Natural Environment Valuation Online Tool

Technical Documentation

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Chapter 2: Forestry Model

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1. The timber module: forest growth and timber profitability

1.1. Timber in NEVO

The Timber tab in NEVO provides information about Woodland and Forestry. Under the woodland heading users are provided with a summary of the number of hectares of existing woodland in an area, this is subdivided by species type (broadleaf and conifer). The details panel also quantifies how many hectares of woodland are located on farm land and on non-farm land.

The term 'forestry' is used in NEVO to refer to woodlands that are managed for timber outputs. The timber module in NEVO provides users with an estimate of the volume of timber that could be produced and the profitability of managing an area for timber production on a decadal basis, taking into account the impact of climate change on the suitability of different locations for forest growth.

Under the Explore function, users can select an area and view a summary of the existing hectares of woodland across England and Wales. When utilising the Alter and Optimise functionalities in NEVO users can define a land use change and the forestry tab in the details panel will display the estimated volume of timber (m2) and profitability (£) of managing all of the new area of woodland land for timber production. The panel provides three estimates relating to three different planting regimes i) all broadleaf, ii) all conifer and iii) a 60-40 broadleaf and conifer split.

The timber volume and profitability are displayed in flows per year as the default. The takes account of the life cycle of a managed woodland, including the fact that different species in different locations will have differing optimal rotation lengths. The flow per year captures these differences in growth rates and harvesting of timber through both thinning and felling.

Users are able to switch to an annuity calculation for timber profits. This provides the annuity equivalent of timber profits over the full rotation (which is species and location specific). Where the growth rate of woodlands is predicted to change as a consequence of climate change this is incorporated into the annuity calculation by averaging over the length of time in each growth rate (yield class).

Limitations

Woodland in NEVO is simplified to two representative woodland types (broadleaf and coniferous) and a mixed 60-40 planting option. However, the underlying models contain wide variety of species which may be of interest to more specialised users.

NEVO uses data on average 2km grid cell characteristics – this approach enables models to be run quickly in the online tool however it is not as refined as site by site calculation with more detailed information on soil types, environmental site classification and management options.

Likewise, simplifying assumptions are made about the management options chosen when planting a new woodland. This allows NEVO to provide a high level analysis which considers multiple ecosystem services. Users may also wish to undertake a more detailed site specific approach e.g. the WCC tool permits more detailed inputs on the ground preparation.

Under Explore current woodlands are treated as being in equilibrium and we do not make any calculations regarding the proportion of existing woodlands that are managed for timber. We are exploring the potential to update NEVO utilising Foresty Inventory data to make inferences about the current profitability and timber production of existing woodlands and forests.

1.2. *Introduction*

The timber module has been developed for the analysis of timber profits under current and future climates. The module consists of two distinct elements i) a model of the impact of climate change on forestry growth using changes in yield classes (YC) and ii) the relationship between yield class and profits from timber. We estimate the impact of climate change on forest growth using changes in yield class (YC), as a function of local and climatic characteristics, modelled with flexible functional forms. Rounded yield class values are then fed into the CARBINE model (Thompson and Matthews, 1989), which produces tree volume under a variety of management regimes. For the purposes of modelling in NEVO we assume a fixed management regime of thinning and felling.

To obtain market values, the CARBINE tree volume is combined with the FC Forest Investment Appraisal Package (FIAP, 2013) to calculate the economic profitability of forests. This linkage brings in timber prices (Lavers and Moore 1983) to allow analysis of revenues and comparison with management costs to yield estimates of profitability. FIAP provides price-size curves (price per m^3) for different tree species and average management costs (for activities such as mounding, planting, staking, insurance, drainage, weeding, spraying etc.,) under a variety of silvicultural systems.

1.3. Objectives

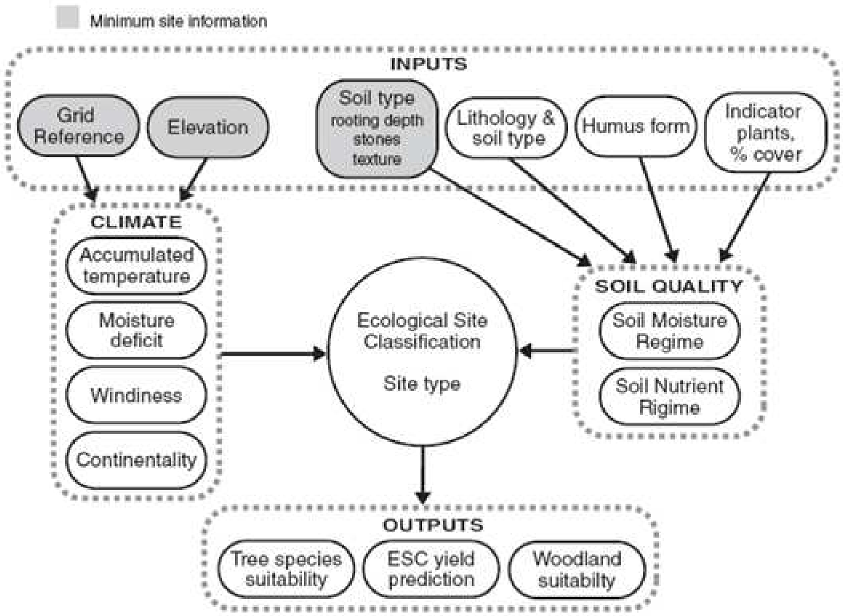
- To model variation in growth rates and timber yield class for representative commercially grown tree species for a variety of physical environmental conditions across Great Britain.
- To incorporate into this analysis the influence of climate change upon growth rates and timber yields.
- To predict timber costs and benefits and hence profitability for different tree species across locations, climate scenarios and a common silvicultural management regime.

1.4. Yield class and profits

1.4.1. Data

In determining the suitability of sites for forest growth we rely on several constructed databases derived from modelling advice throughout in collaboration with experts in the UK Forestry Commission (FC). Expected forest growth is established in the FC Ecological Site Classification model (ESC, 2013). This is a well-established decision model developed by Pyatt et al. (2001) and is based on a synthesis of multi-criteria analysis Ray et al. (1996) and fuzzy-set theory Ray et al. (1998). A schematic overview of the model is presented in Figure 2.1.

Figure 2.1: Schematic diagram of the ESC model.



Source: BVCM Report Matthews (2011)

The ESC model provides an analysis of timber yield which is sensitive to the suitability of land (in terms of soil, moisture, elevation, temperature, etc., (ESC, 2013), and incorporates the judgment of experts who assign characteristics into two macro-classes: climate and soil. Each macro-class is further organised into sub-classes (e.g. accumulated temperature, and soil moisture regime). One output of the model is predicted C, which is the mean annual volume of tree growth under optimal management measured in cubic metres per hectare per year (m^3/ha/yr), for each GB 250m grid cell (ESC, 2013). This output resolution was converted to the common 2km grid used for the wider analysis ESC_SEER (2012). A quantitative summary of the data for the two representative species: Sitka Spruce (SS) for coniferous and Pedunculate Oak (POK) for broadleaf, referred to in this section are presented in Table 2.1.

Table 2.1: ESC results: main yield class characteristics.

Tree type	Mean Esc score (st.dev)	Min	Max
Sitka Spruce (SS)	13.23 (3.81)	0	21
P.Oak (POK)	3.82 (1.95)	0	8

Yield class statistics for Sitka Spruce and Pendunculate Oak across GB by 2km grid cells.

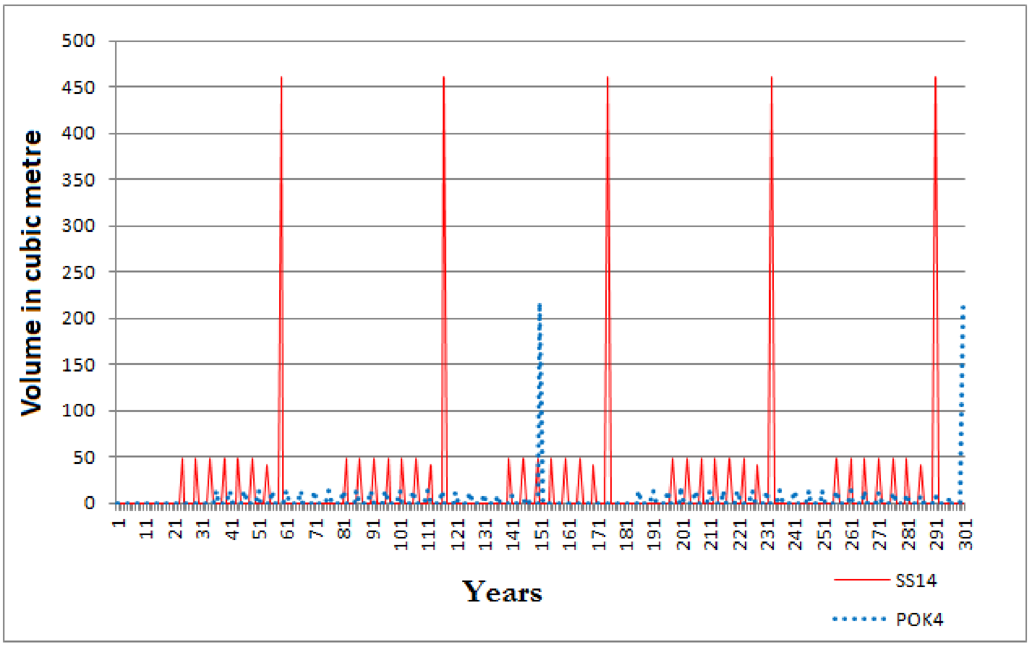
The YC in ESC is represented by a continuous variable which assumes value zero where soil and climatic factors are unsuitable for planting; such as in urban areas. The average ESC YC values are subsequently rounded to the nearest even number as is conventional in forestry studies. The resulting averages in

YC terms are: 14, for SS and 4, for POK, these will be used both in this analysis and in the analysis that follows in the forest greenhouse gas model.

1.4.2. Methodology

Timber profits are obtained by multiplying tree volume by their corresponding market price, incorporating relevant management costs. To obtain tree volumes the ESC rounded YC values were then fed into the CARBINE model (Thompson and Matthews, 1989), which produces tree volume for a variety of management regimes. For the purposes of modelling in both this section and in the forest greenhouse gas model we only consider the management regime: 'thinning and felling. The rate of growth and volume of timber output from SS is both faster and more plentiful than that of POK, with five rotations for only two of POK. A comparison of the average YC timber volume for SS and POK is illustrated in Figure 2.2.

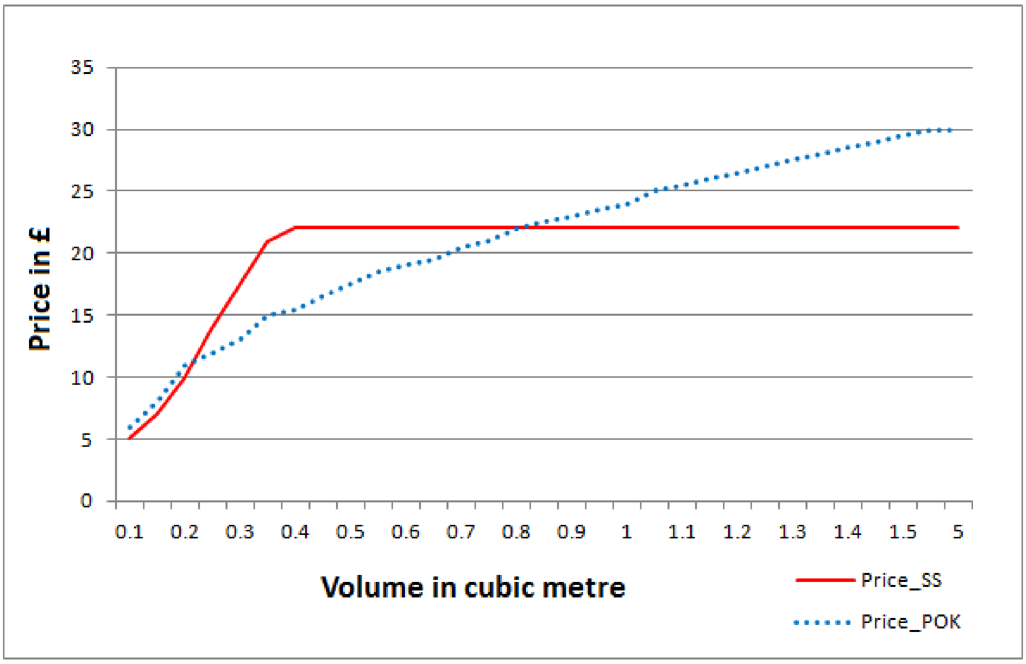
Figure 2.2: Timber volumes over multiple rotations: Sitka Spruce (yield class 14) and Penduncluate Oak (yield class 4).



Shows the volume of timber harvested over a three hundred year period (five rotations of YC14 Sitka Spruce (SS) and two rotations of yield class 4 Penduculate Oak

To obtain market values, the CARBINE tree volume is combined with the FC Forest Investment Appraisal Package (FIAP, 2013) to calculate the economic profitability of forests. This linkage brings in timber prices (Lavers and Moore 1983) to allow analysis of revenues and comparison with management costs to yield estimates of profitability. FIAP provides price-size curves (price per m^3) for SS and POK and average management costs (for activities such as mounding, planting, staking, insurance, drainage, weeding, spraying etc.,) under a variety of silvicultural systems. The price-size curves (otherwise regarded as timber prices) are perpetually monitored by the FC and are expected to remain constant in real terms throughout the period of the analysis. These curves are illustrated in Figure 2.3.

Figure 2.3: Price-Size Curves for Sitka Spruce and Penduncculate Oak.



Comparison of price-size curves (price by volume per cubic metre) for Penduncculate Oak and Sitka Spruce.

Figure 2.3 shows that price per m^3 is not a constant variable, but rather increases with volume. Both curves increase sharply and remain steady after they reach a maximum. This relationship can be explained by considering that when a cubic metre of wood is composed of small volume trees this has a restricted set of end-uses (e.g. fence posts, pulpwood, etc.) reflected in the price. Whereas, when a cubic metre is composed of high volume wood it commands a higher price because it has multiple end-uses (e.g. floor boards, construction materials, furniture, etc.). Once the volume reaches roughly floorboard size it will have a constant price, as shown in Figure 2.3.

The maximum price for SS is £22 for trees with a volume exceeding $0.4m^3$/ha and the maximum for POK is £30 when the volume reached exceeds $1.60m^3$/ha. Differences between species are also reflected in management costs. For example, on average managements costs for POK YC 4 in the first 10 years are £560/ha whereas they are only £230/ha for SS YC 14.

Relevant management costs refer only to variable costs and exclude fixed costs such as fencing, consultancy advice, etc., which are expected to be significant only in the early years of land use conversion. Further, in keeping with the shadow pricing approach (Gregersen and Contreras, 1979, 1992), adopted for the treatment of agriculture, we exclude forestry grant schemes on the grounds that these represent transfer payments. This allows us to inspect the social value of land use conversions but *will differ* from the market value assessments to which private land owners will respond.

Profits are finally calculated as the difference between revenues and costs. However, given the delays between revenues and costs, profits are calculated in Net Present Value (NPV) terms, using a constant social discount rate of 3.5%, and are reported in Table 2.2 with annuity equivalents for each species and YC.

Table 2.2: NPV and annuity values for Sitka Spruce (SS) and Penduncculate Oak (POK).

Species	Yield Class	Net Present Value	Annuity
SS	6	-2262	-84
SS	8	-1865	-71
SS	10	-1336	-51
SS	12	-813	-31
SS	14	-243	-10
SS	16	299	12
SS	18	884	35
SS	20	1278	53
POK	2	-6485	-221
POK	4	-6340	-218
POK	6	-6159	-209
POK	8	-5750	-196

Comparison of current expected profitability of Sitka Spruce and Penduncculate Oak under thinning and felling management regime and a constant social discount rate of 3.5%.

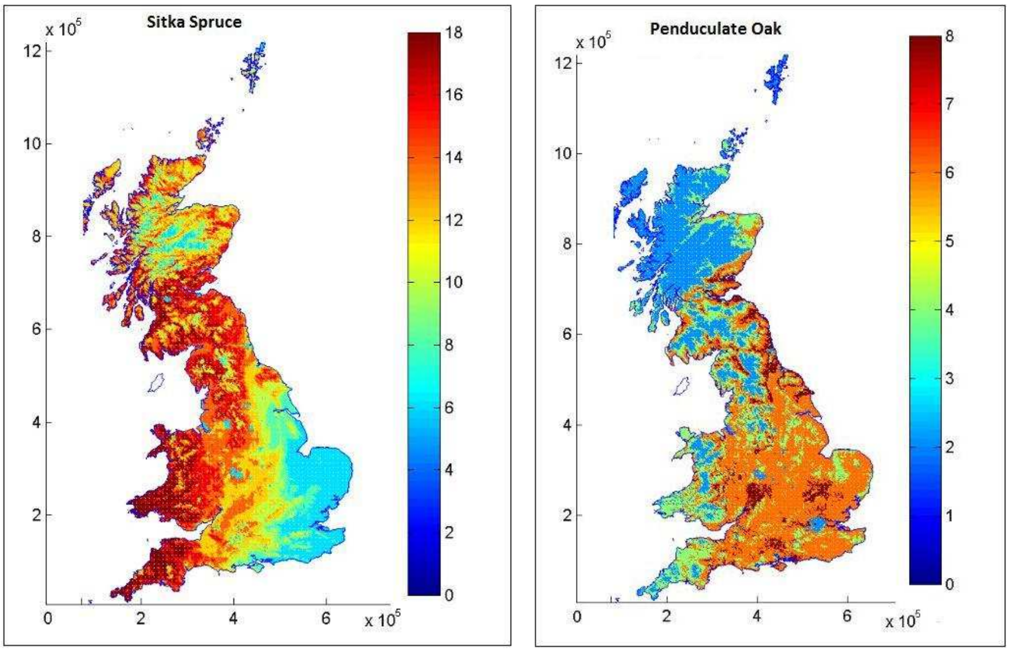
With the exception of the higher YC SS forests the findings in Table 2.2 show that in a number of cases the financial returns are negative. This is the case even under social (as opposed to higher market) discount rates, and with the exclusion of other externalities, such as recreation, and carbon sequestration. Such poor financial performance explains the low prevalence of commercial woodland across the majority of Great Britain.

1.4.3. Results

Figure 2.4 presents projected estimates of the distribution of the baseline tree population by YC score for SS (in the left panel) and for POK in the right one, under current climatic conditions. Reviewing these maps we see that the more suitable regions for growing SS are generally in the west of GB, the north Pennines and in central Scotland. In the right panel we see that suitable regions for POK lie to the north of London, in the Wye Valley and along the Northumbrian coastline (north-east England).

The figure illustrates the current forest baseline in the left panel and the projected current climatic conditions and profits.

Figure 2.4: Timber volumes over multiple rotations based on average yield class (YC) values: Sitka Spruce (YC 14) and Penduncculate Oak (YC 4).



Maps of expected forest growth for Sitka Spruce and Penduculate Oak under current climatic conditions.

1.5. Impact of climate change on forestry growth

Historically, forests have been fairly resilient to the effects of short run variation weather patterns. However, evidence of climate change shows that winters are getting wetter, which contributes to soil erosion, and windier which affects the altitude at which some species can thrive, and summers drier impacting on growth rates (Broadmeadow and Nisbet, 2012; Broadmeadow, 2002; Broadmeadow and Ray, 2005). There is also a spatial element associated with erratic weather patterns, such that we cannot model the effects using non-spatially specific variables

1.5.1. Data

From a practical point of view, the ESC database provides expected YC values under climate change scenarios. However, direct outputs from ESC cannot be used for some aspects of our modelling. For this reason we derive estimates of YC (ESC_SEER, 2012) and combine these with local and climatic factors taken from the following datasets CLIMATE (2012), SOIL (2012), and TERRAIN (2012).

A new model was developed to determine the impact of climate change on forest growth. Results were generated from a cross-sectional analysis of the co-dependencies of variables taken from the datasets mentioned. Hence factors drawn from the dataset have been selected to be as similar as possible to the input variables used in ESC. The key variables in the model are:

- Mean temperature and precipitation during the growing season over the period 1961 to 1990. These are the key variables to be modified in analysing the effect of future climate change.
- Average slope and elevation of the cell, which are further determinants of the YC
- Easting and Northing. These variables are ancillary to the description of the YC changes but we expect that they will capture spatial correlation in other explanatory factors not explicitly mentioned here.
- Soil characteristics defined in (SOIL, 2012), are set out as a series of binary variables:
    - **Water regime**, this variable measures the dominant annual soil water regime which is determined by the number of months at a particular water-table level. The variable takes value 1 if the soil is defined as not wet (e.g. water-table is not wet within 80cm for 3 or more months per annum); 0 otherwise.
    - **pH**: if higher than 5.5 this is considered by FC to be a rich or very rich soil type (Pyatt et al., 2001, p.14). This variable takes value 1 if pH > 5.5; 0 otherwise.
    - **Water capacity**, this variable refers to water storage capacity expressed as millimetres per meter (mm/m). It takes value 1 if water in soil > 75mm; 0 otherwise.
    - **Carbon in soil**, this variable describes the soil health; healthy soil is where the percentage of organic carbon in top and sub-soil is within a range: > 1.2% and < 25%, where it takes the value 1 in our model; 0 otherwise.

1.5.2. Methodology

The relationship between YC and local characteristics can be represented by very complex non-linear functions. Therefore using a simple linear regression model or other parametric specifications for the YC will almost certainly result in biased outcomes due to uniformed assumptions made by researchers. It is for this reason that we rely on semi-parametric regression models which enable the distribution of explanatory variables to be kept flexible, changing in accordance with the data. The SS and POK are separately modelled and both are analysed using the generalized additive model approach developed by (Wood, 2003). This approach compares favourably with previously tried semi-parametric approaches as it allows estimates of the degree of non-linearity directly from the data without any need for further assumptions. The initial model is set to explore non-linearities in all continuous variables as a smooth function: s(.). Note that smooth functions cannot be applied to non-continuous variables, such as dummy variables, which need to be included in a parametric form. Informed by the results of the model, the subsequent semi-parametric model includes the climatic variables as step functions and keeps all the other variables as non-linear. To preserve the complex, non-linear effect of climatic variables on YC, the set of step functions used to capture the effect of temperature and rainfall are given generically by:

Equation 2.1:

$$Temp_1 = \begin{cases} 0 & \text{if Temperature} \leq K \\ (\text{SEER}_{MT_{6190}} - \text{K}) & \text{if Temperature} > K \end{cases}$$

$$Temp_2 = \text{SEER}_{MT_{6190}}$$

$$Rain_1 = \begin{cases} 0 & \text{if Rain} \leq J \\ (\text{SEER}_{MP_{6190}} - \text{J}) & \text{if Rain} > J \end{cases}$$

$$Rain_2 = \text{SEER}_{MP_{6190}}$$

The values for the thresholds *K* and *J* are chosen following the results of the smooth functions for temperature and rainfall estimated by the model with all continuous variables as non-linear functions. The temperature threshold (K) differs for each and is set to 12°C for SS and 9°C for POK. For rainfall the threshold (J) is set to 400mm for both species. This threshold refers only to the average rainfall quantity in the growing season.

The generic model, used to estimate values for SS and POK, is given in Equation 2.2 and is estimated separately for SS and POK and the results are given in Table 2.3.

Equation 2.2

$$YC = \alpha + \beta_1 Wr + \beta_2 pH + \beta_3 Wc + \beta_4 Carbon + \beta_5 s(slope) + \beta_6 s(elevation) \\ + \beta_7 s(easting, northing) + \beta_8 Temp_1 + \beta_9 Temp_2 + \beta_{10} Rain_1 + \beta_{11} Rain_2 + \\ \beta_{12} Temp_1 Rain_1 + \beta_{13} Temp_1 Rain_2 + \beta_{14} Temp_2 Rain_1 + \beta_{15} Temp_2 Rain_2 + \varepsilon$$

where ε is the normally distributed error term; dummy variables: *Wr* is the water regime, *pH* is the soil-pH level, *Wc* is water capacity, and *carbon* is carbon in soil; variables in the smooth functions, s(.) are: *slope*, *elevation*, and *Easting* and *Northing*; and variables in the parametric step functions are: *average temperature* and *precipitation*. Equation 2.2 introduces climatic factors as linear terms which enable the integration in NEVO to be performed faster.

1.5.3. Results

Table 2.3: Predicted timber yield class (YC) for Sitka Spruce and Penduncular Oak as a function of cell characteristics for all 2km GB grid cells

Parameter	Description	SS	POK
		Flexible functions	
		edf(std.err)	***Edf(st.err)***
S(Easting, Northing)	Ancillary variable (captures non-focal local variation)	28.80(29.00)***	28.91(29.0)***
S(slope)	Average slope of the cell	8.40(8.90)***	8.38(8.90)***
S(elevation)	Average elevation	8.88(9.00)***	8.44(8.91)***
		Fixed factors	
		Coeff (st.err)	***Coeff (st.err)***
Water regime (Dummy variable)	Annual dominant soil water regime. 1= if water-table is not wet i.e. is within 80cm for 3 or more months; 0=otherwise	0.0589(0.0108)***	0.1237(0.0061)***
Water capacity (Dummy variable)	Water storage capacity expressed as millimetres per meter (mm/m). 1= water in soil > 75mm/m 0=otherwise	-0.0284(0.0131)*	0.0610(0.0076)***
pH (Dummy variable)	Soil Health. 1= Non-acid soils (pH>5.5); 0= otherwise	0.0306(0.0160)	0.2837(0.0089)***
Carbon	Carbon in soil (% of organic carbon in top soil). 1= if between 1.2% & 25%; 0=otherwise	-0.088(0.0114)***	-0.0291(0.0070)***
Temp1	Temperature threshold : >K K=12°C for SS. K=9 °C for POK	4.669(0.293)***	0.6330(0.0630)***
Temp2	Temperature (°C)	-4.935(0.007)***	0.1836(0.0186)***
Rain1	Rainfall threshold: > J J=400mm for SS and POK	0.1358(0.0065)***	-0.0542(0.0038)***
Rain2	Rainfall (mm)	-0.137(0.0065)***	-0.1370(0.0065)***
Temp1Rain1	(Temperature threshold: > K) *(Rainfall threshold >J)	0.0194(0.0009)***	-0.0039(0.0005)***

The results presented in Table 2.3 are given in two stages: in the first stage we report the "*effective degree of freedom -edf*" of the smooth functions which explain the estimated level of non-linearity for the slope, elevation and easting and northing variables; in the second we report the coefficients of linear parameters such as dummies variables; and rainfall and temperature expressed as a step-function.

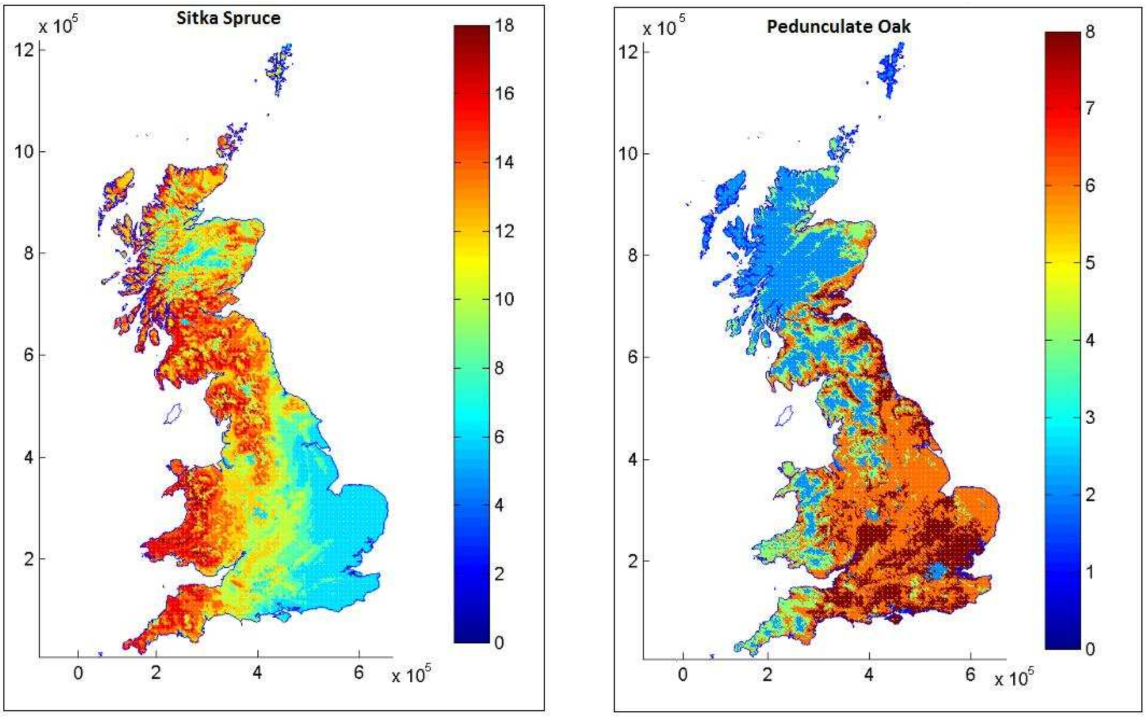
All the variables modelled as smooth function are highly non-linear, in fact the higher the *edf*, the more "non-linear" the estimate: s(.). For example, an *edf* equal to one means that the best approximation for that variable is linear. In our data, all variables are better represented by a non-linear function. The parametric variables are all highly significant and with the expected sign. The impact of pH and water regime dummies is positive on YC for both species, indicating that yield increases in response to increases in these factors. Whereas, water capacity is negative for SS and positive for POK, indicating that a rise in water capacity leads to a fall in the yield for SS, but a rise in it for POK. This finding is consistent with other work such as (S. Broadmeadow & Nisbet, 2012). The temperature effect is positive under the threshold and negative above for SS, however, the opposite is true for the YC for POK, which is always positive, but the effect found above the threshold (9^oC) is one third of that below it. The interaction between rainfall and temperature is always positive when both variables are below or above the threshold for SS. This implies that SS benefits either when temperature is below 12^oC and rainfall below 400mm or temperature is above 12^oC and rainfall above 400mm. However, dry weather with increased temperature has a negative impact on SS forest growth. POK presents opposite climatic effects: when both rainfall and temperature variables are below or above the threshold level YC for POK, here this is expected to decline, whereas, POK will benefit from dry weather and increased temperature and vice versa. These results are consistent with expectations of YC values for SS and POK and are illustrated in Figure 2.4**,** where we see that POK performs better in the south-east of England with dry warmer weather and SS is more suitable for colder and wetter climates found in the north-west of England.

The results for SS and POK are both highly satisfactory with R-square above 85% (see Table 2.3). The SS model explains 92% of YC variation and the average Mean Square Error (MSE) is 1.01 (median 0.3) which implies that the predicted YC (rounded to the nearest even number) is generally very well-determined. The POK model explains approximately 89% of YC variation with a mean MSE of 0.31 (median 0.11).

1.6. Conclusion

The results we present are also consistent with FC findings FC (2002) revealing that temperature and precipitation are important factors for tree growth. Changes in tree volume are expected to occur under different climate change scenarios. However, climatic factors are not constant across space, and local factors can smooth these impacts. We expect that productivity of SS will increase in the south-west of Scotland and in north Wales mainly as a result of warmer temperatures, and is likely to decrease in the south-east of England mainly due to reduced summer rainfall and longer periods of drought. POK productivity is also expected to increase in all areas of GB with the exception of the west of England which as we have explained, will not be suitable for commercial broadleaf tree production.

Figure 2.5: The estimated forests suitability for Sitka Spruce and Penduncculate Oak under the future climatic conditions from our semi-parametric model coefficients.



Maps report the estimated forest growth for Sitka Spruce and Penduncculate Oak under 2060 climate conditions. Changes predicted are significant for both species.

Converting our semi-parametric coefficients into spatial data points we are able to map the outcome as shown in Figure 2.5. These maps illustrate the predicted planting pattern that results for SS in the left panel and POK in the right one. Both species will face significant changes guided by a combination of warmer and drier seasons with significant spatial variation. The effects depicted will be relevant for policy makers considering commercial afforestation or management of existing forest stands, as well a guide for single farmer production choices.

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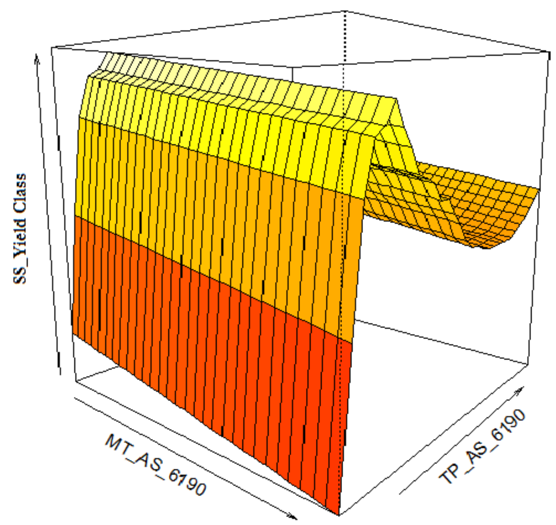
1.8. Appendix A: Interaction effects and expected non-linearity between climate variables and timber productivity

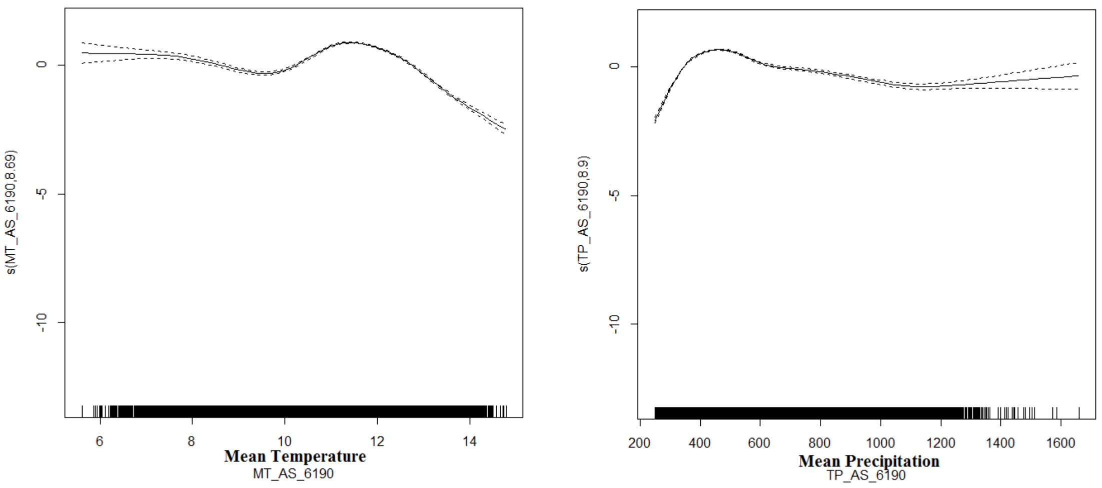
The semi-parametric model with all continuous variables as smooth functions (s(.)) describes significant interaction effects between mean temperature and precipitation for both Sitka Spruce (Figure 2.6) and Pedunculate Oak (Figure 2.8). Further the relationship between climatic variables and Yield class is non-linear and single smooth functions depict the expected non-linearity (Figures 2.7 and 2.9). Building on this evidence from several semi-parametric models we define the model and step-functions reported in earlier in this chapter**.**

Figure 2.6: Sitka Spruce: smooth function for both temperature and precipitation variables



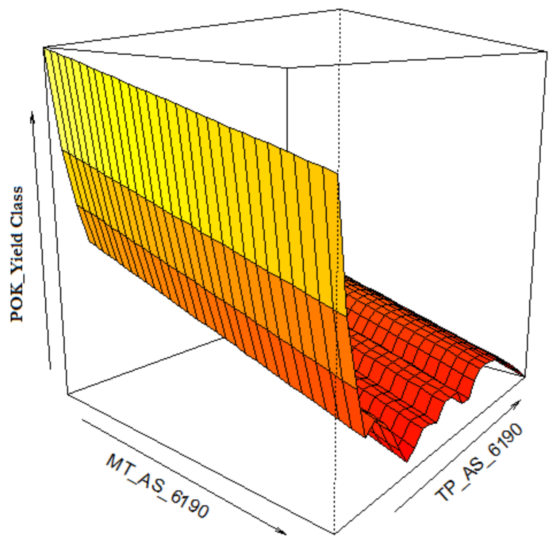
Shows the interaction effect of temperature and precipitation on SS productivity

Figure 2.7: Sitka Spruce: single smooth function for temperature and precipitation



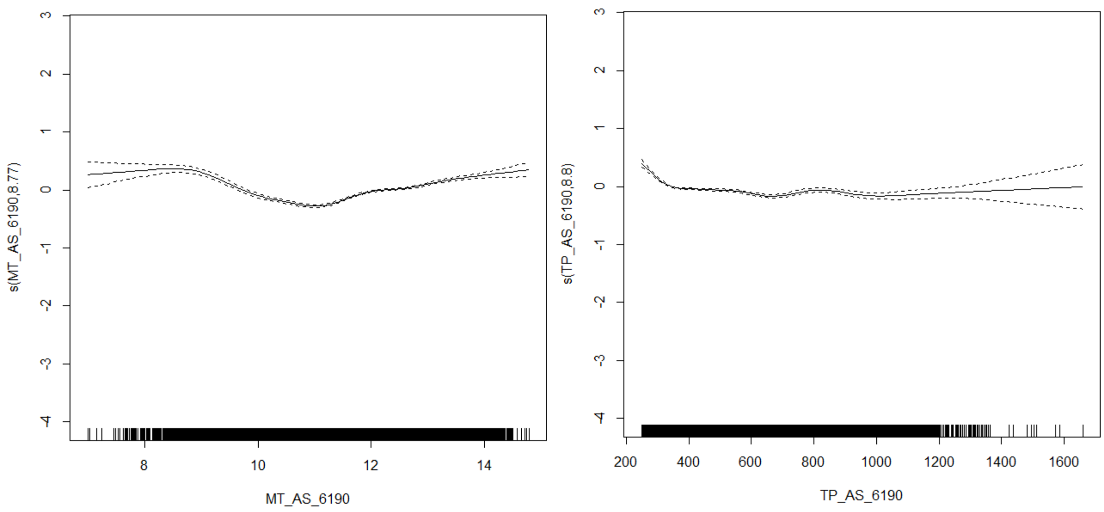
Shows the non-linear function for temperature and precipitation. Both graphs have been used for the definition of the step-functions in the model of forest growth (yield classes - Equation 2.2)

Figure 2.8: Pendunculate Oak: smooth function for temperature and precipitation variables



Shows the interaction effect of temperature and precipitation on POK productivity.

Figure 2.9: Penduculate Oak: single smooth function for temperature and precipitation



Shows the non-linear function for temperature and precipitation. Both graphs have been used for the definition of the step-functions in Forestry section (Equation 2.2).