Modelling and mapping timber values using geographical information systems

Ian J. Bateman and Andrew A. Lovett

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Ian Bateman and Andrew Lovett are at the Centre for Social and Economic Research on the Global Environment (CSERGE) and the School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK. Email address: I.BATEMAN@UEA.AC.UK.

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1 INTRODUCTION

Changes in UK forestry policy (Countryside and Forestry Commissions, 1996) combined with ongoing reforms of the Common Agricultural Policy (e.g. the MacSharry Reforms) have strongly suggested that the area of the UK under forestry is likely to expand very significantly over the next half century. Furthermore, recently announced strategic priorities from the Forestry Commission (1998) emphasise the need to undertake geographical targeting of resources. Clearly the incorporation of information concerning spatial variations in tree productivity is a desirable feature for such decision-making. This paper describes models of timber production for two tree species: Sitka spruce and beech, chosen as representative softwood and broadleaf species. The methodology developed as part of the study differs from previous approaches in that it uses a geographical information system (GIS) to integrate databases covering a very large and diverse study area; the whole of Wales. A GIS is a software package capable to storing and analysing any type of spatially referenced information (e.g. elevation, rainfall, soil type, etc.). Furthermore, the GIS can produce maps of results, such as predicted timber yield, for the entire study area. These maps can detail both quantitative timber production and the value of that yield thus facilitating ready incorporation within the declared decision-making system.

In Section 2 we present a brief overview of the data collected for this study. Statistical models of Sitka spruce and beech growth rates are presented in Sections 3 and 4 respectively while Section 5 presents a side analysis examining the impact of aspect upon growth rates. Section 6 presents GIS created maps of predicted yield class while Section 7 applies the findings of previous research regarding the value of timber yield to produce maps of the timber value produced by planting different locations. Section 8 presents conclusions and outlines some related research demonstrating applications and extensions to the analysis presented in this paper.

2 DATA

A review of the previous literature (Bateman and Lovett, 1998) shows that tree growth rates depend upon a variety of species, environmental and silvicultural factors. Early studies examined the impact of variables such as elevation, rainfall, windiness, slope and aspect, soil type and moisture transport. More recently silvicultural factors such as management, crop age and improvements in genetic stock have been highlighted. All studies have of course noted the need to consider species when modelling timber yield.

Given the variety of factors determining tree growth the cornerstone of any analysis is that high quality data needs to be available. Two major data sources were used for this study:

(i) The Forestry Commission (FC) Sub-Compartment Database (SCDB). This holds information on each discrete stand (sub-compartment; SC) in the FC's estate including the location of the stand, species type, the estimated growth rate (the ‘yield class’ (YC) measured as the expected timber production in $m^3\ ha^{-1}\ yr^{-1}$ averaged over the expected length of rotation), the year in which the stand was planted and the year in which its growth rate was estimated, whether this was the first or subsequent rotation, and a variety of management regime information including whether the site is being left in a semi-natural state or is a designated nature reserve, etc. Records for several thousand Sitka spruce compartments and several hundred beech stands from across Wales were extracted for use in our analysis.

(ii) The Soil Survey and Land Research Centre (SSLRC, Cranfield) Land Information System (LandIS) database (Hallett, et al., 1996). Details were obtained for the entire area of Wales providing information on environmental variables such as temperature, rainfall, soil type and moisture characteristics, workability, etc.

In addition to the information provided by SCDB and LandIS, data were also obtained from the Forestry Commission concerning the topographical shelter (topex) of a site and its windiness. A digital elevation model for the whole of Wales was constructed using data derived from the Bartholomew 1:250,000 digital database and additional information from the SCDB. This model was used to derive slope and aspect variables for the entire study area.

3 MODELLING SITKA SPRUCE TIMBER YIELD

As discussed previously, tree growth is determined by a variety of variables. The standard approach to understanding the influence of each variable is through the statistical technique of regression analysis (Lewis-Beck, 1980). Here, for each species in question, changes in tree growth across stands are related to the various environmental and silvicultural characteristics of each SC.[1] Statistical tests identify those variables which do not have a significant influence upon tree growth. These are omitted and the remaining variables constitute our YC model. Regression analysis provides an estimate of the impact of each of the significant variables upon YC. This is expressed as a number or 'coefficient' for each of the significant variables showing the extent to which changes in that variable either increase or decrease growth rates (controlling for all other predictor variables in the equation). So, for example, we would expect that the coefficient for SC elevation would be negative showing the extent to which YC declines as we consider stands at progressively higher elevations. Conversely, better soils will have a positive coefficient showing their beneficial impact on growth rates.

A variety of models were investigated with the database of Sitka spruce and environmental variables (Bateman and Lovett, 1998). Our preferred model used information from some 4307 SCs, the results being reported in Table 1[2]. The first column of this table lists in turn each of the variables which were found to have a significant impact upon YC (we have indexed these variables from (i) to (xvi) to aid the clarity of the subsequent discussion). The second column gives the coefficient (defined above) for each of these variables while the final column gives a measure of the statistical significance of each variable. We can discuss each of these in turn starting with the elevation variable which is listed in row (i) of the table.

INSERT TABLE 1 ABOUT HERE

The elevation of each SC is measured in metres above sea level, therefore the negative coefficient on elevation, shown in the second column, tells us that for each increase in elevation of 1m we should expect a fall in YC of just 0.0088. Therefore, if we had two SCs which were

[1] A variant upon this approach is to first group the various characteristics of each sub-compartment into a smaller set of 'factors' through techniques such as principal component analysis (PCA). These factors are then entered into a regression analysis (as described in the paper) in place of the individual characteristic variables. Such a PCA analysis is presented in Bateman and Lovett (1997) however it proved to be no substantial improvement upon the analysis presented here (and more difficult to interpret).

identical in all respects except that one was 100m higher than the other then we would expect YC to be 0.88 lower at the higher elevation SC. The third column gives a common measure of the significance of each variable; the modulus of the t-ratio (for its derivation see any introductory text on statistical analysis). When this value rises above approximately 2 then we can say that we are 95% sure that the variable in question is having a significant effect upon YC (with the extent of that effect being given by the coefficient). The higher the modulus of the t-ratio then the greater the statistical significance of that variable in determining YC, however, a quick inspection of this final column shows that all the values listed have significant effects (in fact we can be more than 99% sure that all of the variables shown have a significant impact on YC). Not surprisingly, elevation proves to be one of the most significant determinants of tree growth.

The simple example of two sites varying only in terms of their elevation is helpful for illustrative purposes. However, in reality as elevation changes so do many other factors one of which, rainfall, is included in row (ii) of the table. In such a wet area as Wales it is excess of water rather than drought which limits tree growth. So it is perhaps not surprising that the coefficient for rainfall is negative showing that, within our study area, higher rainfall is associated with lower rates of tree growth. Here an increase of 1m (i.e. 1000 mm) in annual rainfall results in a 1.67 reduction in YC.

Row (iii) shows that, as expected, YC is higher for more sheltered sites while rows (iv) and (v) indicate that sites with relatively better (brown earth) or poorer (lithomorphic) soils yield correspondingly higher or lower YC. The remaining rows of Table 1 summarise the impact of a variety of environmental and silvicultural influences. YC is found to be slightly higher for larger area sites (row (vi)) and an interesting positive relationship is found with the year in which the stand was planted (row (vii)); a result which may be reflecting improvements in genetic stock and/or silvicultural practice as time passes. This variable is measured on a scale from year 0 (which is when Sitka spruce records were first added to the SCDB in the 1920s) to 75 (the present day, 75 years later).

The planting year effect has to be considered in conjunction with the finding that trees in the first rotation of a given SC do not produce as much timber as subsequent rotations (row (viii);

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[2] The 'degree of fit' (adjusted R^2) was 42.8% which compared well to previously published models of timber growth rates. Further discussion of this and other models is provided in Bateman and Lovett (1998).

the coefficient showing that an initial rotation produces tree growth which is on average 2 YC (i.e. 2 m^3 ha^{-1} yr^{-1}) lower than subsequent rotations). Similarly Sitka spruce trees grown in a mixed species SC do not yield quite as much timber as those grown in monoculture stands (row (ix)). This may reflect the fact that single species stands can be managed in a manner which is optimal for that species or that monocultures tend to condition the environment in which they grow to their own advantage.

Rows (x) to (xv) of Table 1 capture the effects of somewhat unusual sites as proxied by the designations assigned to them by the FC. The first three of these all exhibit negative coefficients indicating that these sites produce below-average levels of tree growth once the factors considered in previous rows are accounted for. These include sites that are classified as 'unproductive' or are part of a 'forest reserve' or 'semi-natural area' and therefore may not be managed as intensively as possible. Rows (xiii) to (xv) contain designations which were found to produce above average levels of timber growth as indicated by their positive coefficients. These are, in turn, areas of 'ancient woodland' (which may reflect the advantages of an area which has been pre-conditioned by trees), 'forest park' (which may reflect similar conditions to ancient woodland) and areas designated as 'uncleared' in which the density of trees may be lower promoting growth rates amongst those remaining. The final row (xvi) of Table 1 shows the 'constant', that level of YC which would occur of all the other variables were set to zero. However, this is not a situation which occurs anywhere in the case study area (e.g. nowhere in Wales has an annual rainfall of zero!), rather this is a baseline from which prediction for real world sites can be calculated taking into account the levels of the various variables recorded elsewhere in the table. So, for example, if we consider a site for which the elevation is 100m, the rainfall is 1000mm and where the crop has just been replanted after felling the previous rotation then, ignoring other factors (e.g. topex, soil type, special site variables, etc.), our predicted YC will be:

YC = constant + (elevation coefficient x site elevation) + (rainfall coefficient x site rainfall)
+ (planting year coefficient x planting year)

and using the values from Table 1 we obtain:

YC = 16.7097 + (- 0.0088 x 100) + (- 0.0017 x 1000) + (0.0499 x 75)
= 17.87

Therefore our best estimate for this site under these conditions is that it will produce a YC of about 18, i.e. the expected timber production averaged over the expected length of rotation will be about $18m^3\ ha^{-1}\ yr^{-1}$. We can readily calculate YC predictions for a wide variety of site types. For example, if in the above case we had considered a first rotation SC rather than one which had just been replanted then our prediction of timber growth would be almost 2YC lower (see the coefficient on row (viii) of Table 1).

4 MODELLING BEECH TIMBER YIELD

The analysis of YC for beech sub-compartments followed the same methodology adopted in our investigation of Sitka spruce sites. However, data was much more restricted and our preferred model relies on just 205 sites,[3] results being reported in Table 2.

INSERT TABLE 2 ABOUT HERE

Considering the results presented in Table 2, row (i) shows that, as before, tree growth is negatively related to elevation. However, while this is a highly significant relationship, this is not the case for the other environmental characteristic variables found significant in Table 1. This is most probably a consequence of the much lower sample size used in the beech study and a greater availability of data would probably show that many of the variables identified as affecting Sitka spruce would also determine beech growth rates. However, the strong impact of the planting year (row (ii)) is reconfirmed. In this case records for beech stretch back well into the 19^{th} Century such that the present day becomes year 162 in the beech model.

Row (iii) shows that beech SCs within designated Environmentally Sensitive Areas exhibit lower growth rates than average, possibly as a result of less intensive silvicultural practices within ESA. Conversely, stands in areas of scenic beauty were found to grow slightly better than average, however this relationship is the only one of all those reported in both Tables 1 and 2 which records a t-ratio of less than 2 and so cannot be considered as indicating a statistically significant relationship. The final row reports the regression constant which should be interpreted as before.

Table 2 is considerably less sophisticated than the model for Sitka spruce. Nevertheless, valid predictions can be made on the basis of these results. For example, treating the coefficients in the same manner as before, for beech trees planted in the present day at an elevation of 100m in a designated ESA our predicted YC would be:

$$YC = -4.4280 + (0.0799 \times 162) + (-0.0039 \times 100) + (-1.4812) = 6.64$$

Therefore our best estimate for this site under these conditions is that it will produce a YC of about 6 (YC estimates are conventionally rounded to the nearest even number), i.e. the expected timber production averaged over the expected length of rotation will be about $6m^3\ ha^{-1}\ yr^{-1}$.

5 THE IMPACT OF ASPECT UPON YIELD CLASS

The integration of the SCDB and LandIS databases within a GIS permits an interesting extension of our Sitka spruce and beech analyses. We can add information regarding the aspect of each of the sites into our analysis and re-estimate the models. While this does not appreciably alter the coefficient estimates produced (details in Bateman and Lovett, 1997), it does allow the estimation of how aspect (direction of slope) might raise or lower the YC of a site relative to average growth rates. Results from this investigation are shown in Figure 1. Here the angles of the compass are displayed on the horizontal axis ranging from due north clockwise to due south and back to due north again. The vertical axis shows the difference from average growth rates which each aspect angle produces. Results

[3] However, the 'degree of fit' (adjusted R^2) is still reasonable at 34.4%.

from our Sitka spruce analysis are indicated by the thick unbroken line. This shows that aspect has a substantial impact upon growth rate, raising it by about 1YC ($1m^3$ ha^{-1} yr^{-1}) for sites with a south easterly aspect (about 135°) and depressing growth by a similar extent for sites with a north westerly aspect (about 315°). This is as expected, as the positive solar forcing effect of a south facing aspect is mitigated by the prevailing westerly winds such that the optimal site is one which catches the southerly sun while being protected from the wind, and the worst site is one which is neither assisted by the sun nor protected from the wind. This results makes an interesting comparison with the broken line which is taken from a study of Sitka spruce in upland areas of Northern Britain (Worrell and Malcolm, 1990a,b). Here the radiative forcing effect of the southerly sun is completed negated by the impact of the prevailing wind such that optimal aspect become due east.

Returning to Wales, results for our beech database are shown by the unbroken thin line. This does not show a strong prevailing wind effect, primarily because beech are located at much lower altitudes than are many of the Sitka spruce SCs. With beech the optimal aspect seems to be just to the east of due south (about 165°). However, the major difference is that aspect plays a much less prominent part in determining beech growth rates, although again this is simply a reflection of the lower elevations of beech SCs.

INSERT FIGURE 1 ABOUT HERE

6 MAPPING YIELD CLASS

The GIS can store data layers for all the environmental variables, such as elevation, rainfall, etc., which our regression models show influence tree growth. So, considering the model of Sitka spruce given in Table 1, the GIS can hold maps of all the variables shown in rows (i) to (v). Therefore, at any location across Wales we can use our GIS to select the value of each of these variables at that point. We can then multiply these values by their respective coefficients (from Table 1), add in the Constant (row (xvi)), and produce an estimate of Sitka spruce YC for that location. However, Table 1 also tells us that YC is influenced by the management and designation variables shown in rows (vi) to (xv). For the ‘designation’ variables (rows (x) to (xv)) data could be taken from FC maps. However, the size of the SC (row (vi)) and when it was planted (row (vii)) are variables which are under the control of the forester and so we could consider large or small areas or stands which were planted in either the present day or at some point in the past. The assumptions we make will clearly affect our predictions of YC. For illustrative purposes we can consider stands which are the median size found in the SCDB (33ha for Sitka spruce) and, as we are primarily interested in using this approach to plan new forests, we assume that planting takes place in the present day (i.e. year 75 in Table 1). Taking these values, multiplying by the respective coefficients and adding these to the effect of the other predictors listed in Table 1 we can obtain our overall estimate of Sitka spruce YC for that location.

The GIS implements this operation such that it can be repeated for all locations across the entire area of Wales. In so doing a map of predicted YC is produced. Figure 2 illustrates the map obtained using the assumptions discussed above. Inspection of this map clearly shows the very strong influence which environmental characteristics have upon our predictions of YC. The influences of lower altitude, better soil and less-excessive 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 picked out. Less extreme upland areas such as the Preseli Mountains produce YC values which lie between these extremes. Also clearly noticeable is the adverse excess 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 (and across) the English border. The detrimental effect 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[4].

INSERT FIGURE 2 ABOUT HERE

A similar YC mapping exercise was also carried out for our beech model. Although this highlights the result that hardwood growth rates are much lower than those produced by

[4] Interestingly both Pembrey and Newborough (Anglesey) are the sites of large forests; an illustration of the common finding that forests are often confined to the most marginal land.

softwoods, the general YC pattern is similar to that of Figure 2. As a consequence this map is not reproduced here (see Bateman and Lovett, 1997 for details).

7 MAPPING TIMBER VALUES

While the YC maps are of interest, in determining land-use policy planners have to trade the net benefits (benefits minus costs) of woodland against those of competing land uses such as agriculture. In this situation information on YC levels is difficult to assess against data on the financial returns from agriculture[5]. To facilitate common-unit comparability we developed a series of models for both Sitka spruce and beech to convert any given YC level to its corresponding financial value (Bateman, 1996). These models took into account a variety of factors, of which the most important where:

(a) the financial costs of planting, maintaining and felling a woodland;
(b) the financial benefits of the maincrop, other timber produced (thinnings, etc.) and the grants and subsidies available;
(c) the rate at which delayed costs and benefits (i.e. those which do not occur in the present day but arise at other times during the rotation) are 'discounted' (i.e. converted to a present day equivalent).

The discounting process is particularly important for such a long term investment as woodland and is the subject of extensive debate elsewhere (for an introduction see Price, 1987). One of the fundamental rationales for discounting is that £1 received today must be worth more than £1 received at some point in the future by at least the amount of interest that could have accrued through investment of the former amount. By the same argument £1 received in the future has a present value of less than £1. The rate of discount (i.e. the rate through which future amounts are related to present day equivalent values) need not be the same as the rate of interest as it should also reflect individuals impatience and a variety of other factors (see Pearce, et al.,

[5] However, it should be noted that in many cases, from the perspective of society, the value of much Welsh agriculture is actually negative as the value of its outputs is exceed by the subsidies and grants paid by taxpayers (Bateman et al., 1999b).

1989, for a review). Because of this factor, our timber valuation models were constructed to consider a wide range of discount rates (from 1% to 12%). Once a discount rate is specified this is then applied to all the costs and benefits listed under (a) and (b) above to derive the present day value of those amounts. By adding together all of the discounted benefits and subtracting all of the discounted costs we obtain the 'net present value' (NPV) of a given woodland. This can then be compared with the agricultural return from that land[6].

Once we have an economic model which can directly relate YC to money value we can then easily convert our YC maps, such as Figure 2, into maps of the value of the timber produced. Figure 3 illustrates the timber NPV map for Sitka spruce across the whole of Wales. This was calculated using a discount rate of 3%, an amount which approximates to the rates of return from agriculture, the principal competing land use in the study area. The NPV sums shown in the map strongly reflects the YC distribution discussed previous and consequently our comments are as before.

INSERT FIGURE 3 ABOUT HERE

The values shown in Figure 3 deserve some comment. As can be seen NPV sums range from below £4,000 to above £8,000 per hectare. What is the meaning of an NPV of £8,000? Put simply it means that a land owner faced with the decision of planting trees on a hectare of land, and thereby committing to an investment which on better land (such as that which would produce an NPV of £8,000) might last in the region of 40-50 years, should expect a stream of costs and benefits over that period the *present value* of which would be a surplus of benefits over costs of about £8,000. Note that this is *not* the same as saying that undiscounted benefits will exceed costs by £8,000 over that period. Indeed the very substantial value of a hectare of timber at felling might mean that in crude terms undiscounted benefits exceed costs by very much more than £8,000 over the rotation. However, while these benefits accrue at felling (say 45 years hence) and are therefore heavily discounted back to the present day, the major planting costs

[6] This comparison can be conducted in two ways. Either the agricultural NPV of the land can be calculated over the lifetime of the plantation (e.g. one rotation) or the annual equivalent of the NPV (i.e. that amount of money which if received annually over the rotation would be of equivalent value to the whole rotation NPV) can be calculated and compared with the annual value of agriculture. Bateman (1996) presents results from both approaches.

occur immediately and are unaffected by discounting (as £1 spent today has a present value of £1!). Information on the expected NPV amount is very important as the landowner can now assess this value against the costs and benefits of committing the same land to a different use (say agriculture) over the same period. If the NPV of this alternative use does not exceed £8,000 then the investment in woodland should be made, otherwise it should not.

We can use the same procedure as described above to generate the NPV map for beech across the whole of Wales illustrated in Figure 4. This is not to suggest that such wholesale afforestation is desirable or even feasible (indeed it is not as beech trees do not grow on some of the exposed uplands of Wales for which we have generated results – however we have left the low predicted value in this map for no particular reason other than aesthetics). However, as before, this indicates the areas in which NPV sums are highest (and lowest).

INSERT FIGURE 4 ABOUT HERE

8. CONCLUSIONS AND RELATED RESEARCH

Comparison of the NPV maps for Sitka spruce (Figure 3) and beech (Figure 4) is interesting; the values for the former being universally higher than those for the latter. This result arises because beech has a much longer rotation period and so felling benefits are much more discounted than those for Sitka spruce. This result is one of the main reasons why softwoods have been consistently favoured over hardwoods as the species of choice for commercial plantations. However, hardwoods may have higher non-market values than softwoods. In particular they may generate higher landscape and recreational values and in other work we have applied the travel cost method (Bockstael, et al., 1991) to produce estimates of the expected recreational values of such woodlands (Bateman et al., 1999a; Brainard et al., 1999). Similarly, maps of the carbon storage value of woodlands can be generated (Bateman, 1996). These various values can be added to the timber NPV estimates discussed in this paper and then compared with maps representing the agricultural value of the present land use (Bateman et al., 1999b). Results from this analysis allow the identification of those areas which should stay in agricultural use, those which should convert to softwood forests and those to hardwood. Full discussion of these results would require a paper substantially longer than the present one. However, in essence, this wider analysis indicates that there is substantial scope for conversion of agricultural land into both softwood and hardwood woodlands and that these woodlands should be primarily concentrated in high accessibility, urban fringe areas rather than in the upland reaches which have been the location of much of the forest expansion witnessed this century. However, in order to achieve this outcome, incentive payments are required to reward new foresters for the non-market benefits which their woodlands will provide. Until that occurs the market priced returns of forestry (i.e. timber and the present grant and subsidy payments) may be insufficient to induce any more than a minor growth in lowland woodland.

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Table 1: Best fitting model for Sitka spruce YC

Variable (characteristics of the SC)	Coefficient	Significance |t-ratio|
(i) Elevation (in metres above sea level)	-0.0088	22.31
(ii) Average annual accumulated rainfall (in mm)	-0.0017	15.65
(iii) Topographical shelter (topex)	0.0243	3.20
(iv) Brown earth etc. soils	0.8049	10.00
(v) Lowland lithomorphic soils	-4.8827	5.05
(vi) Area of SC (ha)	0.0040	10.43
(vii) Year in which the stand was planted (0 to 75)	0.0499	10.31
(viii) If the SC is in its first rotation	-1.9280	17.64
(ix) If the SC has a mix of species	-0.3083	4.02
(x) If the SC is in a designated unproductive site	-0.0854	10.49
(xi) If the SC is in a designated forest reserve	-0.4340	4.59
(xii) If the SC is in a designated semi-natural area	-5.1415	6.73
(xiii) If the SC is in a designated area of ancient woodland	0.9477	10.10
(xiv) If the SC is in a designated FC park	0.9266	3.00
(xv) If the SC is in a designated uncleared land	2.6411	11.61
(xvi) Constant	16.7097	47.92

Table 2: Best fitting model for beech YC

Variable (characteristics of the SC)	Coefficient	Significance |t-ratio|
(i) Elevation (in metres above sea level)	-0.0039	4.22
(ii) Year in which the stand was planted (0 to 162)	0.0799	6.25
(iii) If the SC is in a designated ESA[1]	-1.4812	2.98
(iv) If the SC is in a designated area of scenic beauty[2]	0.4751	1.75
(v) Constant	-4.4280	2.30

Notes: 1. SC within a designated Environmentally Sensitive Area.
2. SC within a designated Area of Outstanding Natural Beauty/National Scenic Area

Figure 1: Aspect effects for Sitka spruce and beech in differing locations

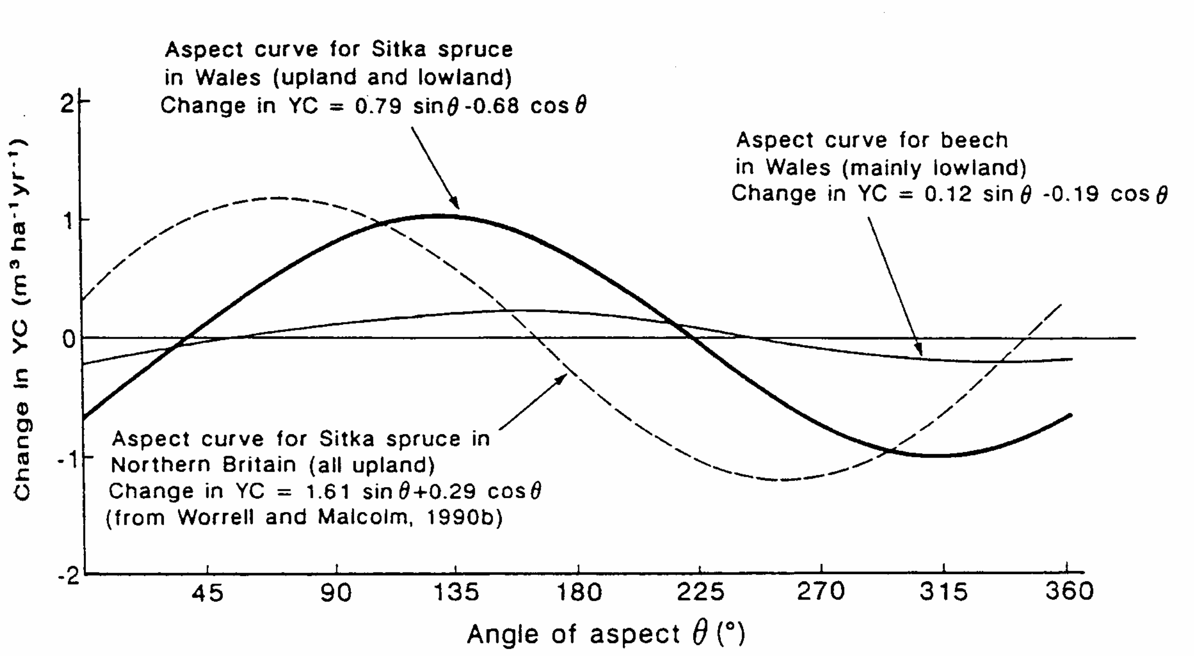

Figure 2: Predicted YC for Sitka spruce.

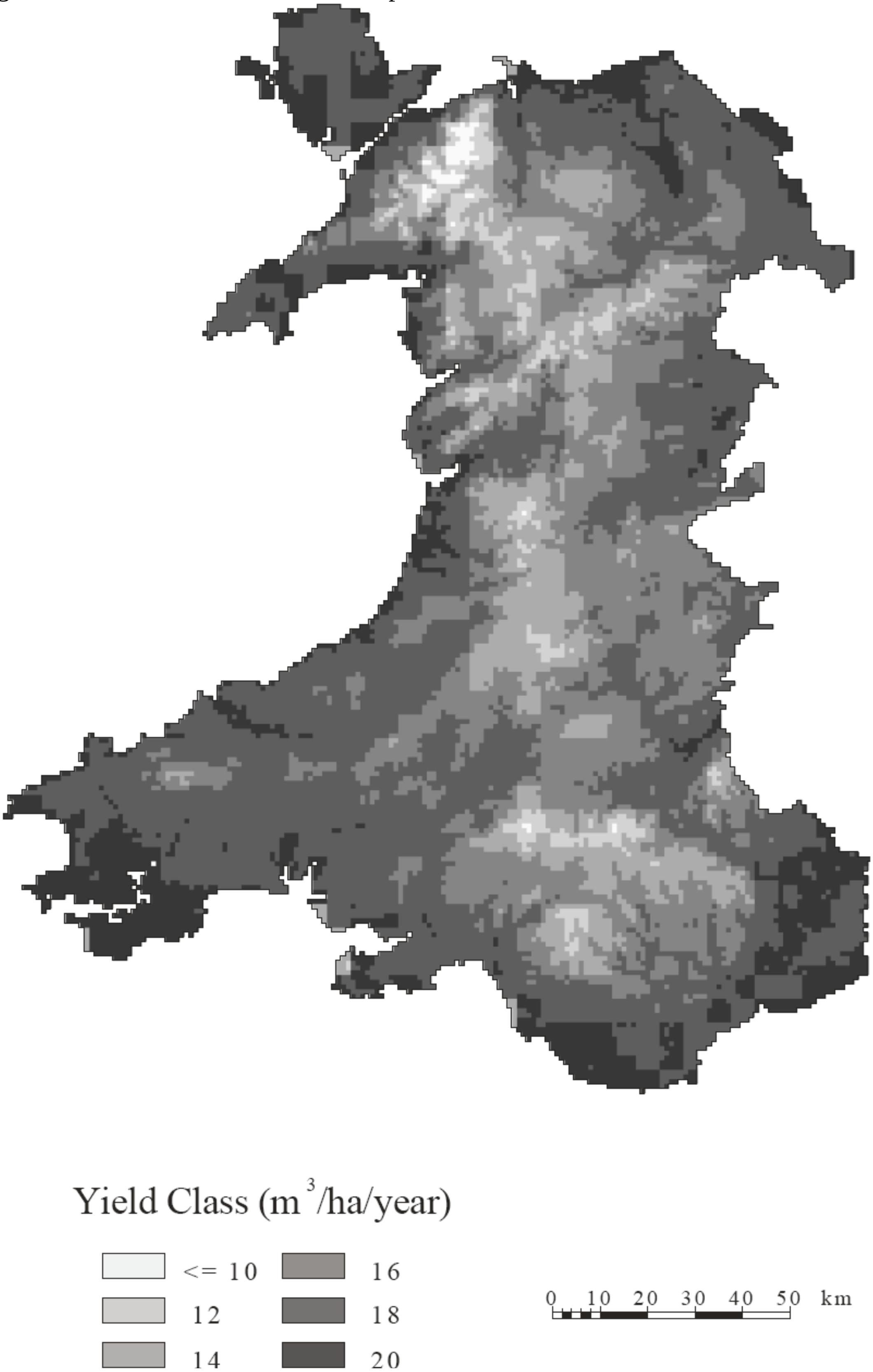

Figure 3: Estimated timber values (NPV) for Sitka spruce (£/ha; 1990 prices; discount rate = 3%)

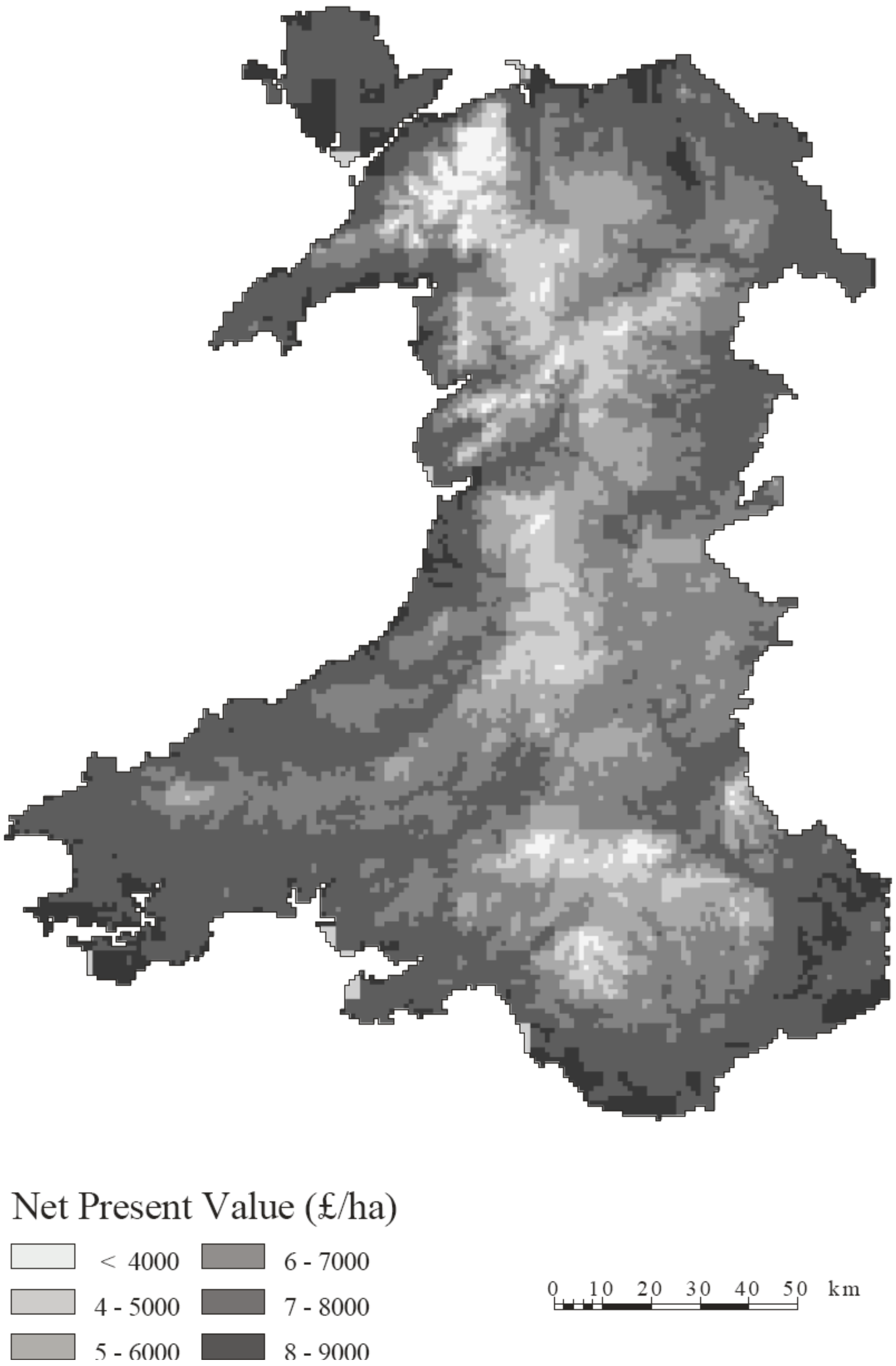

Figure 4: Estimated timber values (NPV) for beech (£/ha; 1990 prices; discount rate = 3%)