon storage function for live trees of a given species and yield class is taken and run from planting to felling date (F). This function is restarted after each F to simulate replanting;
(ii) Emissions from thinnings and products deriving from prior rotations are summed and subtracted from (i). Note that the emissions functions from any given rotation will

extend beyond the lifespan of the next rotation, i.e., such functions overlap such that in any given year there may be emissions from more than one previous rotation. However, there are no emissions prior to first thinning of the initial rotation;[26]

(iii) 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 (i) and (ii) to yield the marginal net annual change in carbon storage.

The above calculations are performed for each year in our 1,000-year analysis. The process is then repeated using the other YCs considered in stage (i) above. Finally the entire calculation is repeated using functions for the other species under consideration.

Valuation of the marginal net annual change in carbon storage is achieved by reference to the relevant unit values for each year given in Fankhauser (1994b) as discussed previously. We thereby derive a stream of marginal carbon storage values for each species, and within each YC, under consideration. These are undiscounted values to which any desired discount rate may be applied to calculate net present value or annuity equivalents as required.

As a final step we use our GIS to apply these various valuations to the maps of predicted YC for the two species under consideration presented in Chapter 6. In so doing we produce maps of live wood carbon storage value. The GIS is also used to relate our soil carbon values to the LandIS soil type data layer and produce a map of soil carbon flux values.[27] By superimposing these maps and adding their values we obtain a joint live wood and soil carbon sequestration value map. Finally, by subtracting the thinnings and wood product emissions levels for the relevant species, we obtain a map of the overall net carbon flux value for a given species for all locations in our case study area. Such a map allows us to readily identify those areas which, if afforested, would yield optimal carbon storage values.[28]

## Modelling carbon storage in trees

### *Carbon storage in Sitka spruce live wood*

As discussed previously, carbon sequestration in an unthinned standing crop follows an approximately S-shaped time trend. Figure 7.1 showed 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 (as the majority of UK plantations are subject to thinning we shall concentrate upon such stands for the remainder of this analysis). However, as we showed in Chapter 5, within each species both TD1 and F can be shown to

[26] Note that we ignore emissions from vehicles and machinery involved in planting and felling.
[27] Skidmore *et al*. (1991) use an expert systems approach to map forest soils from a GIS.
[28] Cieszewski *et al*. (1996) provide an analysis of error propagation within carbon flux assessments.

be functions of yield class and discount rate.[29] 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 we wish to discount storage values, 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, in the first major UK study of this issue, adopts 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 we start the modelling process by explicitly considering the S-shaped curve which is total carbon storage in unthinned live wood (uTWCS). The Bureau of Transport and Communications Economics (BTCE, 1996a) discusses a number of functional forms for modelling this curve; however, for simplicity we adopt the cubic given in Equation (7.1):

$$\mathrm{uTWCS}_{\mathrm{i,YC},t} = \beta_{1\mathrm{iYC}} + \beta_{2\mathrm{iYC}}t + \beta_{3\mathrm{iYC}}t^2 + \beta_{4\mathrm{iYC}}t^3 \tag{7.1}$$

where:

$$\begin{aligned} \mathrm{i} &= \text{species (for Sitka spruce, i} = \text{SS; for beech, i} = \text{BE)} \\ \mathrm{YC} &= 4, 6, 8, \ldots 26 \text{ (for i} = \text{SS)} \\ t &= \text{years from planting } (t = 0, 1, 2, \ldots \mathrm{F}) \end{aligned}$$

*A priori* we would expect $\beta_1 = 0, \beta_2 > 0, \beta_3 > 0$ and $\beta_4 < 0$.[30] In order to estimate Equation (7.1), data for Sitka spruce YC12 were taken from R. Matthews (1992, 1993).[31] Initial investigations confirmed that an optimal statistical model based on Equation (7.1) gave estimates of $\beta_1$ which were not significantly different from zero (as expected) and so this element was dropped from our final model which is reported as Equation (7.2).

$$\begin{aligned} \mathrm{uTWCS}_{\mathrm{SS},12,t} \;=\; & 0.43727t + 0.10747t^2 - 0.0010267t^3 \\ & \;(4.40) \qquad\quad (28.09) \qquad\quad (-29.21) \end{aligned} \tag{7.2}$$

$R^2 = 99.9\%$; $n = 81$. Figures in brackets are $t$-statistics.

29 Recall that discount rate is held constant in Figure 7.1 such that only the yield-class effect is illustrated.

30 The $\beta_4$ term provides a potential advantage over non-declining functional forms such as the logit, which cannot capture a possible reduction in the volume of a stand if left unmanaged with natural regeneration permitted.

31 These data are based upon a superior total/merchantable volume function to that used in Matthews (1991) upon which the estimates of Pearce (1991) are based.

Not surprisingly, given the predictability of tree growth patterns, Equation (7.2) fits the data extremely well. All estimated coefficients are very highly significant ($p < 0.001$ in all cases) and have expected signs and magnitudes.

We now need to generalise across yield classes. The work of Cannell and Cape (1991) shows that, within a given species, carbon storage varies linearly across YC. We can therefore derive a species-specific YC adjustment factor, which we denote $A_{iYC}$, to permit us to adjust from the YC of our baseline data (YC12) to any other Sitka spruce YC. Cannell and Cape (1991) report curves linking timber volume, biomass, carbon storage and stand age for a variety of Sitka spruce YCs. Using this information we can estimate an adjustment factor for Sitka spruce of $A_{SS,YC} = 0.08333$ YC (note that when YC $= 12$ then $A_{SS,12} = 1.0$).[32] A generalised function for $uTWCS_{i,YC}$ for i $=$ SS and any YC can then be derived as in Equation (7.3):

$$uTWCS_{SS,YC,t} = A_{SS,YC} * uTWCS_{SS,12,t} \tag{7.3}$$

These functions will continue to rise until $t =$ F. However, as noted, F is a complex function of both the discount rate ($r$) and YC. This relationship was investigated using the YC/discount rate analysis of optimal felling dates reported in Chapter 5. Our resultant best-fit model is shown in Equation (7.4):

$$\begin{aligned} F_{SS,YC} = \; & 114.43 - 997.3r + 7167r^2 - 2.8657\mathrm{YC} + 0.05919\mathrm{YC}^2 \\ & (32.67) \quad (–6.25) \quad (3.62) \quad (–9.21) \quad (5.79) \end{aligned} \tag{7.4}$$

where:

$F_{SS,YC} =$ optimal felling date for a given yield class (YC) of a specified tree species (here Sitka spruce, SS)

$r =$ discount rate (expressed as a decimal)

$R^2 = 96.6\%$; $n = 39$. Figures in brackets are $t$-statistics.

Equation (7.4) fits the data extremely well for the range of observed F with all parameters significant at $p < 0.001$. It shows, as noted previously, that F declines with both $r$ and YC, although the clear significance of the square terms in Equation (7.4) indicates that this is not a simple, straight-line relationship.

We now consider thinned crops. To do this we first need to estimate TD1. Examination of the yield models given in Edwards and Christie (1981) shows a clear relationship between TD1, F and YC as demonstrated in Table 7.4 for their Sitka spruce yield models.

[32] For derivation, see Bateman (1996).

Table 7.4. *Date of first thinning (TD1) for Sitka spruce yield models (r = 0.05 throughout)*

| YC | Optimal felling year (F)[1] | Year of first thinning (TD1)[2] | Ratio (TD1/F) |
|---|---|---|---|
| 6 | 68 | 33 | 0.485 |
| 8 | 67 | 29 | 0.433 |
| 10 | 64 | 26 | 0.406 |
| 12 | 58 | 24 | 0.414 |
| 14 | 54 | 22 | 0.407 |
| 16 | 51 | 21 | 0.412 |
| 18 | 50 | 20 | 0.400 |
| 20 | 50 | 19 | 0.380 |
| 22 | 49 | 18 | 0.367 |
| 24 | 48 | 18 | 0.375 |

*Sources:* [1] From Chapter 5, this volume.
[2] From Edwards and Christie (1981); models for 2m spaced planting with no delay in thinning.

Inspecting Table 7.4 shows that, as YC rises and F falls, so TD1 declines. One simple method of capturing this relationship is to first model the ratio TD1:F as a function of YC as shown in Equation (7.5):

$$\begin{aligned}\mathrm{RATIOTD1}_{\mathrm{SS,YC}} &= \underset{(32.21)}{0.48149} - \underset{(-5.27)}{0.0049061\mathrm{YC}}\end{aligned} \tag{7.5}$$

where:

$\mathrm{RATIOTD1}_{\mathrm{SS,YC}}$ = ratio of TD1 to F across YC for Sitka spruce
$R^2 = 77.7\%$; $n = 10$. Figures in brackets are $t$-statistics.

While the small sample size used in Equation (7.5) is not ideal, individual $t$-statistics are highly significant and, as no further data are available, this seems a reasonable approach. TD1 can now be calculated for any given YC by multiplying the corresponding felling date by Equation (7.5) as shown in Equation (7.6):

$$\mathrm{TD1}_{\mathrm{SS,YC}} = (0.48149 - 0.0049061\mathrm{YC}) * \mathrm{F}_{\mathrm{SS,YC}} \tag{7.6}$$

As shown in Figure 7.1, once thinning commences total tree carbon storage falls progressively below that predicted by our uTWCS function. Using data from R. Matthews (1991, 1992, 1993) we can measure this proportion as the thinning factor (TF) detailed in the final column of Table 7.5.

Statistical investigation showed that $\mathrm{TF}_{\mathrm{SS},t}$ (the thinning factor for Sitka spruce in year $t$) could be well predicted by the natural log of the number of years since

Table 7.5. *Thinning factor for Sitka spruce ($TF_{SS,t}$): YC12*

| Years after date of first thinning ($t^* = t - \text{TD1}$) | Total unthinned tree carbon storage (tC/ha) ($\text{uTWCS}_t$) | Total thinned tree carbon storage (tC/ha) ($\text{tTWCS}_t$) | Reduction in total potential tree carbon storage arising from thinning (tC/ha) | Thinning factor $\left[\text{TF}_{\text{SS},t} = \frac{\text{tTWCS}_t}{\text{uTWCS}_t}\right]$ |
|---|---|---|---|---|
| 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 in R. Matthews (1991, 1992, 1993).

thinning had commenced in a given plantation (denoted $t^*$ where $t^* = t - \text{TD1}$ for all $t \geq \text{TD1}$; note that where $t < \text{TD1}$ (i.e. before thinning commences) we constrain TF to equal 1). Equation (7.7) details our best-fitting model of $\text{TF}_{\text{SS},t}$.

$$\text{TF}_{\text{SS},t} = \underset{(37.90)}{1.000} - \underset{(-13.41)}{0.1158} \ln t^* \tag{7.7}$$

$R^2 = 96.3\%$; $n = 9$. Figures in brackets are $t$-statistics.

We are now able to calculate total live wood tree carbon storage for thinned stands of Sitka spruce in any year $t$ ($\text{tTWCS}_{\text{SS,YC},t}$):

$$\text{tTWCS}_{\text{SS,YC},t} = \text{uTWCS}_{\text{SS,YC},t} * \text{TF}_{\text{SS},t} \tag{7.8}$$

The function shown in Equation (7.8) increases in each year from planting until felling after which replanting is assumed to follow within one year and the function returns to zero and restarts its growth path. Given that this model is discontinuous it cannot readily be differentiated. Consequently, marginal carbon storage was calculated by solving equation (7.8) iteratively for each year in our time series and calculating the annual change.[33]

[33] 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.

### *Carbon storage in beech live wood*

The modelling of carbon storage in beech live wood followed the methodology used for Sitka spruce and therefore will be only briefly described. Information regarding sequestration in beech is somewhat sparser than for its widespread coniferous counterpart, so much so that our analysis is based upon the estimates for oak (YC4) given in Dewar and Cannell (1992), adjusted by consulting the YC4 model for beech given in Edwards and Christie (1981). This exercise relies on the findings of G. Matthews (1993), who suggests that, within YC bands, carbon storage for oak and beech will be similar. Using this approach, observations on the S-shaped unthinned carbon storage curve $\mathrm{uTWCS}_{\mathrm{BE},4,t}$ were built up for use in the estimated model:

$$\begin{aligned} \mathrm{uTWCS}_{\mathrm{BE},4,t} \; = \; & 0.2414t + 0.030752t^2 - 0.00014252t^3 \\ & (2.17) \qquad (13.73) \qquad\quad (-13.24) \end{aligned} \tag{7.9}$$

$R^2 = 99.9\%$; $n = 26$. Figures in brackets are $t$-statistics.

As with Sitka spruce, the model of total carbon storage in unthinned beech live wood fits the data very well. All parameter estimates are highly significant ($p < 0.05$ for $t$ and $p < 0.000$ for $t^2$ and $t^3$) and coefficients have expected signs and magnitudes (the latter differing logically from those of our Sitka spruce model).

An adjustment factor for beech ($\mathrm{A}_{\mathrm{BE,YC}}$) was calculated as before to allow comparison across YC, the data given in Dewar and Cannell (1992) implying that $\mathrm{A}_{\mathrm{BE,YC}} = 0.25\ \mathrm{YC}$ (note that when $\mathrm{YC} = 4$, then $\mathrm{A}_{\mathrm{BE},4} = 1.0$). A generalised function for $\mathrm{uTWCS}_{\mathrm{i,YC}}$ for $\mathrm{i} = \mathrm{BE}$ and any YC can then be derived as:

$$\mathrm{uTWCS}_{\mathrm{BE,YC},t} = \mathrm{A}_{\mathrm{BE,YC}} * \mathrm{uTWCS}_{\mathrm{BE},4,t} \tag{7.10}$$

We can now estimate F for beech as a function of $r$ and YC using the data reported in Chapter 5. Our best-fit model is:

$$\begin{aligned} \mathrm{F}_{\mathrm{BE,YC}} = \; & 173.86 - 1901.4r + 8870.8r^2 - 5.387\mathrm{YC} + 0.2500\mathrm{YC}^2 \\ & (20.78) \quad (-18.07) \quad (11.99) \qquad (-2.25) \qquad (1.47) \end{aligned} \tag{7.11}$$

$R^2 = 97.8\%$; $n = 32$. Figures in brackets are $t$-statistics.

Equation (7.11) fits the data very well and reconfirms the relationships noted regarding Sitka spruce. All estimates are significant at $p < 0.05$ or better with the exception of the $\mathrm{YC}^2$ term which has $p = 0.152$. While this is in itself insignificant the term is retained both for comparison with our previous model and because it yields a slight improvement in adjusted model fit.

Table 7.6. *Date of first thinning (TD1) for beech yield models (r = 0.05 throughout)*

| YC | Year of first thinning (TD1)[1] | Optimal felling year (F)[2] | Ratio (TD1/F) |
|---|---|---|---|
| 4 | 35 | 81 | 0.432 |
| 6 | 30 | 75 | 0.400 |
| 8 | 25 | 71 | 0.352 |
| 10 | 25 | 69 | 0.362 |

*Sources:* [1] From Edwards and Christie (1981); models for 1.2m spaced planting with no delay in thinning.
[2] From Chapter 5, this volume.

The year of first thinning (TD1) is also estimated as before. Table 7.6 presents the data for this analysis. As can be seen, the lack of variation in YC for British beech considerably reduces the number of observations available.

As before we now estimate $RATIOTD1_{BE,YC}$, as shown in Equation (7.12):

$$RATIOTD1_{BE,YC} = \underset{(15.29)}{0.47666} - \underset{(-3.03)}{0.012861}YC \tag{7.12}$$

$R^2 = 82.1\%$; $n = 4$. Figures in brackets are $t$-statistics.

The very low number of observations underpinning Equation (7.12) is problematic although it is not clear how further data could readily be generated. Nevertheless, relationships are as expected and this seems acceptable as a methodological exercise. TD1 can now be calculated for any given YC as:

$$TD1_{BE,YC} = (0.47666 - 0.012861YC) * F_{SS,YC} \tag{7.13}$$

Dewar and Cannell (1992) do not report any information from which a thinning factor ($TF_{BE}$) might be derived. However, we can obtain an estimate for this by examining the beech yield models of Edwards and Christie (1981). Figure 7.3 illustrates implicit $TF_{BE}$ from data given in the latter.

Inspection of Figure 7.3 shows that $TF_{BE,t}$ is very similar to $TF_{SS,t}$ as detailed in Table 7.5. In both cases TF follows a roughly logarithmic pattern, falling rapidly once thinning commences and becoming fairly stable after about thirty years. We can therefore assume an approximate equality between these relationships and use Equation (7.7) to define $TF_{BE,t}$. Given this, we are now able to calculate total live wood tree carbon storage for thinned stands of beech in any year

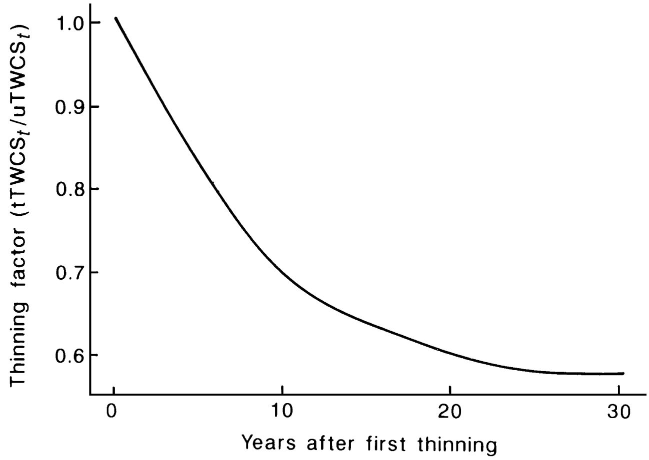


Figure 7.3. Thinning factor for beech. (*Source:* From data given in Edwards and Christie, 1981.)

$t$ ($tTWCS_{BE,YC,t}$) as:

$$tTWCS_{BE,YC,t} = uTWCS_{BE,YC,t} * TF_{BE,t} \tag{7.14}$$

## Modelling carbon liberation from felling waste and timber products

The methodology adopted for modelling carbon liberation from felling waste and timber products was common to both Sitka spruce and beech. Earlier in this chapter it was shown that end use has a major impact upon overall carbon flux. Examining Table 7.2 indicates that, for all but the shortest lifespan products, carbon liberation appears to follow a roughly normal distribution. Short lifetime products (those from which virtually all carbon is liberated within five years of felling) have modal liberation during the year of felling after which liberation rates fall swiftly over time. Assuming an approximately straight-line, downward-sloping liberation distribution for the latter and a normal distribution centred upon the modes listed in Table 7.2 for all other products, we obtain the product-specific carbon liberation schedules illustrated in Figure 7.4 for Sitka spruce and Figure 7.5 for beech. These are expressed as a proportion of the total amount of carbon stored by one hectare of live wood (i.e. excluding soil flux) during the course of a full rotation.

In Figure 7.4, panels (a) to (e) show carbon liberation distributions for Sitka spruce products and waste categorised according to longevity. So, for example, from panel (a) we can see that nearly 10 per cent of the total carbon stored in live wood by a rotation of Sitka spruce is liberated in the year of felling ($t = 0$) via short lifetime (five year maximum) products (e.g. paper and fuel) and waste (including felling waste). Conversely, panel (c) shows that in the same year only

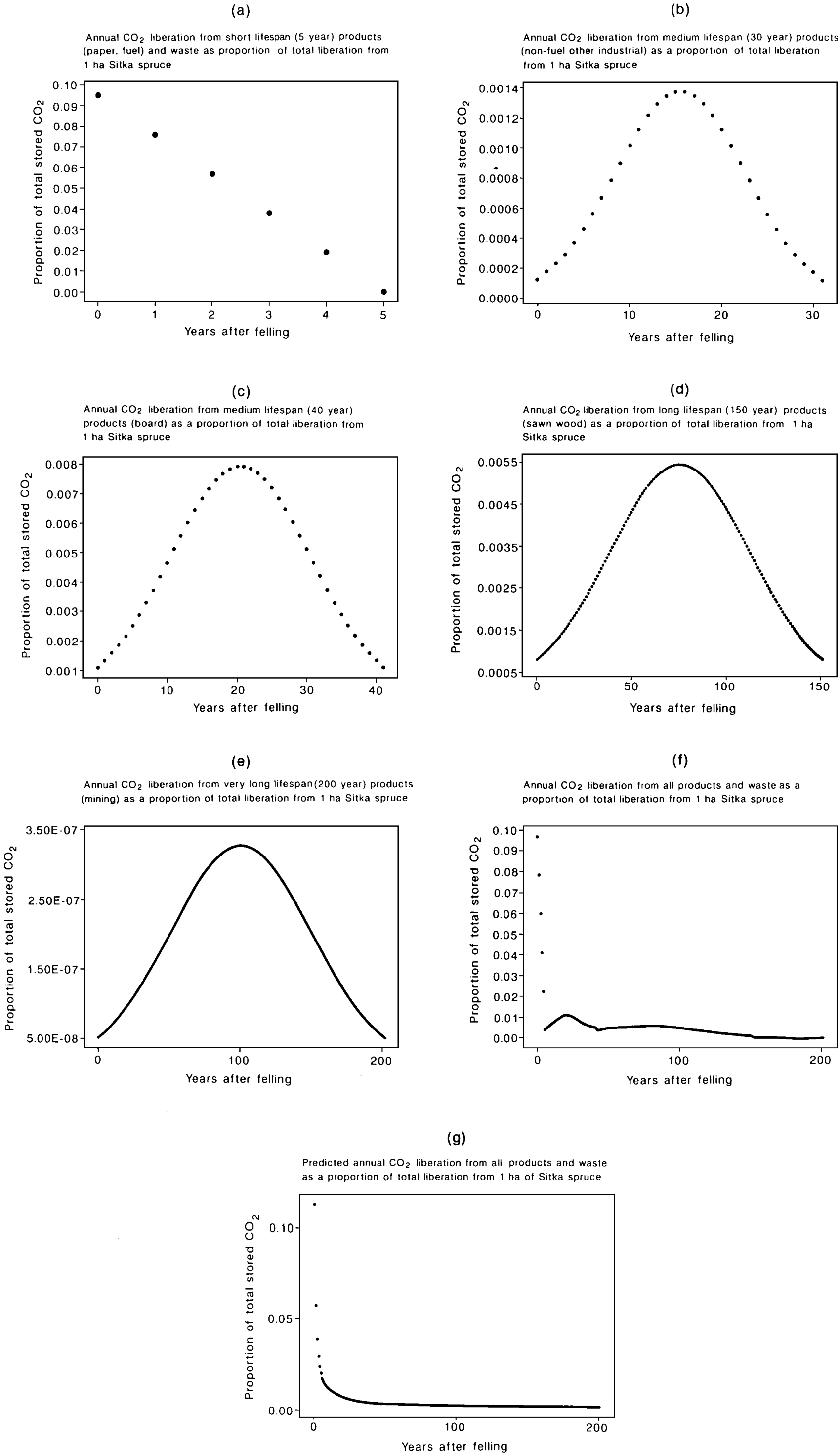


Figure 7.4. Annual carbon liberation distributions for products and waste expressed as a proportion of total carbon sequestration in wood from one rotation of Sitka spruce.

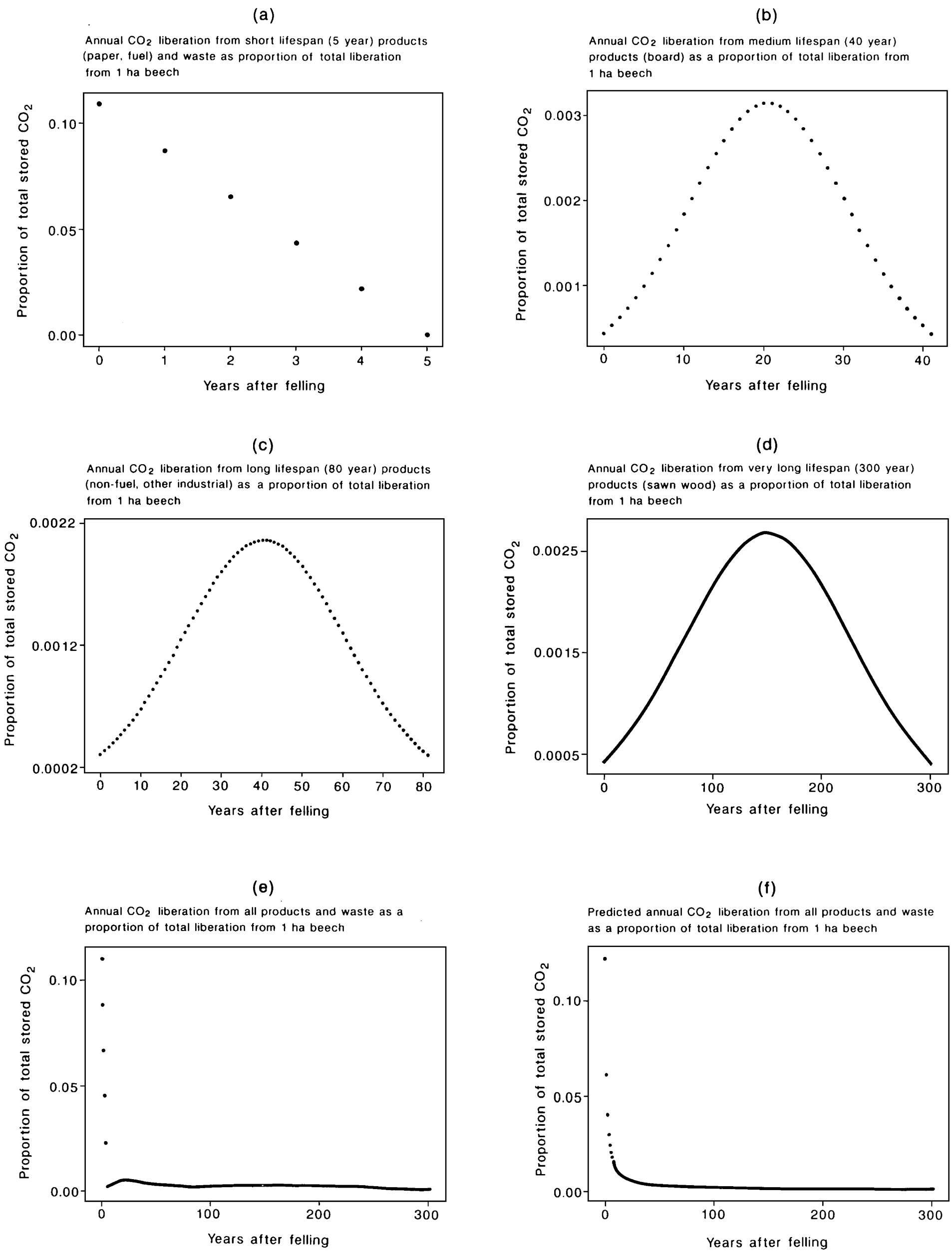


Figure 7.5. Annual carbon liberation distributions for products and waste expressed as a proportion of total carbon sequestration in wood from one rotation of beech.

0.1 per cent of total live wood stored carbon is liberated via medium lifespan (forty year maximum) products (e.g. board). Panel (f) sums all these distributions to produce an overall carbon liberation distribution. This shows that liberation is highest in the felling year and then falls rapidly to some low positive amount which then gradually declines over an extended period. A number of statistical models were fitted to these data, the optimal model being reported in equation (7.15) with predictions being illustrated in panel (g) of Figure 7.4.

$$\begin{aligned} \mathrm{LIB\%}_{\mathrm{SS},t} &= \underset{(6.30)}{0.0017146} + \underset{(36.53)}{0.110363}\,\mathrm{ETREND}_{\mathrm{SS},t} \end{aligned} \tag{7.15}$$

where:

$\mathrm{LIB\%}_{\mathrm{SS},t}$ = annual carbon liberation from all products and waste as a proportion of the total carbon stored in live wood by one rotation of Sitka spruce

$\mathrm{ETREND}_{\mathrm{SS},t}$ = $1/(1+t')$ where $t' = 0$ at felling (F) and maximum $t' = 200$

$R^2$ = 87.0%; $n = 201$. Figures in brackets are $t$-statistics.

The $\mathrm{ETREND}_{\mathrm{SS},t}$ variable provides a good fit to the carbon liberation data as illustrated by the similarity between actual and predicted liberation distributions shown in panels (f) and (g), respectively, of Figure 7.4. Equation (7.15) implies that all carbon stored in live wood by a rotation of Sitka spruce will be liberated by $t' = 200$, after which we constrain $\mathrm{LIB\%}_{\mathrm{SS},t}$ to equal zero.

Turning to Figure 7.5, panels (a) to (d) detail carbon liberation proportion distributions by product category for beech, while panel (e) illustrates their sum. Again this was modelled using a variety of approaches and functional forms with the best model being:

$$\begin{aligned} \mathrm{LIB\%}_{\mathrm{BE},t} &= \underset{(4.01)}{0.0007818} + \underset{(45.97)}{0.121461}\,\mathrm{ETREND}_{\mathrm{BE},t} \end{aligned} \tag{7.16}$$

where:

$\mathrm{LIB\%}_{\mathrm{BE},t}$ = annual carbon liberation from all products and waste as a proportion of the total carbon stored in live wood by one rotation of beech

$\mathrm{ETREND}_{\mathrm{BE},t}$ = $1/(1+t')$ where $t' = 0$ at felling and maximum $t' = 300$

$R^2$ = 87.6%; $n = 301$. Figures in brackets are $t$-statistics.

Equation (7.16) for beech has the same form and explanatory variable as for Sitka spruce in equation (7.15). A similar high degree of fit is achieved, as illustrated by comparing actual and predicted liberation in panels (e) and (f), respectively, of Figure 7.5. Equation (7.16) implies that all carbon stored by a rotation of beech will be liberated by $t' = 300$ after which we constrain $\mathrm{LIB\%}_{\mathrm{BE},t}$ to equal zero.

## Modelling carbon storage and loss from soils

Examining Table 7.3 it is tempting to conclude that we should model individual soil category carbon changes, including some element for altitude. Indeed the integrative and analytical capabilities provided by a GIS invite such an approach. However, we are painfully aware of the paucity of data that underpins Table 7.3 and of the numerous complications (such as the implications of replanting) which have yet to be quantified. We therefore adopt a simplified and conservative approach to modelling soil carbon flux along the lines of Dewar and Cannell (1992), Sampson (1992) and R. Matthews (1993), all of whom assume a constant, smooth and marginally diminishing carbon flux path for all soils.

Erring on the conservative side, Table 7.3 supports a net long-term increase in soil carbon equilibrium levels for non-peaty soils at a range of altitudes of about 50 tC/ha. For peat soils a net long-term loss of some 750 tC/ha seems defensible. Following our literature review we know that for both peat and non-peat soils the rate of carbon flux will be highest immediately after felling and decline such that 95 per cent of soil carbon change will have been achieved after about 200 years.

Equation (7.17) calculates the proportion of the total change in soil carbon ($\mathrm{PROPT\Delta SC}_t$) which will have been achieved in any year $t$, where $t = 0$ at planting. Notice that $\mathrm{PROPT\Delta SC}_t = 1.00$ when $t = 263$ (based on the assumption that 95 per cent of total soil carbon change occurs by $t = 199$) after which it is constrained to equal 1.00 throughout the remainder of the period under analysis.

$$\mathrm{PROPT\Delta SC}_t = 0.1793022 \ln \mathrm{TIME1}_t \tag{7.17}$$

where:

$$\mathrm{TIME1}_t = t + 1 \text{ and } t = 0 \text{ at planting.}$$

Equation (7.17) implies a diminishing marginal proportion of soil carbon change over the period $0 \le t \le 263$ (i.e. annual carbon changes are highest in the year in which the first rotation is planted and decline thereafter). These marginal values can be obtained by simple, one-period differencing. Multiplying these annual proportions by the total change (50 tC/ha for non-peat soils and −750 tC/ha for peat soils) gives the annual soil carbon gains and losses (in tC/ha).

## Results

### *Net carbon storage in live wood, products and waste*

Setting aside soil carbon impacts (discussed subsequently), the carbon storage and liberation equations reported above for Sitka spruce and beech were operationalised through a custom-written Fortran program.[34] This program yielded estimates of carbon sequestration value by species for a range of YC and discount rates. For

[34] This program is listed, with sample output, in Bateman (1996).

Table 7.7. *NPV of net carbon flux (sequestration in live wood and liberation from products and waste) for an optimal rotation of Sitka spruce: various yield classes and discount rates (£, 1990)*

| Discount rate (%) | YC4 | YC6 | YC8 | YC10 | YC12 | YC14 | YC16 | YC18 | YC20 | YC22 | YC24 | YC26 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.5 | 811 | 1,166 | 1,491 | 1,815 | 2,122 | 2,415 | 2,692 | 3,002 | 3,308 | 3,609 | 3,902 | 4,228 |
| 2 | 699 | 1,007 | 1,290 | 1,570 | 1,837 | 2,089 | 2,364 | 2,634 | 2,897 | 3,151 | 3,404 | 3,652 |
| 3 | 536 | 774 | 1,005 | 1,208 | 1,415 | 1,629 | 1,816 | 2,015 | 2,199 | 2,391 | 2,567 | 2,781 |
| 5 | 342 | 496 | 643 | 785 | 916 | 1,035 | 1,160 | 1,278 | 1,393 | 1,503 | 1,626 | 1,761 |
| 6 | 284 | 411 | 535 | 653 | 761 | 859 | 963 | 1,060 | 1,156 | 1,253 | 1,367 | 1,466 |

each discount rate/YC combination, three net carbon sequestration values were calculated:

(i) the net present value (NPV) of the initial optimal rotation
(ii) the NPV of a perpetual series of optimal rotations (to $t = 1{,}000$, assuming replanting after felling), and
(iii) the annuity equivalent of the latter.

Bateman (1996) reports full results of all these analyses for all three measures. For brevity, here we report just the first of these measures for Sitka spruce (Table 7.7) and beech (Table 7.8).

Considering Tables 7.7 and 7.8 we can see that both yield class and discount rate have highly significant impacts upon net carbon sequestration 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.[35] The resultant regression models are reported in Table 7.9.

As can be seen, the models reported in Table 7.9 fit the data well. These models can now be applied to our maps of predicted timber YC, as derived in Chapter 6, to produce maps of the net carbon sequestration value derived from consideration of storage in live wood and emissions from thinnings and wood products (but not soil carbon impacts) for the entire Welsh study area. Discounting effects can be analysed by simply selecting the equation from Table 7.9 which refers to the desired species/discount rate combination. As examples, Figure 7.6 illustrates the resultant NPV map for an optimal first rotation of Sitka spruce using a 3 per cent discount rate,[36] while Figure 7.7 illustrates the respective value for beech.

The images detailed in Figures 7.6 and 7.7 strongly reflect the underlying pattern of timber yield and consequently echo the environmental determinants of such growth rates. Notice that the pattern of net carbon flux values is similar for the two species, reflecting 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, carbon flux NPV sums are consistently higher for Sitka spruce than for beech. This arises because the superior growth rate of Sitka spruce directly fixes more carbon, more quickly, than beech does. As a consequence the former is far less affected by the process of discounting, and resultant NPV levels are higher.

Figures 7.6 and 7.7 are calculated holding the discount rate constant at 3 per cent. Table 7.10 relaxes this restriction and, for both of the species under consideration, compares the NPV of net carbon flux for live wood, waste and products across a

[35] Bateman (1996) also reports equations predicting the NPV in perpetuity and the annuity equivalent carbon storage values.
[36] This rate is chosen here to reflect recent debate concerning an appropriate social discount rate (Pearce and Ulph, 1998); see Chapter 5.

Table 7.8. *NPV of net carbon flux (sequestration in live wood and liberation from products and waste) for an optimal rotation of beech: various yield classes and discount rates (£, 1990)*

| Discount rate (%) | YC2 | YC4 | YC6 | YC8 | YC10 | YC12 |
|---|---|---|---|---|---|---|
| 1.5 | 886 | 1,673 | 2,401 | 3,059 | 3,690 | 4,326 |
| 2 | 706 | 1,332 | 1,889 | 2,421 | 2,941 | 3,437 |
| 3 | 466 | 875 | 1,246 | 1,607 | 1,924 | 2,262 |
| 5 | 242 | 454 | 649 | 830 | 1,003 | 1,178 |
| 6 | 186 | 349 | 497 | 638 | 775 | 907 |

Table 7.9. *NPV of carbon in live wood, waste and products from an optimal rotation of Sitka spruce and beech: linear predictive equations with yield class as the single explanatory variable: various discount rates*

| Species | Discount rate (%) | Intercept ($t$-value) | Slope ($t$-value) | $R^2$ (adj.) |
|---|---|---|---|---|
| Sitka spruce | 1.5 | 254.32 (14.62) | 152.83 (145.11) | 99.9 |
| Sitka spruce | 3 | 187.70 (9.90) | 100.46 (87.48) | 99.9 |
| Sitka spruce | 6 | 106.77 (9.06) | 52.71 (73.89) | 99.8 |
| Beech | 1.5 | 281.86 (4.68) | 341.52 (44.20) | 99.7 |
| Beech | 3 | 148.14 (4.92) | 178.34 (46.18) | 99.8 |
| Beech | 6 | 56.18 (5.54) | 71.80 (55.19) | 99.8 |

range of discount rates.[37] The table gives frequency counts and percentages for the number of 1 km cells within each value band.

Analysis of Table 7.10 shows that both the choice of discount rate and the choice of species have substantial impacts upon net carbon storage values. As before we find that the slower timber growth rate of beech results in lower discounted values of carbon sequestration than those for Sitka spruce. However, as expected, this divergence of values between species declines as the discount rate falls.

### *Extending the analysis to include soil carbon flux*

Equation (7.17) 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-peaty soils; −750 tC/ha for peaty soils) by the marginal proportion change in each year. This annual soil carbon gain or

[37] Annuity equivalents are reported in Bateman (1996).

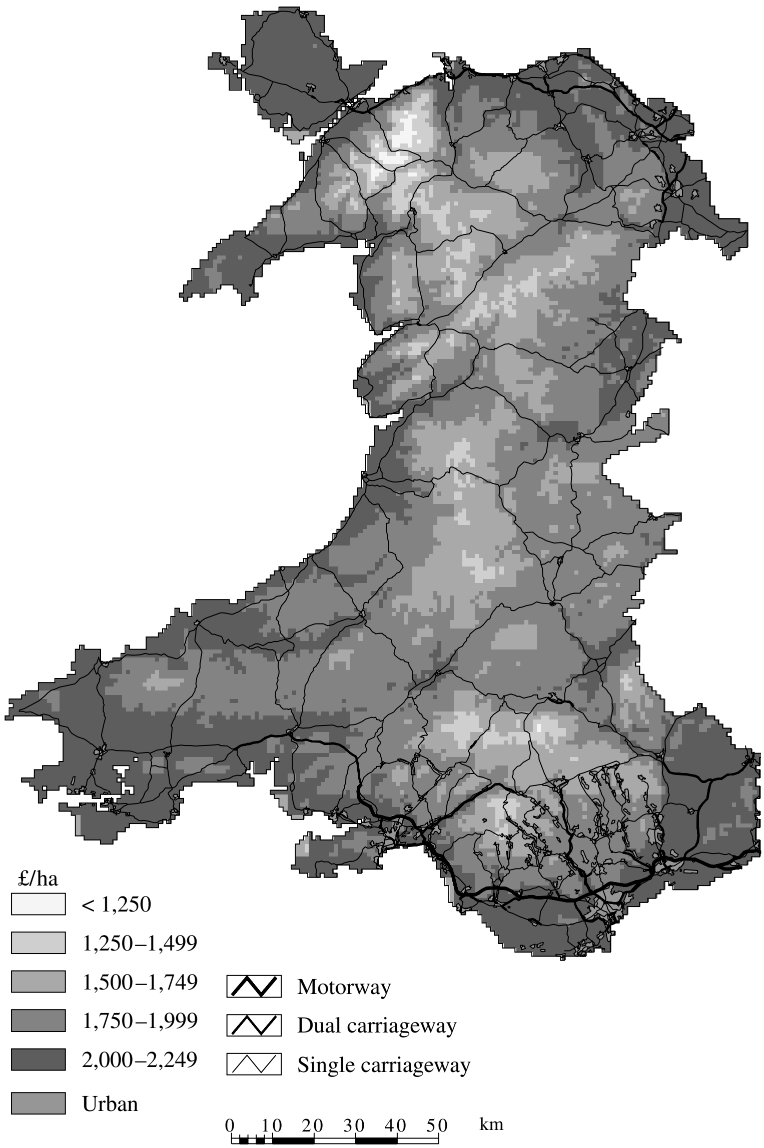


Figure 7.6. NPV of net carbon storage in live wood, products and waste from an optimal first rotation of Sitka spruce: 3% discount rate.

loss was subsequently valued using the Fankhauser values as discussed previously. These values were then discounted at various rates, and net present value perpetuity sums calculated as shown in Table 7.11.[38]

[38] Given that soil carbon change is a slow process (Milne and Brown, 1997), taking many rotations to complete, calculation of first rotation NPV sums is of less interest here than in our analysis of tree carbon fixing values. Annuity equivalents are reported in Bateman (1996).

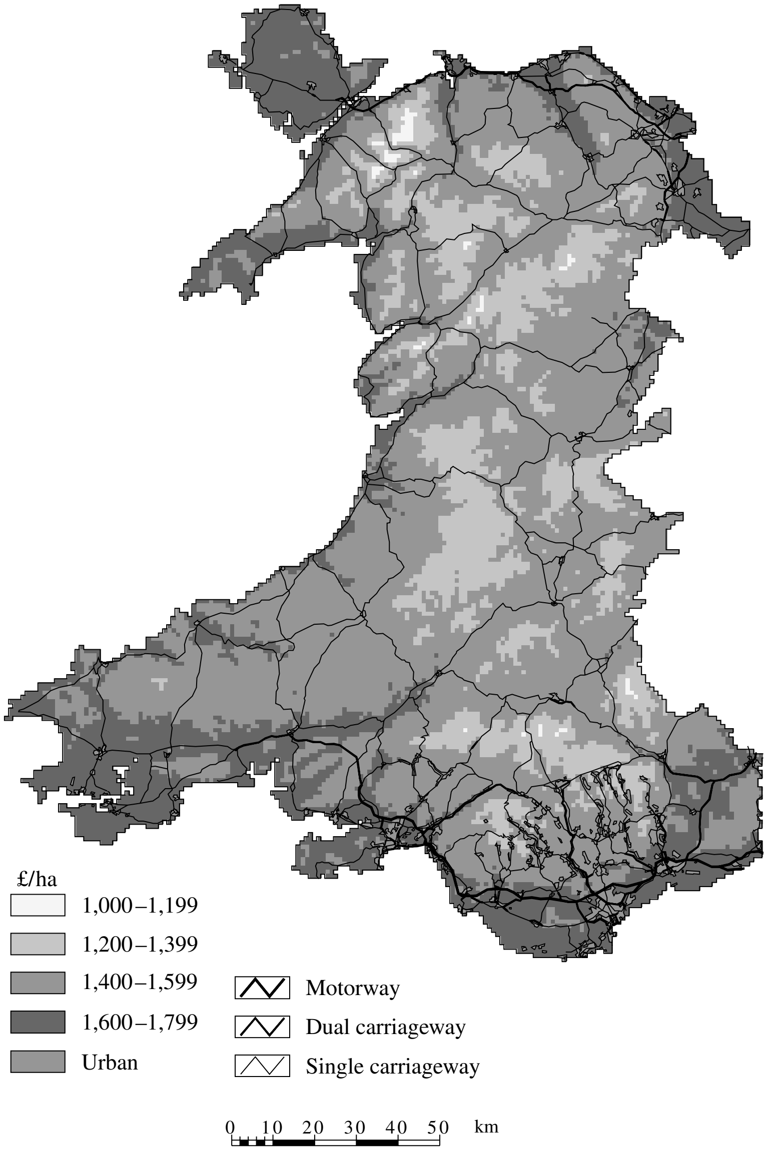


Figure 7.7. NPV of net carbon storage in live wood, products and waste from an optimal first rotation of beech: 3% discount rate.

Maps of soil carbon flux values were created by applying the values given in Table 7.11 to a soil map derived from the LandIS database (see the discussion in Chapter 6). Given the lack of detailed information concerning soil flux impacts, the resultant maps (reproduced in Bateman, 1996) contain only two values, representing the presence or absence of peaty soils, the latter being generally confined to extreme upland areas where carbon storage is already low due to depressed tree growth rates.

Table 7.10. *NPV of Sitka spruce and beech carbon flux for live wood, waste and products: various discount rates* (r)

| | Sitka spruce | | | | | | Beech | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $r = 1\%$ | | $r = 3\%$ | | $r = 6\%$ | | $r = 1\%$ | | $r = 3\%$ | | $r = 6\%$ | |
| NPV (£/ha) | Freq.[1] | % | Freq.[1] | % | Freq.[1] | % | Freq.[1] | % | Freq.[1] | % | Freq.[1] | % |
| 250–499 | — | — | — | — | 1 | 0.005 | — | — | — | — | 161 | 0.783 |
| 500–749 | — | — | — | — | 228 | 1.109 | — | — | — | — | 20,402 | 99.217 |
| 750–999 | — | — | 5 | 0.024 | 8,042 | 39.109 | — | — | — | — | — | — |
| 1,000–1,249 | — | — | 50 | 0.243 | 12,292 | 59.777 | — | — | 159 | 0.773 | — | — |
| 1,250–1,499 | 5 | 0.024 | 624 | 3.035 | — | — | — | — | 7,809 | 37.976 | — | — |
| 1,500–1,749 | 27 | 0.131 | 3,621 | 17.609 | — | — | — | — | 12,595 | 61.251 | — | — |
| 1,750–1,999 | 71 | 0.345 | 8,648 | 42.056 | — | — | 1 | 0.005 | — | — | — | — |
| 2,000–2,249 | 571 | 2.777 | 7,615 | 37.033 | — | — | 41 | 0.200 | — | — | — | — |
| 2,250–2,449 | 2,036 | 9.901 | — | — | — | — | 387 | 1.882 | — | — | — | — |
| 2,500–2,749 | 3,561 | 17.318 | — | — | — | — | 4,057 | 19.730 | — | — | — | — |
| 2,750–2,999 | 6,371 | 30.983 | — | — | — | — | 8,457 | 41.127 | — | — | — | — |
| 3,000–3,249 | 7,643 | 37.169 | — | — | — | — | 7,620 | 37.057 | — | — | — | — |
| 3,250–3,499 | 278 | 1.352 | — | — | — | — | — | — | — | — | — | — |
| Mean | 2,859.75 | | 1,900.39 | | 1,005.36 | | 2,907.06 | | 1,518.99 | | 608.08 | |
| s.d. | 384.82 | | 319.28 | | 266.81 | | 320.42 | | 273.61 | | 236.07 | |

*Note:* [1] From a total of 20,563 1 km land cells.

Table 7.11. *NPV perpetuity sums*[1] *for soil carbon flux: all tree species (£/ha)*

| | Discount rate (%) | | |
|---|---|---|---|
| Soil type | 1.5 | 3 | 6 |
| Non-peaty | 743 | 601 | 476 |
| Peaty | −11,144 | −9,018 | −7,141 |

*Notes:* [1] Calculated for $t = 0$ to 999.

Table 7.12. *Number of 1 km land cells*[1] *at differing levels of NPV for net carbon flux (live wood, waste, products and soils): Sitka spruce, various discount rates* (r)

| Soil type | NPV (£/ha, 1990) | $r = 1\%$ | $r = 3\%$ | $r = 6\%$ |
|---|---|---|---|---|
| Peaty | −9,500:−9,001 | 33 | — | — |
| | −9,000:−8,501 | 438 | — | — |
| | −8,500:−8,001 | 5 | — | — |
| | −8,000:−7,501 | 13 | 117 | — |
| | −7,500:−7,001 | — | 298 | — |
| | −7,000:−6,501 | — | 14 | — |
| | −6,500:−6,001 | — | — | 489 |
| Non-peaty | 500:999 | — | — | 3 |
| | 1,000:1,499 | — | 1 | 9,650 |
| | 1,500:1,999 | — | 181 | 10,421 |
| | 2,000:2,499 | 32 | 7,907 | — |
| | 2,500:2,999 | 538 | 11,985 | — |
| | 3,000:3,499 | 5,349 | — | — |
| | 3,500:3,999 | 13,933 | — | — |
| | 4,000:4,499 | 222 | — | — |

*Note:* [1] From a total of 20,563 1 km land cells.

In order to assess the full impact of tree 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 calculated previously. The resultant total annual carbon flux values were then discounted at various rates to yield the net present value for any desired period. Table 7.12 lists the NPV of total net carbon storage for Sitka spruce across various discount rates (values for beech are similar but reflect our comparison in Table 7.10 by being consistently below those for Sitka spruce; as such they are not reproduced here).

The most striking feature of Table 7.12 is the highly bipolar distribution of results. Planting on peat soils causes very large soil carbon losses which overwhelm any

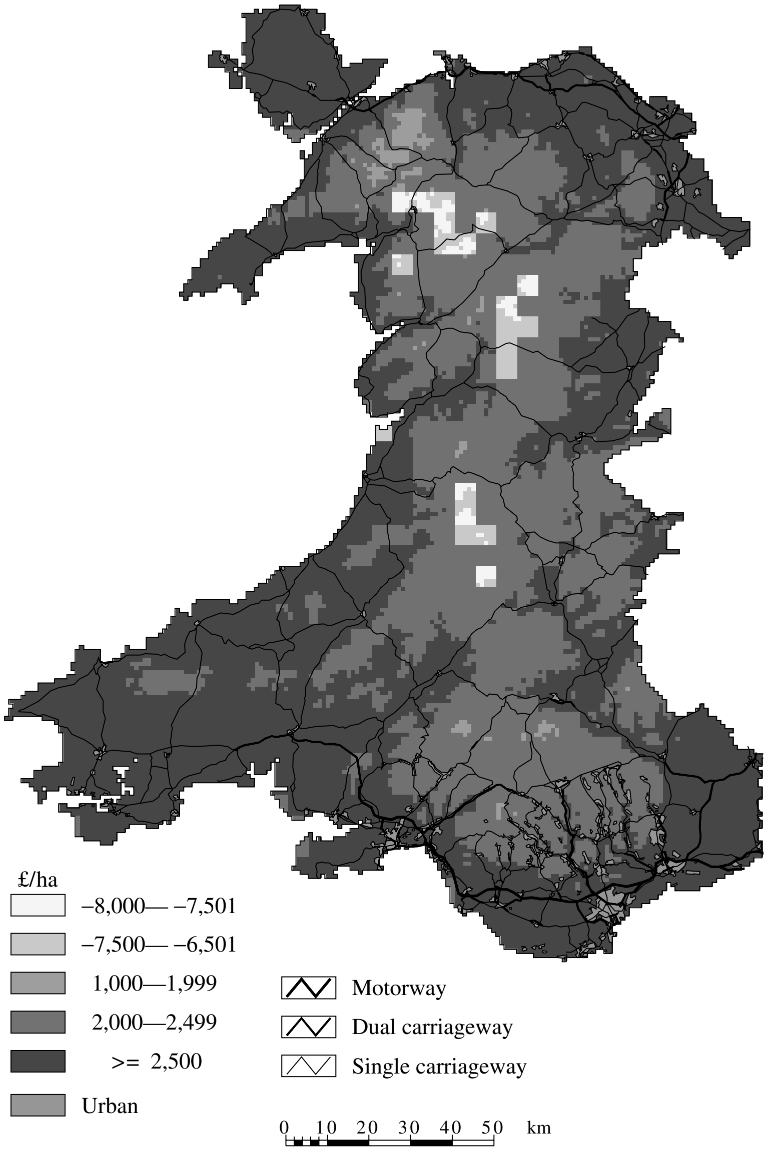


Figure 7.8. NPV of net carbon flux (live wood, products, waste and soils), Sitka spruce: 3% discount rate.

values generated by storage in live wood. Elsewhere, however, the value of carbon storage is both positive and substantial. Given the nature of this distribution, mean values and variance measures are somewhat inappropriate; however, the spatial distribution of values is well illustrated in Figure 7.8 which shows the NPV values for net carbon flux generated by Sitka spruce when assessed using a 3 per cent discount rate.

Consideration of Figure 7.8 shows that, with respect to carbon storage values, planting on peat soils is clearly to be avoided, a result which underpins the findings of Adger *et al*. (1992) discussed previously. However, elsewhere such planting is creating substantial public-good benefits which have not commonly figured in CBA appraisals of forestry proposals.

## Summary and conclusions

The objective of this chapter was both generally to advance the methodology for modelling carbon sequestration and, specifically, to produce maps of the value of net carbon flux induced by planting trees in locations across Wales. This was achieved by first reviewing the existing literature regarding the value of carbon sequestration or liberation *per se*. Here we concluded that the work of Fankhauser represents the current state of the art and duly adopted his valuations for use later in the chapter. Our second and principal objective was 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 a highly extended 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. Similarly 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.

Such maps are directly compatible with those estimated in previous chapters for woodland recreation and timber production values. In Chapter 9 we combine all of these maps to derive the total value generated by woodland in a given area. However, before that, in Chapter 8, we examine the value of agricultural output in those areas, which would constitute the major opportunity cost of conversion of land use from farming into woodland.