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Modelling and mapping timber yield and its value

Introduction

In this chapter we present various models of timber production for the two species under consideration: Sitka spruce and beech. In the next section we present a brief review of previous studies. These have exclusively been based upon relatively small-scale surveys of tree growth; furthermore, they have also generally been confined to comparatively small areas and often to one topographic region, e.g. upland areas. Our study differs from these previous models in that it employs a GIS to utilise large-scale existing databases covering a very large and diverse study area: the whole of Wales. The subsequent section presents details regarding the various datasets used in this study and discusses how these data were transformed for the purposes of subsequent regression analysis. Subsequently, results from our models of Sitka spruce and beech growth rates are presented, while the following section presents and analyses GIS-created map images of predicted yield class. The final section applies the findings of the previous chapter to produce monetised equivalents of these results.

Literature review and methodological overview

Literature review

It is clear that tree growth rates depend upon a variety of species, environmental and silvicultural factors. Early work in this field relied on simple rules of thumb based upon relatively little supporting data (Busby, 1974) or analyses of single factors. Reviews across this literature provide a number of clues regarding the specification of a yield class model. An early focus of interest was the impact of elevation upon productivity (Malcolm, 1970; Mayhead, 1973; Blyth, 1974). Subsequent papers considered the various routes by which elevation affected YC including windiness (Grace, 1977), slope and aspect (Tranquillini, 1979). Other work examined the impact of factors such as soil type, soil moisture transport and droughtiness (Page, 1970; Blyth and MacLeod, 1981; Jarvis and Mullins, 1987) and crop age (Kilpatrick and Savill, 1981). However, the estimation of statistical models across the full range of likely explanatory variables is a relatively recent innovation. Amongst such investigations we could find no examples concerning the productivity of beech and believe the model presented subsequently to be the first such investigation of this species. However, there has been more attention paid to the other species under analysis, Sitka spruce, which has been separately studied by both Richard Worrell (then of the University of Edinburgh) and Douglas Macmillan (then of Macauley Land Use Research Institute, MLURI).[1]

While there had been a number of earlier considerations of factors affecting the growth of Sitka spruce (Malcolm, 1970; Malcolm and Studholme, 1972; Mayhead, 1973; Blyth, 1974; Busby, 1974; Gale and Anderson, 1984), the work of Worrell (1987a,b) and Worrell and Malcolm (1990a,b) is notable as being the first to adopt a multiple regression approach across a wide range of explanatory variables. These were: elevation (including separate dummy variables for hilltop and valley bottom sites); windiness; temperature; aspect (measured as sine and cosine); and a full range of soil dummy variables. However, while they provide vital pointers for our own modelling exercise, Worrell's results are not transferable to our Welsh case study. This is partly due to the upland Scottish location of Worrell's experiment but primarily as a result of the focus of his study. Worrell was mainly interested in detecting the influence of elevation upon yield class in upland areas.[2] To this end he selected eighteen principal sample sites,[3] all of which had relatively steep slopes, and took measurements along a vertical transect at each site. By locating samples at sites ranging from 50 m to 600 m above sea level a very strong, central tendency relationship with elevation could be established. However, such a model is only applicable to similar, steeply sloping sites (strictly speaking, only the subset of those found within Scotland), and is not readily generalisable to the plethora of environmental conditions found in an area the size of Wales.

A similar, though less extreme, consideration prevents us applying the findings of Macmillan (1991). Here again the study is geographically confined, this time to lowland Scotland, although the 121 sites used are not selected to emphasise the influence of any particular explanatory variable and are therefore somewhat more generalisable within lowland areas. However, while in many cases this would be adequate, with respect to our study area the topographic variability of Wales means that a model based purely upon lowland data is insufficient for our needs.

[1] We are grateful to both Richard Worrell and Douglas Macmillan for extensive discussions of their work.
[2] An important question given that this is the location of much of the existing stock of Sitka spruce.
[3] The number of individual tree measurements is not reported.

Nevertheless, the Macmillan paper is interesting both because it uses multiple regression with a prior principal components analysis (PCA) of explanatory variables (reporting a final degree of explanation of $R^2 = 36.8$ per cent) and because the data collected have been more recently re-analysed using GIS techniques (Elston *et al.*, 1997) to produce a somewhat improved model ($R^2 = 43.9$ per cent)[4], a result which underlines the potential advantages of applying GIS methods within this field.[5]

A short note regarding model fit is justified here. As discussed in the previous chapter yield class (YC) is the average annual growth rate of a plantation assessed over an optimal rotation. YC is therefore given in m^3/ha/yr. However, YC values are rounded to the nearest even number so that while we have stands with YC 6 or 8 we do not have sites with YC 7. While this does not invalidate statistical analysis, as YC is the dependent variable, this approach to measurement does induce variance into the dataset and therefore makes high degrees of explanation difficult to attain. As such the absolute value of fit statistics such as R^2 should be treated with some caution and instead we should consider, where possible, relative degrees of fit compared to those attained in other studies.

Overview of modelling approach

These prior studies provide very useful indications regarding the likely explanatory variables which should be considered in our analysis. The differences in modelling approach are also of interest and we consequently decided to investigate both a PCA and standard multiple regression methodology. However, subsequent analysis showed that PCA models were narrowly outperformed by those obtained using standard regression techniques. Given their relatively straightforward interpretation, here standard regression models are reported in preference to those obtained using PCA, results from the latter being given in Bateman and Lovett (1998) and Bateman (1996).

While our approach to modelling is similar, in other key respects the methods of Worrell and Macmillan were not appropriate to the specific types of question asked in our research. Our central aim was to identify areas over the entire surface of Wales which might be suitable for conversion out of agriculture and into forestry. This necessitated the development of a methodology which was capable of producing estimates for both upland and lowland areas and which had the capability of extrapolating such findings across the entire surface area of the country. To this end

[4] Although not specified in this or the Macmillan paper, this appears to be an unadjusted R^2 statistic.

[5] Earlier discussions of the potential for applying GIS to forestry research and management are given in Aspinall (1991), Davidson (1991) and Blakeway-Smith *et al.* (1993).

we adopted a GIS-based approach to modelling.[6] This takes our base YC data from the Forestry Commission (FC) Sub-Compartment Database (SCDB) which holds information on each discrete stand (sub-compartment) in the FC's estate (described in detail subsequently).[7] As this covers both upland and lowland sites, results from such a model are more generalisable than those described previously. Use of the SCDB has the added bonus of massively increasing our sample size relative to previous studies. However, rather than relate YC to the environmental variables reported in the SCDB, for reasons discussed below we extract these from a separate source, the Soil Survey and Land Research Centre's Land Information System (LandIS) database (described subsequently).[8]

Data and data manipulation

This research relies upon a range of data sources. Aside from the SCDB and LandIS, further environmental and topographic data were obtained from a variety of sources. In this section we describe all these data and how they were manipulated prior to consideration within the subsequent statistical investigation of tree growth. It is important to remember that, while the SCDB holds detailed data regarding individual plantation sites, it does not extend to the large part of Wales which is unplanted. Therefore the environmental variables given in the SCDB are, for our purposes, unsuitable predictors of YC as complete land surface coverages for these variables are not available and therefore cannot be used for extrapolation of estimates to presently unplanted areas. The complete land area coverages of variables held in LandIS and the other data described subsequently are therefore needed to allow for this extrapolation of regression results.

The FC Sub-Compartment Database (SCDB)

The SCDB is the Forestry Commission's central forest inventory containing details for all stands in the estate. As such it provides an invaluable source of high-quality data, listing many thousands of sub-compartments for a variety of species across both upland and lowland Wales. The FC kindly provided SCDB data collected in the period 1972 to 1993 for a wide range of species among which were just over 6,000 Sitka spruce and over 700 beech records (the disparity reflecting the dominance

[6] For other examples of GIS applied to agricultural or forest planning, see Gemmell (1995), Moxey (1996), Corbett and Carter (1997), Hill and Aspinall (2000) and the ESRI website (e.g. at www.esri.com/industries/forestry/index.html).

[7] We are greatly obliged to Adrian Whiteman, Chris Quine and the Forestry Commission for use of the SCDB.

[8] We are greatly obliged to Arthur Thomasson, Ian Bradley and the Soil Survey and Land Research Centre (Cranfield) for use of LandIS.

of conifers over broadleaves in our Welsh study area).[9] Some of the information given in the SCDB concerned internal FC administration and was not of interest to our investigation and so the final list of variables extracted for this study was as shown in Table 6.1. This also indicates how certain of these data were manipulated to produce further (often binary dummy) variables. In doing this, one-way analyses of variance on the dependent variable (YC) were used to identify likely significant divisions in the data.

The SCDB also contains a variety of environmental variables specific to sub-compartments such as soil type, altitude, terrain type and windblow hazard class. Normally these would be ideal for modelling purposes. However, as the SCDB only holds such data for plantation sites rather than as uninterrupted national coverages, findings based upon such data would not form a suitable basis for extrapolation to other, currently unforested areas. This is somewhat unfortunate as these site-specific data are almost certainly more accurate than those obtainable from more general databases such as LandIS. This means that the regression models produced using LandIS are unlikely to fit the YC data as well as those using the site factor information given in the SCDB. However, for the purposes of this research, the advantage of being able to extrapolate out across the entire surface of Wales and consider currently unplanted areas easily outweighs such costs (which we subsequently argue, on the basis of our results, are likely to be small).

The SSLRC Land Information System (LandIS)

Background

The first systematic attempt to analyse and record British soil information was the 'County Series' of maps initiated by the Board of Agriculture in the late eighteenth and early nineteenth centuries. Until comparatively recently this remained the standard and unsurpassed source of soil data. During the 1940s the Soil Survey of England and Wales (SSEW) began a detailed mapping initiative. However, by the late 1970s, only one-fifth of the country had been covered. In 1979 the SSEW, which in the late 1980s became the Soil Survey and Land Research Centre (SSLRC), commenced a five-year project to produce a soil map of the whole of England and Wales and to describe soil distribution and related land quality in appropriate detail.

The data collected in this exercise were digitised, spatially referenced, and subsequently expanded to include climate and other environmental information (Bradley and Knox, 1995). The resulting Land Information System (LandIS) database was initially commissioned by the Ministry of Agriculture, Fisheries and Food, with the

[9] The FC was, as always, most willing to allow access to its data, for which we are most grateful.

stated aim of 'providing a systematic inventory capable of being used or interpreted for a wide range of purposes including agricultural advisory work, but also for the many facets of *land use planning and national resource use*' (Rudeforth *et al.*, 1984, emphasis added). However, while the system has been used in a variety of ways, particularly in relation to modelling agricultural pollution (see examples in Hallett *et al.*, 1996 and the SSLRC website[10]), the present research represents one of the first attempts to use LandIS for its originally intended purpose: national land use planning.

The data

Definitions, derivations and accuracy of the data extracted from LandIS are presented in Bateman (1996) and are summarised in Table 6.2. Further details of LandIS and the data therein are given in Jones and Thomasson (1985) and Hallett *et al*. (1996), with discussion of Welsh conditions given by Rudeforth *et al*. (1984). LandIS data are supplied at a 5 km resolution.

An immediate problem with applying the LandIS data to modelling yield classes arose from the plethora of differing soil codes contained in the database. These are taken from the Soil Survey of England and Wales (1983) which lists many hundreds of separate soil types, a large number of which were present in our Welsh dataset. This level of detail far exceeds that used in previous yield class studies such as Worrell (1987b) who uses seven soil type dummies derived from information given in the SCDB, which in turn relies on the standard FC classification of soils. The large number of soil codes given in LandIS was a problem both because of its implication for degrees of freedom in our intended regression analysis and because any such results would be of little practical use to the forester familiar with an alternative and simpler system. Furthermore, consultations with an expert in the field of soil science and forestry suggested that, for our purposes, many of the SSLRC soil codes could be merged with no effective loss of information and a substantial increase in clarity.[11] Details of the final categorisation are given in the bottom row of Table 6.2.

Other data

Topex and wind hazard

Data referenced to a 1 km grid on both the topographical shelter of a site (topex) and wind hazard were supplied by the Forestry Commission.[12] Topex is usually

[10] See www.silsoe.cranfield.ac.uk/sslrc/services/dataproducts/landis.htm.

[11] Dr Bill Corbett of the School of Environmental Sciences, University of East Anglia, and formerly of the Soil Survey of England and Wales, kindly advised on the merging of soil codes to produce a simple eight-category system which groups together similar soils.

[12] Our thanks go to Chris Quine at Roslin, the Forestry Commission's northern research station.

Table 6.1. *Variables obtained from the SCDB*[1]

Variable name[2]	Values	Notes and recodings (in italics)
Grid reference	Easting, Northing	100 m resolution O.S. grid references
Land use/crop type	PHF = plantation high forest	
	PWB = uncleared windblown area	*Uncleared* = 1 if PWB; = 0 otherwise
	PRP = research plantation	*Research* = 1 if PRP; = 0 otherwise
Storey	1 = single storey	*Single* = 1 if single storey; = 0 otherwise
	2 = lower storey	
	3 = upper storey	
Species	SS = Sitka spruce	Used to identify target species
	BE = beech	
	other	
Planting year	Discrete variable	*Plantyr*: year in which stand was planted
Survey year	Discrete variable	*Survyr*: year in which stand was surveyed
Yield class	Even number	*YC*: tree growth rate: average m^3/ha/year over an optimal rotation (the dependent variable)
Productive forest area	Hectares	*Area*: stocked area of the sub-compartment
Unproductive forest area	Hectares	*Unprod*: the area within the sub-compartment which has a permanent effect upon the crop, e.g. rocky outcrops, etc.
Rotation	1 = 1st rotation on formerly non-forest land	*1stRot* = 1 for 1st rotation; = 0 otherwise
	2, 3 etc. = 2nd, 3rd rotation, etc.	*2ndRot* = 1 for 2nd or subsequent rotation; = 0 otherwise
	9 = historical woodland sites	*Historic* = 1 if historic site; = 0 otherwise
	S = ancient, semi-natural woodland	*Semi-nat* = 1 if ancient/semi-natural woodland; = 0 otherwise
Mixture	P = single species crop	*MixCrop* = 1 if mixed species crop; = 0 otherwise
	M = mixed species crop	
Legal status	P = purchased by FC	*Purchased* = 1 if purchased; = 0 otherwise
	L = leased	*Leased* = 1 if leased; = 0 otherwise
	E = extra land, managed by FC outside its legal boundary	*Extra* = 1 if extra; = 0 otherwise
Landscape	1 = National Park	*NatPark* = 1 if National Park; = 0 otherwise
	2 = AONB/National Scenic Area	*AONB/NSA* = 1 if AONB/National Scenic Area; = 0 otherwise
	3 = ESA (where not included in 1 or 2 above)	*OthESA* = 1 if ESA area not included in above; = 0 otherwise
Forest Park	1 = Forest Park	*FPark* = 1 if forest park; = 0 otherwise
Conservation	1 = SSSI (Site of Special Scientific Interest)	*SSSI* = 1 if SSSI; = 0 otherwise
	2 = NNR (National Nature Reserve)	*NNR* = 1 if NNR; = 0 otherwise
	3 = Non-FC Nature Reserve	*NonFCNR* = 1 if non-FC nature reserve; = 0 otherwise
FC conservation	1 = Forest Nature Reserve	*FCNR* = 1 if Forest Nature Reserve; = 0 otherwise
	2 = Other FC conservation	*FCcons* = 1 if other FC; = 0 otherwise
Ancient monument/Woodland	S = scheduled ancient monument	*Ancient* = 1 if S, U or W; = 0 otherwise *Monument* = 1 if S or U; = 0 otherwise
	U = unscheduled ancient monument	
	W = ancient woodland	
		Further recodes from above: *NpAonbSa* = 1 if any of *NatPark* or *AONB/NSA*; = 0 otherwise *Cons* = 1 if any of *NNR*, *NonFCNR*, *FCNR*, *FCcons*; = 0 otherwise *Reserve* = 1 if any of *Cons*, *AONB/NSA*, *OthESA*; = 0 otherwise *Park* = 1 if any of *NatPark*, *FPark*, *SSSI*; = 0 otherwise

Notes: [1] Except where shown otherwise.
[2] Variables are listed in the order in which they appear in the database.

determined as the sum of the angle of inclination for the eight major compass points of a site (Hart, 1991). Thus, a low angle sum (low topex value) represents a high degree of exposure. The resultant GIS data coverage was labelled *Topex1km*.

Table 6.2. *Variables obtained from LandIS*

Variable name	Label	Definition
Accumulated temperature	*Acctemp*	Average annual accumulated temperature (in ^{o}C) above 0^{o}C
Accumulated rainfall	*Rainfall*	Average annual accumulated rainfall (in mm)
Available water	*Avwatgra*	Amount of soil water available for a grass crop after allowing for gravity-induced drainage
	Avwatcer	As for *Avwatgra* but adjusted for a cereal crop
	Avwatpot	As for *Avwatgra* but adjusted for potatoes
	Avwatsb	As for *Avwatgra* but adjusted for sugar beet
Moisture deficit	*Mdefgra*	The difference between rainfall and the potential evapotranspiration of a grass crop
	Mdefcer	As for *Mdefgra* but adjusted for a cereal crop
	Mdefsbpt	As for *Mdefgra* but adjusted for a sugar beet/potatoes crop
Field capacity	*Fcapdays*	Average annual number of days where the soil experiences a zero moisture deficit
Return to field capacity	*Retmed*	Median measure from a distribution of the number of days between the date on which a soil returns to field capacity and 31 December of that year
	Retwet	The upper quartile of the above distribution (measure of return to field capacity in wet years)
	Retdry	The lower quartile of the above distribution (measure of return to field capacity in dry years)
End of field capacity	*Endmed*	Median measure from a distribution of the number of days between the 31 December and the subsequent date on which field capacity ends
	Endwet	The upper quartile of the above distribution (measure of the end of field capacity in wet years)
	Enddry	The lower quartile of the above distribution (measure of the end of field capacity in dry years)
Workability	*Workabil*	A categorical scale indicating the suitability of the land for heavy machinery work in spring and autumn
Spring machinery working days	*SprMWD*	The average number of days between 1 January and 30 April where land can be worked by machinery without soil damage
Autumn machinery working days	*AutMWD*	The average number of days between 1 September and 31 December when land can be worked by machinery without soil damage
Soil type	*Soil*X	SSLRC soil type classification code: *Soil1* = lowland lithomorphic; *Soil2* = brown earths; *Soil3* = podzols; *Soil4* = surface water gley; *Soil5* = stagnogley (perched watertable); *Soil6* = ground water gley; *Soil7* = peats; *Soil8* = upland lithomorphic; *Soil23* = areas with *Soil2* or *Soil3*

Blakeway-Smith *et al.* (1994) define wind hazard on the basis of four factors: wind zone, elevation, topex and soil type.[13] The resultant continuous variable (*Wind1km²*) is inversely linked with tree productivity and growth rates.

Elevation and associated variables

The work of Worrell and Malcolm (1990a) shows that elevation and its associated characteristics are key predictors of yield class. However, such a variable is not included in the LandIS database and the SCDB only gives heights for existing plantation sites. Clearly for extrapolation purposes this is inadequate and so an alternative source of data was required. At the time the research was undertaken access to the Ordnance Survey digital elevation models (DEMs) was impractically expensive for UK university researchers (although a more recent access agreement has altered this situation). Therefore a DEM was created from three other sources: the Bartholomew 1:250,000 digital contour database for the UK, summit points from Bartholomew's paper maps and the spot heights of plantations from the SCDB. The accuracy of the derived DEM was tested by omitting various data points from the calculation, using the DEM to estimate heights from those points and comparing actual with predicted values. These tests (detailed in Bateman, 1996) showed that the DEM performed well and so was re-estimated using all available data and incorporated into our yield class estimation model. The elevation data were also used to generate two further GIS surface variables: slope angle (*Dsl2*) and aspect angle (*Wsaspgr2*). Data on all these variables were produced at a 500 m × 500 m cell resolution.

Creating GIS surfaces for explanatory variables

Prior to the regression analysis two fundamental issues had to be addressed regarding the definition of a common extent and resolution for the environmental variables as these parameters differed across the various data sources used. Data were supplied at a wide array of resolutions ranging from the (nominal) 100 m accuracy of the SCDB to the 5 km tiles of the LandIS variables. While the technical operation of interpolating from a coarse to a finer resolution is relatively straightforward within a GIS (Berry, 1993), it needs to be recognised that the precision achieved may be rather higher than the underlying accuracy of the data (Goodchild, 1993), so deciding upon a common unit size was a matter for some deliberation. Standardisation upon the smallest unit (100 m) did not seem a sensible choice. For instance, the 100 m reference used in the SCDB is, the FC admit, spuriously

[13] Blakeway-Smith *et al.* (1994) also discuss a funnelling variable which tends to have higher values in valley bottoms. Zobeck *et al.* (2000) show how GIS techniques can also be adapted to the prediction of wind erosion of soils, which may in turn impinge upon yields.

precise. On the other hand, aggregation up to the 5 km scale of the coarsest data was thought likely to result in a loss of much relevant detail (e.g. for topographic features). As a compromise, a 1 km grid was settled upon and all the data were converted to this resolution.

The spatial extent of Wales was defined by converting a vector outline of the Welsh coast and border with England (from the Bartholomew 1:250,000 scale database) to a raster grid representation consisting of 1 km^2 cells. This resulted in a layer within the GIS containing 20,563 land cells and values of the variables in the LandIS and non-SCDB datasets described above were then estimated for each grid cell.[14] For characteristics such as topex or elevation this was done by aggregation and averaging, whereas with the LandIS variables each 1 km grid square was given the value of the 5 km cell it fell within. With all data now at a common resolution and extent we now had the necessary complete surfaces of potential predictor variables for use in our regression model and from which extrapolation across all areas, whether currently planted or not, would be possible.

A final task concerned the extraction of values for all environmental variables for each yield class observation in the SCDB. This was achieved by using point-in-polygon operations within the GIS to identify the 1 km grid cell corresponding to each sub-compartment grid reference.

Yield models for Sitka spruce and beech

Sitka spruce

Our regression analyses followed the approach set out by Lewis-Beck (1980) and Achen (1982). An initial objective concerned the identification of an appropriate functional form for our models. Tests indicated that a linear model performed marginally better than other standard forms and, given that such a form is both easily interpretable and typical of other studies, this seemed a sensible choice.[15]

A variety of stepwise regression analyses were undertaken yielding models composed of raw variables, PCA factors and a combination of these. Resultant models are reported in full in Bateman (1996) and Bateman and Lovett (1997, 1998). For reasons of brevity, here we only report the best-fitting regression models for Sitka spruce and beech. These models used raw variables rather than PCA factors as predictors of YC. Furthermore, a number of observations are omitted from these models, mainly those for which the measurement of YC was taken relatively soon

[14] This exercise revealed some relatively minor missing observations in the LandIS database. Measurements for these cells were proxied using interpolation and related techniques. For details see Bateman and Lovett (1997).
[15] Semi-log (dependent and independent), double-log and quadratic forms were also tested and cross-product terms investigated.

Model 6.1. *Best-fitting regression model predicting Sitka spruce YC*

Predictor	Coeff.	S.d.	*t*-ratio	*p*
Constant	16.7097	0.3487	47.92	<0.001
Rainfall	−0.00167	0.00011	−15.65	<0.001
Wselvgr2	−0.00878	0.00039	−22.31	<0.001
Topex1km	0.02426	0.00759	3.20	0.001
Soil23	0.80489	0.08046	10.00	<0.001
Soil1	−4.8827	0.9660	−5.05	<0.001
Area	0.00395	0.00038	10.43	<0.001
Plantyr	0.04989	0.00484	10.31	<0.001
1stRot	−1.9280	0.1093	−17.64	<0.001
MixCrop	−0.30832	0.07670	−4.02	<0.001
Park	0.94769	0.09385	10.10	<0.001
Ancient	0.9266	0.3089	3.00	0.003
Uncleared	2.6411	0.2276	11.61	<0.001
Unprod	−0.08543	0.00814	−10.49	<0.001
Reserve	−0.43395	0.09452	−4.59	<0.001
Semi-nat	−5.1415	0.7644	−6.73	<0.001
	$n = 4{,}307$	$R^2 = 43.0\%$	$R^2(\text{adj.}) = 42.8\%$	

after planting (full details in Bateman and Lovett, 1998).[16] Assessment of YC for young trees is inherently more difficult than for more mature stands and tests indicated that omitting those stands measured at a particularly young age improved model fit, suggesting that such a procedure reduced random measurement error and yielded more reliable results (results for models without any observations omitted are given in Bateman and Lovett, 1998, and are similar in coefficients to those reported here). This procedure left a sample of 4,307 Sitka spruce sub-compartments, for which our best-fitting model is reported as Model 6.1.

The first point to note about Model 6.1 is that the use of the SCDB permitted a very substantial increase in sample size, which, at over 4,300, compared very favourably to the few hundred observations typically used in many YC studies. This is in part responsible for the comparatively high degree of explanation provided by the model, which exceeds all conventional studies and is comparable with the GIS-based study of Elston *et al.* (1997) cited previously.

Inspection of the model revealed a number of highly significant predictors of YC. With respect to the environmental characteristics of sites we can see that YC fell with increasing rainfall (*Rainfall*)[17] and elevation (*Wselvgr2*) and increased as

[16] The idea of omitting plantations which were measured relatively soon after planting was suggested by Chris Quine and Adrian Whiteman of the Forestry Commission and Douglas Macmillan of the Macauley Land Use Research Institute, to whom we are grateful.

[17] This result underscores the fact that Wales is a high rainfall area. Waterlogging rather than drought is the main water-related problem in the area.

topographical shelter improved (*Topex1km*). Because of its categorical nature, soil type is considered as a series of dummy variables, two of which proved statistically significant. YC was significantly elevated by planting on brown earth or podzol soils (*Soil23*, which is a simple combination of *Soil2* and *Soil3*) and significantly depressed by planting on lowland lithomorphs (*Soil1*). Both results conformed to prior expectations.

The model also highlighted the importance of silvicultural factors. The positive relationship with the size of the plantation (*Area*) is interesting and, to our knowledge, has not previously been formally identified. This would seem to indicate that trees growing as part of a large plantation are more likely to thrive than those in small areas. This might be because large stands provide advantages in terms of the ease of adopting species-specific management regimes, or because such stands tend to condition their environment to their own advantage (for example, by reducing competition from both flora and fauna). Conversely, this latter factor may be one of the pressures militating against smaller stands. A strong and positive influence of the time variable (*Plantyr*) is also identified. This is usually explained as reflecting improvements in silvicultural methods such as the introduction of ploughing, fertiliser applications or enhancement of the genetic stock.

Two further silvicultural factors were identified. Trees planted on ground which has not been previously used for afforestation (*1stRot*) perform worse than those planted in successive rotations. This may be because second rotation trees have, on average, been planted more recently than those in the first rotation (although a relatively low correlation with *Plantyr* indicated that this may not be all of the story) or because second rotation trees inherit a nutrient-enriched and/or pH-modified soil base from their forebears. Trees also seem to perform less well when grown in a mixed species plantation (*MixCrop*) than in monoculture, a finding which suggests that there may be a timber productivity benefit associated with the amenity cost of the latter.

Next, a number of site factors arising from the interaction of environmental characteristics and management practice appear important. YC was significantly higher in parkland areas (*Park*), a result which may reflect more careful silvicultural management. The higher YC associated with planting in areas which were previously ancient woodland (*Ancient*) seems to be the corollary of the impact of *1stRot*. A further and rather interesting boost to growth is implied by the variable *Uncleared* which identifies trees growing in areas that have been previously affected by windblow but have not yet been cleared. It seems that the surviving trees actually profit from windblow in that their immediate neighbours (and competitors) are removed, thus boosting their access to sunlight and nutrients. However, while growth rate may benefit from such events, the ensuing lack of cover raises the probability that the survivors will subsequently fall victim to windblow themselves.

Table 6.3. *Comparing actual with predicted YC for Sitka spruce (cell contents are counts)*

	Predicted YC									
Actual YC	4	6	8	10	12	14	16	18	20	All
4	0	0	1	0	0	0	0	0	0	1
6	0	0	7	63	0	0	0	0	0	70
8	1	3	12	161	220	0	0	0	0	397
10	0	0	9	169	395	141	0	0	0	714
12	0	0	4	176	516	285	63	0	0	1,044
14	0	0	0	90	415	276	124	33	1	939
16	0	0	0	0	201	313	179	33	1	727
18	0	0	0	0	0	152	144	45	3	344
20	0	0	0	0	0	0	41	26	3	70
22	0	0	0	0	0	0	0	1	0	1
All	1	3	33	659	1,747	1,167	551	138	8	4,307

Predicted YC compared to actual YC	Percentage of total sample
Prediction is two classes too high	12.8
Prediction is one class too high	23.4
Predicted YC equals actual YC	27.9
Prediction is one class too low	25.2
Prediction is two classes too low	11.4

Finally, three negative environmental/management factors were identified. Plantations with higher amounts of unproductive land (*Unprod*) not surprisingly perform worse than otherwise similar sites. Sub-compartments which fall within the boundaries of conservation areas (*Reserve*) also exhibit relatively lower YC, as do areas which are allowed to remain as semi-natural habitat (*Semi-nat*). These results may reflect the application of less intensive silvicultural techniques in such areas.

In order to examine its predictive capabilities, Model 6.1 was assessed by rounding the predictions to the nearest point on the YC scale and then comparing them with actual YC for the 4,307 observations used in the model. Results of this analysis are presented in Table 6.3 which shows that 76.5 per cent of YC predictions are within one division of actual YC.

Beech

Compared to the situation for Sitka spruce, the SCDB contains only a small number of beech compartments within our study area. These observations were analysed in a similar manner to before (for full details see Bateman and Lovett, 1997, 2000a), and this analysis identified a much higher proportion of stands being assessed

Model 6.2. *Optimal model for beech*

Predictor	Coeff.	S.d.	*t*-ratio	*p*
Constant	−4.428	1.923	−2.30	0.022
Wselvgr2	−0.00386	0.00091	−4.22	<0.001
Plantyr	0.07995	0.01279	6.25	<0.001
AONB/NSA	0.4751	0.2710	1.75	0.081
OthESA	−1.4812	0.4969	−2.98	0.003
	$n = 205$	$R^2 = 35.7\%$	R^2(adj.) $= 34.4\%$	

at relatively young ages. Details of models using all observations are given in Bateman (1996) and Bateman and Lovett (1997), with related analysis being given in Bateman and Lovett (2000a). However, here we report results for only the subset of 205 sites unaffected by the early measurement problem. The best-fitting model for these sites is reported as Model 6.2.

Examining Model 6.2 we can see that, as for our Sitka spruce results, the yield class of beech declines with increasing elevation (*Wselvgr2*) and rises as we consider more recently planted sub-compartments (*Plantyr*). However, the smaller sample size of just over 200 observations fails to reveal many of the previously noted relationships, with just two management regime variables proving significant (and one of these only at $\alpha = 10$ per cent). Nevertheless, the overall degree of explanation is reasonably satisfactory as is the predictive power of the model, as indicated in the actual versus predicted test summarised in Table 6.4.

As a side analysis, regression models for both species under investigation were re-estimated after inclusion of variables representing the aspect of each sub-compartment. In both cases, aspect variables proved to have only a weak impact on yield class;[18] however, the nature of this effect is interesting and is illustrated in Figure 6.1 which compares the results with those of Worrell and Malcom (1990b) in their study of Sitka spruce in the uplands of northern Britain.

Inspection of Figure 6.1 tells a clear and coherent story. In the upland areas of northern Britain the intensity of the prevailing westerly wind causes aspect to be a major factor determining tree growth such that trees in relatively sheltered, east-facing ($\theta = 90^{\circ}$) sites perform significantly better than those facing west ($\theta = 270^{\circ}$). The radiative energy advantage of south-facing slopes is completely negated by the impact of the prevailing wind. In our Welsh study of Sitka spruce we consider both upland and lowland sites. Here both the magnitude and statistical significance of the impact of aspect is reduced. Furthermore, the reduction in the power of the prevailing wind (occurring because we are considering sites at lower altitude as well as the less arduous conditions of Wales relative to northern Britain) means that

[18] At best only significant at $\alpha = 10$ per cent. Full details are reported in Bateman and Lovett (1997, 1998).

Table 6.4. *Comparing actual with predicted YC for beech (cell contents are counts)*

	Predicted YC			
Actual YC	4	6	8	All
2	0	1	0	1
4	9	29	2	40
6	7	66	20	93
8	0	29	37	66
10	0	0	5	5
All	16	125	64	205

Predicted YC compared to actual YC	Percentage of total sample
Prediction is two classes too high	1.5
Prediction is one class too high	23.9
Predicted YC equals actual YC	54.6
Prediction is one class too low	20.0
Prediction is two classes too low	0.0

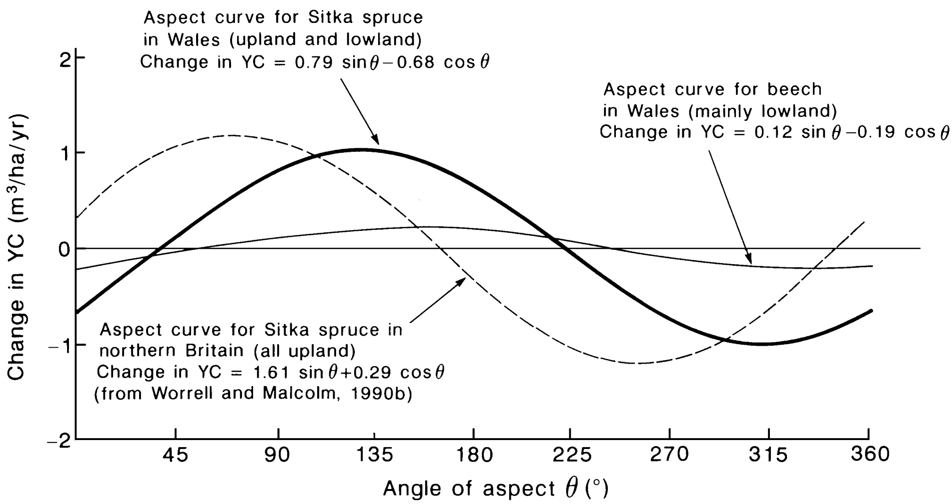

Figure 6.1. Aspect effects for Sitka spruce and beech in differing locations.

the solar energy advantage of southerly sites can now be detected, as our aspect effect is now maximised at south-east (rather than east) facing sites. This trend is continued when we consider our beech sub-compartments. Here, most sites are at lower elevations such that the absolute magnitude (and statistical significance) of the aspect effect is markedly reduced. Furthermore, the reduction in the impact of the prevailing westerly wind means that the solar energy advantage of being south-facing is further boosted such that we find that the aspect curve for beech sites now peaks for sites facing south-south-east.

Mapping yield class

We have now estimated yield class (YC) models for both of the tree species considered. In this section these models are used to generate GIS-based maps of YC which are presented and analysed below.

Producing predicted yield class maps within a GIS

To generate a YC map (or, more specifically, a raster image) the GIS requires data on predictor variables for all the grid cells in the area for which we wish to estimate yield, in this case the 20,563 1 km squares representing the entire land area of Wales. If we take our model (6.1) of Sitka spruce yield as an example, we can see that this is predicted by a constant and a number of explanatory variables. The constant is in essence a data layer in its own right which has identical values (here 16.709) for all land grid cells. The first explanatory variable in this model is the predictor *Rainfall* for which we have estimates from the LandIS database. We can therefore begin to build up our predicted YC map by employing the GIS software to calculate a new raster map which contains the values from multiplying the values in the *Rainfall* grid by the relevant coefficient (–0.00167).

The above procedure was repeated for all predictor variables. However, some variables were related to management (e.g. *Area*), policy (e.g. *Reserve*) or when the site was planted (e.g. *Plantyr*). These are not specifically spatial variables so they were treated by holding them at certain fixed values (i.e. as for the constant) and varying some of them in a sensitivity analysis. The variables *MixCrop*, *Ancient*, *Unprod*, *Reserve*, *Park*, *Uncleared* and *Semi-nat* are all dummies for infrequently occurring, unusual sites and were consequently held at zero (their modal value) for all analyses. Similarly the variable *Area* was held at its median value of 33 ha. Given the very low value of the coefficient on this variable and its relatively small range (see the descriptive statistics given in Bateman, 1996), sensitivity analysis did not seem justified here. However, this was not the case for the variables *Plantyr* and *1stRot* and full sensitivity analyses were conducted for these.

Once the data coverage for each predictor variable has been multiplied by its estimated coefficient all the resulting maps can be overlaid and their values summed to obtain the final prediction of YC in each area. The same methodology was then employed to generate a YC map from our beech model.

Timber yield maps for Sitka spruce

In producing YC maps based on our Sitka spruce model we considered the impact of changing the *Plantyr* variable from 0 (being the base year in which the Forestry Commission started to plant Sitka spruce) to 75 (being the present day, i.e. Sitka spruce planting commenced about 75 years ago) thereby arguably reflecting technological progress over that period. For both of these analyses we initially held $1stRot = 1$, i.e. we examined first-rotation trees at both of these time periods. However, many present-day Sitka spruce plantations are now in their second rotation. Therefore, we also tested the effect of letting $1stRot = 0$ (i.e. second rotation) when $Plantyr = 75$.

Raster maps were produced using the procedure outlined in the previous section. Plate 1a illustrates the predicted YC image created from our Sitka spruce model with $Plantyr = 75$ (present day) and $1stRot = 0$ (replanting on a previously planted site).

Inspection of Plate 1a clearly shows the very strong influence which environmental characteristics have upon our predictions of YC. The influences of lower altitude, better soil and lower rainfall combine to produce high YC. The pattern of lower YC produced by higher elevations is particularly noticeable, with the mountain ranges of Snowdonia, the mid Cambrians and the Brecon Beacons clearly evident. Less extreme upland areas such as the Preseli Mountains produce YC values which lie between these extremes. Also rather noticeable are the adverse effects of the rain-shadow lying to the east of the Cambrians which results in large areas of relatively depressed YC values stretching in some cases up to the English border. The negative impact of sandy and estuarine soils upon growth can also be seen in the small but significantly depressed areas of low yield at places such as the tip of the Gower Peninsula and nearby Pembrey, the southernmost part of Anglesey and the Llandudno peninsula.[19]

Plate 1a assumes $1stRot = 0$ (i.e. predictions for plantations which are not in their first rotation) and $Plantyr = 75$ (i.e. predictions for trees planted in the mid 1990s). To provide a contrast with these assumptions, maps of predicted YC for Sitka spruce with $Plantyr = 0$ (i.e. trees planted at the start of Forestry Commission operations in 1920) and $1stRot = 1$ (i.e. sites with trees in their first rotation) were also produced. Following the predictions of Model 6.1 both of these latter scenarios give lower YC predictions than those illustrated in Plate 1a, although the pattern of YC variation remains similar. These differences are quantified in Table 6.5 which presents the frequency distributions of predictions from these three scenarios. As can be seen, differences are substantial, with these two alternatives producing appreciably lower YC predictions in each case.

While our YC maps seem highly plausible (and we would defend them as such for the majority of Wales), Table 6.5 and Plate 1a do indicate a weakness in our models in their ability to estimate YC for extreme environmental conditions such as, for example, mountain tops. Our best-fitting model for Sitka spruce fails to

[19] Interestingly both Pembrey and Newborough (Anglesey) are the sites of large forests, underlining the point that forests are often confined to the most marginal land.

Table 6.5. *Predicted Sitka spruce YC under three scenarios*

	Plantyr = 75; *1stRot* = 0		*Plantyr* = 75; *1stRot* = 1		*Plantyr* = 0; *1stRot* = 1	
YC	Freq.	%	Freq.	%	Freq.	%
2	—	—	—	—	10	0.049
4	—	—	1	0.005	46	0.224
6	1	0.005	15	0.073	367	1.785
8	16	0.079	54	0.263	2,255	10.966
10	56	0.272	504	2.451	4,691	22.813
12	554	2.694	2,524	12.274	8,747	42.538
14	2,609	12.688	5,106	24.831	4,447	21.626
16	5,209	25.332	9,287	45.164	—	—
18	9,416	45.791	3,072	14.939	—	—
20	2,702	13.140	—	—	—	—
Mean	17.05		15.12		11.38	

Notes: The column headings define the values of the variables *Plantyr* and *1stRot* used in each map, where: *Plantyr* = year in which stand was planted (0 = 1920; 75 = 1995); *1stRot* = 1 if stand is the first planted in that sub-compartment, = 0 otherwise (i.e. sub-compartment is in second or subsequent rotation).

The frequency columns refer to the number of 1 km grid squares. Each map consists of 20,563 such squares.

predict any sites of less than YC6. However, clearly if trees were planted at or near mountain peaks they might well not survive or would at best produce only very low YC. Similarly our model does not predict any cells to have YC in excess of 20, yet our dataset indicated a few cases of YC being as high as 24. We therefore appear to be overestimating YC at the lower extreme and under estimating at the upper end of the range.

Two factors seem pertinent in explaining this. First, we are predicting average YC over 1 km grid squares. This will tend to remove extremes and therefore gives some support to our findings. Second, as there is relatively little planting at the extremes of altitude, low YC observations are under-represented in the FC's sub-compartment database resulting in a lesser ability of statistical models based on such data to estimate accurately for such locations.[20] However, while these are problems, the actual versus predicted YC comparison reported in Table 6.3 suggests that the degree of over- and underestimation at the tails is not too serious.

[20] A third possibility, discussed in Bateman (1996), is a resolution issue. Our DEM estimates elevations based upon surrounding points and therefore may not fully capture the upper extremes of altitude. Any underestimation of elevation at the tops of mountains may result in overestimation of YC at those points.

Table 6.6. *Predicted beech YC under two scenarios*

	Plantyr = 162; *1stRot* = 1		*Plantyr* = 144; *1stRot* = 1	
YC	Freq.	%	Freq.	%
3	—	—	1	0.005
4	—	—	84	0.409
5	17	0.083	1,970	9.580
6	421	2.047	10,437	50.756
7	7,003	34.056	8,071	39.250
8	12,925	62.856	—	—
9	197	0.958	—	—
Mean	7.69		6.25	

Note: The frequency columns refer to the number of 1 km grid squares. Each map consists of 20,563 such squares.

Timber yield maps for beech

As with Sitka spruce, we attempted to produce maps of predicted beech YC considering the impact of changing the *Plantyr* and *1stRot* variables. In the case of the *Plantyr* variable, unlike our Sitka spruce analysis there was no distinct year in which beech planting commenced. Thus, although we have a date at which *Plantyr* = 0, this corresponds simply to the oldest record in the dataset (some 162 years ago) rather than to some actual initial planting date. Accordingly it was decided to adopt a somewhat different strategy here and our sensitivity analysis examined two values: *Plantyr* = 144 (which equalled both the mean and median planting date of the early 1970s); and *Plantyr* = 162 (mid 1990s). The dataset showed that most beech sub-compartments were in their first rotation and so this sensitivity analysis was not performed, *1stRot* being held at a value of 1 for all beech images.

We therefore produced two YC maps for beech and Plate 1b illustrates the version holding *Plantyr* = 162 (and *1stRot* = 1). Both maps show a similar pattern of YC distribution to that of Sitka spruce; however, the range of these distributions is far narrower than for the latter as is shown in Table 6.6. As before, *ceteris paribus*, increasing *Plantyr* leads to a rise in predicted YC.

Producing timber yield value maps

In Chapter 5 we developed models for estimating timber values which were sensitive to a variety of factors including the following:

(i) species: Sitka spruce or beech
(ii) a full range of yield class levels
(iii) a full range of subsidy and grant schemes

(iv) single, optimal-length rotation or perpetual replanting
(v) a range of discount rates
(vi) private or social values
(vii) NPV and annuity sums.[21]

Note that, at this point in our analysis, we have not included the woodland recreation values discussed previously or the carbon storage values estimated in the following chapter. Therefore, the 'social' values referred to above and in the remainder of this chapter are only those directly associated with the production of timber. Essentially these take the private values received by farmers or other forest operators and remove grant and subsidy transfer payments and add in the timber-related shadow values (such as the value of ensuring supply continuity) discussed in Chapter 5.

These models produce timber value/YC curves for each combination or 'scenario' of the above factors such as those illustrated for a variety of subsidy schemes in Figures 5.5 and 5.6. As those diagrams showed, for any given subsidy scheme, timber value is approximately linearly related to YC. This result provides a ready method for converting our maps of timber YC to maps of timber value.

For each species and all combinations of factors (iii) to (vi) above, a linear equation linking predicted timber value to YC was estimated (details for all combinations are given in Bateman, 1996). In all cases a simple straight-line model provided an excellent fit.[22] As an example, the function predicting farmers' private annuity value, calculated at a 3 per cent discount rate, for perpetually replanted Sitka spruce receiving grants at non-disadvantaged area rates is:[23]

$$\begin{aligned} \mathrm{ANN}_3^{\mathrm{SS}} = \; & -136.32 + 21.32\ \mathrm{YC} \\ & (-17.88) \qquad (44.90) \end{aligned} \tag{6.1}$$

where:

$\mathrm{ANN}_3^{\mathrm{SS}}$ = farmers' private annuity value per hectare of perpetually replanted Sitka spruce timber production, calculated using a 3 per cent discount rate

YC = yield class

R^2(adj.) = 99.6%. Figures in brackets are *t*-statistics.

With the resultant suite of regression equations having been estimated, the GIS was used to convert our YC maps to their timber value equivalents. For each scenario this was achieved by selecting the appropriate YC map and conversion regression equation. The GIS was then used first to multiply predicted YC across the timber

[21] The relation of NPV and annuity sums was discussed in Chapter 5. Annuity values are likely to be of more interest to the farmer than NPVs.

[22] Lowest R^2(adj.) = 97.2 per cent.

[23] So, for this example, predicted $\mathrm{ANN}_3^{\mathrm{SS}}$ for YC20 Sitka spruce = £290/ha (see the lower curve in Figure 5.4).

yield map by its coefficient in the conversion equation, and second to subtract the constant given in the same equation. The resultant map contains predicted timber values for the desired scenario.

Using this procedure NPV and annuity value maps were created for a variety of scenarios. Figure 6.2 illustrates the social (i.e. removing grants and subsidies) NPV map for perpetually replanted Sitka spruce timber production calculated using a 3 per cent discount rate (remembering that non-timber values such as recreation and carbon sequestration have yet to be added to this value). The distribution of values reflects that of the YC image (Plate 1a) upon which it is based and so comments remain as before.

The number of permutations of the factors considered in this analysis precludes full reporting here (details are given in Bateman, 1996). However, Tables 6.7 and 6.8 report social NPV and annuity equivalents for Sitka spruce timber values across three discount rates, while Tables 6.9 and 6.10 repeat this analysis for beech. For any given discount rate, the distribution of values is given in terms of (i) the number of 1 km grid squares in our study area falling in each value category and (ii) that frequency count expressed as a percentage of the 20,563 1 km squares which constitute Wales.

Considering Tables 6.7 to 6.10 we can see that, for both species, the choice of discount rate has a substantial impact upon values, with higher rates yielding lower NPV and annuity sums. This effect is somewhat more pronounced in the case of Sitka spruce, a result which reflects its short rotation length relative to beech. With a long rotation length (such as that for beech) discount factors are already relatively low at felling irrespective of the chosen discount rate. In such cases, variation in that rate has less impact upon NPV and annuity values than for short rotation species where, with low discount rates, discount factors are still reasonably high at felling. This effect also explains why discounted Sitka spruce values are higher than those for beech despite the latter attracting higher nominal values at felling. In the absence of other monetised benefits, these results clearly illustrate why market-led assessments of forestry projects argue in favour of planting conifers rather than broadleaves.

Conclusions

We have estimated yield class models for Sitka spruce and beech based in part upon variables drawn from GIS databases covering the whole of Wales. This has allowed us to use those models to produce predicted yield maps for both species for the entire Principality. We have then used these maps in conjunction with the timber value model derived in Chapter 5 to produce NPV and annuity equivalent maps. In general we are reasonably happy with this analysis. However, we should mention at

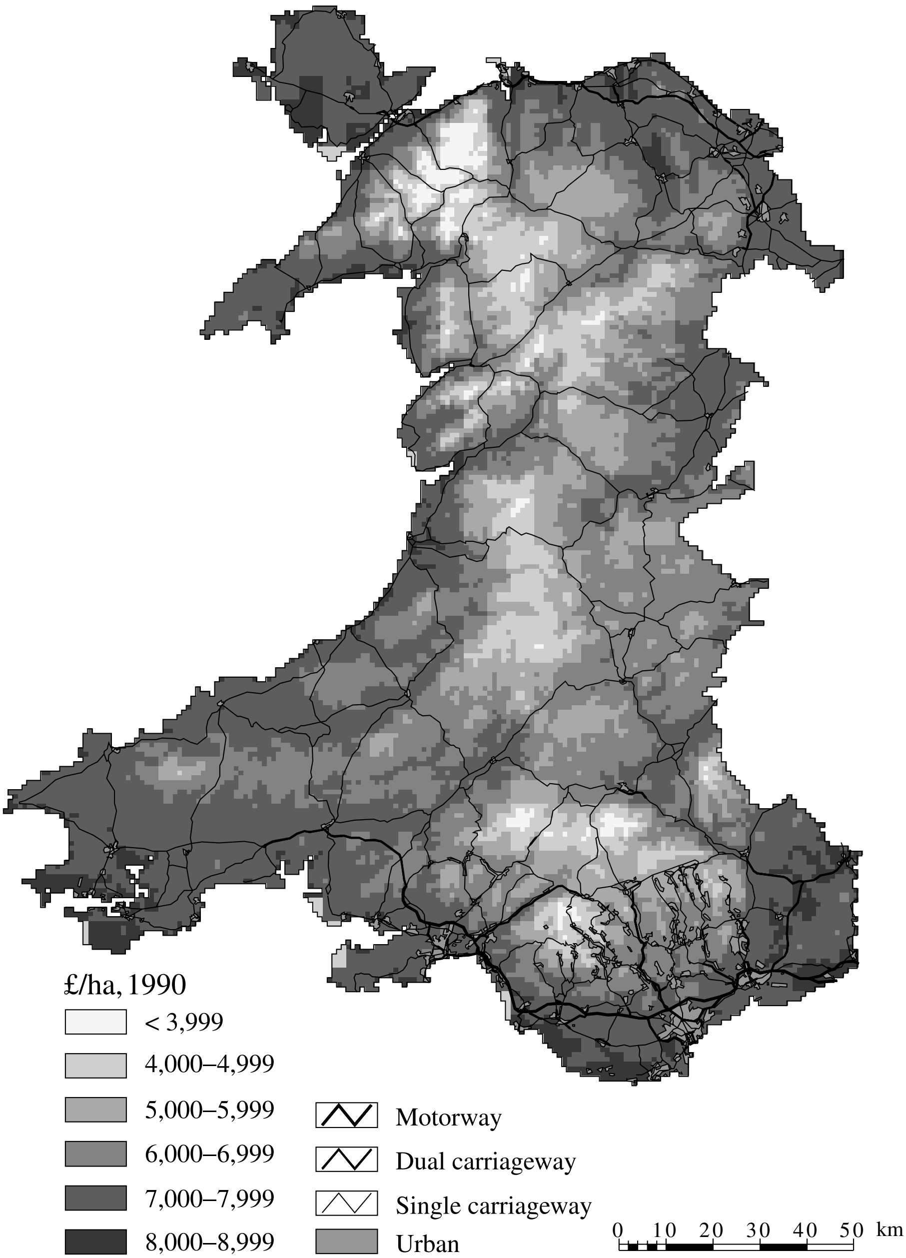

Figure 6.2. Predicted timber social NPV sums for perpetually replanted Sitka spruce: 3% discount rate.

Table 6.7. *NPV sums for perpetually replanted Sitka spruce timber across various discount rates*

	Discount rate, *r* (%)					
	1		3		6	
NPV (£/ha, 1990)	Freq.	%	Freq.	%	Freq.	%
−500– −1	—	—	—	—	1	0.005
0–499	—	—	—	—	31	0.151
500–999	—	—	1	0.005	187	0.909
1,000–1,499	—	—	2	0.010	2,232	10.854
1,500–1,999	—	—	8	0.039	5,786	28.138
2,000–2,499	—	—	20	0.097	11,208	54.506
2,500–2,999	—	—	24	0.117	1,118	5.437
3,000–3,499	1	0.005	48	0.233	—	—
3,500–3,999	—	—	163	0.793	—	—
4,000–4,499	4	0.019	514	2.500	—	—
4,500–4,999	5	0.024	1,019	4.956	—	—
5,000–5,499	10	0.048	1,307	6.356	—	—
5,500–5,999	11	0.053	1,757	8.544	—	—
6,000–6,499	8	0.039	2,556	12.430	—	—
6,500–6,999	17	0.083	3,380	16.437	—	—
7,000–7,499	23	0.112	4,055	19.720	—	—
7,500–7,999	62	0.302	4,534	22.049	—	—
8,000–8,499	80	0.389	1,173	5.704	—	—
8,500–8,999	207	1.007	2	0.010	—	—
9,000–9,499	352	1.712	—	—	—	—
9,500–9,999	525	2.553	—	—	—	—
10,000–10,499	649	3.156	—	—	—	—
10,500–10,999	739	3.594	—	—	—	—
11,000–11,499	826	4.017	—	—	—	—
11,500–11,999	1,112	5.408	—	—	—	—
12,000–12,499	1,194	5.807	—	—	—	—
12,500–12,999	1,595	7.757	—	—	—	—
13,000–13,499	1,820	8.851	—	—	—	—
13,500–13,999	2,162	10.514	—	—	—	—
14,000–14,499	2,225	10.820	—	—	—	—
14,500–14,999	2,605	12.668	—	—	—	—
15,000–15,499	2,600	12.644	—	—	—	—
15,500–15,999	1,561	7.591	—	—	—	—
16,000–16,499	168	0.817	—	—	—	—
16,500–16,999	2	0.010	—	—	—	—
mean (£)	13,362		6,707		2,023	
s.d.	1,938		1,189		438	

Table 6.8. *Annuity values for perpetually replanted Sitka spruce timber across various discount rates*

	Discount rate, *r* (%)					
	1		3		6	
Annuity(£/ha, 1990)	Freq.	%	Freq.	%	Freq.	%
−25– −1	—	—	—	—	1	0.005
0–24	—	—	—	—	21	0.102
25–49	—	—	3	0.015	53	0.258
50–74	1	0.005	16	0.079	479	2.329
75–99	2	0.010	22	0.107	2,183	10.616
100–124	15	0.073	60	0.292	4,068	19.783
125–149	18	0.088	263	1.279	7,318	35.588
150–174	34	0.165	993	4.829	6,434	31.289
175–199	115	0.559	1,682	8.180	6	0.029
200–224	411	2.000	2,413	11.735	—	—
225–249	1,044	5.077	3,962	19.268	—	—
250–274	1,460	7.100	5,175	25.167	—	—
275–299	1,994	9.697	5,626	27.360	—	—
300–324	3,010	14.638	348	1.692	—	—
325–349	4,172	20.289	—	—	—	—
350–374	4,837	23.523	—	—	—	—
375–399	3,380	16.437	—	—	—	—
400–424	70	0.340	—	—	—	—
mean (£)	329		246		133	
s.d.	54		48		30	

Table 6.9. *NPV sums for perpetually replanted beech timber across various discount rates*

	Discount rate, *r* (%)					
	1		3		6	
NPV(£/ha, 1990)	Freq.	%	Freq.	%	Freq.	%
500–999	—	—	—	—	20,563	100.000
1,000–1,499	—	—	10	0.049	—	—
1,500–1,999	—	—	1,281	6.229	—	—
2,000–2,499	10	0.049	14,524	70.626	—	—
2,500–2,999	97	0.472	4,748	23.088	—	—
3,000–3,999	5,410	26.307	—	—	—	—
4,000–4,999	15,046	73.165	—	—	—	—
mean (£)	4,251		2,327		942	
s.d.	495		331		317	

Table 6.10. *Annuity values for perpetually replanted beech timber across various discount rates*

	Discount rate, *r* (%)					
	1		3		6	
Annuity(£/ha, 1990)	Freq.	%	Freq.	%	Freq.	%
40–49	20	0.097	20	0.097	37	0.180
50–59	179	0.870	327	1.590	16,203	78.797
60–69	1,798	8.744	4,756	23.129	4,323	21.023
70–79	6,253	30.409	10,841	52.721	—	—
80–89	8,960	43.573	4,619	22.463	—	—
90–99	3,353	16.306	—	—	—	—
100–149	—	—	—	—	—	—
150–199	—	—	—	—	—	—
200–249	—	—	—	—	—	—
250–310	—	—	—	—	—	—
mean (£)	81		74		58	
s.d.	13		12		12	

least one point of caution regarding the methodology developed in this study. The YC regressions fit the data quite well by the standards of models reported in the literature. Furthermore, the equations linking YC to NPV and annuity equivalents also fit well. If this were not the case the possibility exists that errors in the first of these models might be further propagated by those in the second. This is a point to be wary of in any wider application of such a methodology.

Accepting that such a possible problem does not seem to be present here, the timber value maps produced permit a common unit comparison with the recreation value maps produced previously. Given that woodland recreation frequently takes place in productive woodlands it seems reasonable to assume that these values may be additive.

We now turn our attention to the last forest value we shall consider in our analysis: carbon sequestration.