Programme Area: Bioenergy

Project: Biomass Value Chain Modelling

Title: Report on Tools and Data

Abstract:

This deliverable describes the models used to generate the yield, cost and greenhouse gas emissions of the bioresources included in the scope of Biomass Value Chain Model project. For each bioresource, the description covers a review of models and data, and an explanation of the proposed modelling approaches.

Context:

The development of the BVCM model has been ongoing since the project first started in 2011. The documents published here relate to the intial phases of model development. They do not included later developments and are therefore not representative of the current BVCM model, or in some cases, its findings. For a more recent overview of BVCM and the findings derived from it, readers are encouraged to look at the insights and reports published by the ETI, here: http://www.eti.co.uk/insights and here: http://www.eti.co.uk/library/overview-of-the-etis-bioenergy-value-chain-model-bvcm-capabilities

BVCM is now managed by the Energy Systems Catapult (ESC). Any questions about the ESC should be directed to them at: info@es.catapult.org.uk

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Report on tools and data

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The BVCM Consortium

For the Energy Technologies Institute
12 August 2011

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	V2.0	Reviewed by all WP1 partners Formal submission to the ETI
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Executive Summary

The main objective of this report is to describe the models that will be used to generate the yield, cost and greenhouse gases (GHG) emissions of the bioresources included in the scope of the Biomass Value Chain Model project: winter wheat, sugar beet, oilseed rape, Miscanthus, short rotation coppice (SRC) willow, and forestry. For each bioresource, this description covers a review of existing models and data, an explanation of the proposed respective modelling approaches, with comments on the model functionality, and on the spatially resolved datasets that will drive the proposed models.

Yields

First generation energy crops (winter wheat, sugar beet, oil seed rape) are traditionally arable crops within the standard rotation, for which much more is known with regard to their eco-physiology and management than for second generation energy crops (Miscanthus, SRC-willow). Therefore, process-based models are well established to understand their productivity and impacts. The principles of process-based models are outlined, and how the output from scenario simulations can be used to spatialize the output to create maps of regional resource distribution. It is concluded that future yields can be estimated using empirical (meta-) models, which were derived from outputs of process-based models and which are linked to new climatic data and respective empirical correction factors to account for yield gap, technological progress and Carbon Fertilisation Effect (CFE).

Second generation crops are less well-studied than first generation crops. For Miscanthus, it is thought that empirical, physically-based models can be used to estimate future yields by applying average changes to the climatic input variables and the above mentioned empirical correction factors, with the exception of no CFE.. For SRC willow, the process-based model will be applied to climate change scenarios. In general, far fewer datasets are available to validate any modelling approaches in second generation crops, and so the errors of these yield predictions are likely to be larger than those associated with predictions for arable crops.

Forestry systems have been studied for many years and yield models for stem volume production have been available since the 1950s. More recently developed biomass models can be combined with the most recent forest yield models to estimate potential production of wood resources in the form of stemwood, root and branchwood available from both high forest and short rotation forest (SRF) systems. Much of the functionality needed to provide large scale predictions of potential production from forests has already been developed as an integral part of forest carbon accounting models. Process models for predicting growth rates of a wide range of tree species at the landscape scale are still at an early stage of development and are not suitable for application within this project. Instead a site classification model can be used as a framework for providing forest biomass yield with suitable growth parameters. There is a possibility that simple empirical relationships could be established for estimating yields of forest resources on a spatial basis, provided that the primary interest is in long-term, time-averaged levels of production. However actual production for forestry systems is in fact highly discontinuous and time-dependent. If these fluctuations in biomass production need to be represented, it is unlikely this can be characterised as a simple, continuous model; instead, discontinuous 'spot' scenarios will need to be selected and implemented as tables of spatially-referenced 'lookup values'.

Costs

A methodology is proposed to estimate the regional cost of first and second generation biomass and forest based wood resources within the UK. It will provide annualised regional production cost estimates, as well as the opportunity cost and impact on land of producing bioenergy resources vis-à-vis traditional agricultural crops and forestry. These cost calculations will be based on published secondary data sources using from a combination of farm survey data of actual revenue and costs, and crop and bioenergy specific profitability data published by the industry and various academic and research institutions.

GHG emissions

A methodology to estimate the GHG emissions associated with the production of the bioresources is also proposed. Compared to other existing GHG models developed to assess the supply of bioenergy in the UK, the proposed GHG emissions model features the added functionality of being spatially explicit with regard to the fertiliser requirements, and hence the fertiliser emissions (which are typically the largest source of direct emissions) for first generation resources.

Datasets

Different environmental datasets are required to model the yield and costs of the first generation, second generation biomass and forest based wood resources as well as GHG emission of some bioresource production. They have been identified, e.g. Harmonized World Soil Database HWSD and NATMAP soil data, UKCP09 and UKCIP02 climate scenario data will be used in yield modelling. The characteristics of datasets are different, therefore a rigorous harmonisation method has been proposed.

In this project, all the yield, cost and GHG emission models will be built with spatially explicit features suited to the development of UK wide biomass value chain optimisation modelling.

1 Introduction

The key objective of WP1 is to develop a series of accessible tools that combine spatial data, analysis and statistics, with biomass yield and cost models, up to 2050. Considerable work has already been carried out in the UK around biomass resource mapping, and the consortium members have been leading activities in the UK in this area for conventional arable (first generation) and novel, dedicated (second generation) energy crops as well as forest resources. Therefore, the work in WP1 builds on existing biomass resources data and models.

1.1 Objectives and scopes

The objective of this WP is to provide a spatially resolved database, which compiles land resources (soil, potential land cover/use) and climate data. Simple, physically-based models will provide biomass and yield production per unit area, and economic and environmental models will describe resources costs and Greenhouse Gas (GHG) emissions, respectively.

The main outputs this WP will deliver are:

- GIS database with potential yields of energy crop and forestry systems as well as costs and GHG emission
- Scenarios of constrained (availability of space, or resource) potentials up to 2050
- Spatial biomass resource, yield and cost data aggregated or disaggregated at scale suitable for value chain optimization

This Biomass Value Chain Model Report on Tools and Data summarises the models used to generate the yield, cost, GHG emissions of certain biomass resources and wood based forests; describes the functionality and flexibility of models as well as identify the input and output data. Required datasets and the harmonisation methods are also described.

1.2 Success criteria

This report has been prepared following the success criteria for WP1 as set in the Technology contract (as specified in RFP):

- Review of existing tools and data which allow a spatially resolved quantitative estimate for current and future yields of various arable and perennial crops
- The report will give definitions of the respective meta-models as a functional multiple regression model and discuss its transferability to other time horizons
- A clear summary of the additional functionality being provided in this tool over and above existing tools will be provided.
- A clear explanation of any data aggregation methods used is provided

1.3 Structure of the report

This report is structured into four main sections and several chapters. In Section A, resources model and yield calculation of first generation, second generation biomass crops as well as forest based wood resources are discussed. In Section B, the methods of production and opportunity cost of the above biomass resources are explained. Section C describes the methodology of GHG emissions calculation. Finally, in Section D, different datasets, their characteristics as well as the data harmonisation methods are discussed.

Section A: Resource Models and Yield Calculation

2 First Generation Bioenergy Crops

2.1 Introduction

First generation energy crops are traditionally arable crops within the standard rotation, for which much more is known with regard to their eco-physiology and management than for second generation energy crops. Therefore, numerous detailed process-based models are already developed to understand growth and improve management of wheat (Ritchie and Otter, 1985; Jamieson et al., 1998; Richter et al., 2010), sugar beet (Werker et al., 1998; Richter et al., 2001) and oilseed rape (Gabrielle et al., 1998).

Many applications to regional productivity and climate impact assessments are available. For the UK, the effect of regional climate scenarios on yields of winter wheat (WW) (Richter and Semenov, 2005) was estimated using the process-based growth model, *Sirius* (Jamieson et al., 1998). These simulations showed a significant relationship to soil available water capacity (AWC), a result that could be used to generate maps by incorporating the dominant soil type. Identified management effects, including the selection and parameterisation of new varieties, defined the cause of yield progression. For sugar beet (SBt) a similar approach had been taken to assess the drought risk under UK climate scenarios (Richter et al., 2006a). Similar simulation scenarios can be implemented for oilseed rape to estimate its regional productivity; however, this model is less widely validated, and therefore, the process-model will be evaluated using newly available detailed data (Berry and Spink, 2009).

For all above three first generation bioenergy crops, the simulated outputs are attainable biomass and crop yields based on optimal plant population which are not limited by any crop nutrients and grown free from diseases, pests and weeds. Attainable crop productivity (under experimental conditions) is the highest level of yield that can be achieved given the prevailing conditions defined by variety, soil characteristics, sowing and harvest dates and the weather between these two dates. In contrast, the (on-farm) harvestable yield is the attainable yield limited by sub-optimal conditions such as sub-optimal management, poor crop establishment and growth, e.g. in headlands, harvest losses, losses due to diseases, weeds and pests. Such yield-limiting factors often can be modified through cultural practices to narrow the gap between harvestable and attainable yields. This yield gap (fraction of attainable yield) is well documented in the literature (van Ittersum et al, 2003, Lobell et al., 2009; Jaggard et al., 2010) and will be covered within the scenarios.

In the following, we will outline (a) the principles of process-based models, which were calibrated using experimental data to predict attainable yield and (b) how the output from these models can be used to derive meta-models, which allow creating maps of regional resource distribution (see Figure 2-1).

The goodness of fit for the meta-model, which is the relationship between the biomass/crop yield and the chosen environmental variables, is measured by the variance accounted for and the residual mean square error. The validity of the meta-models is also tested with independent datasets from the outputs of simulations models at different sites and future scenarios and compared to observations in variety trials.

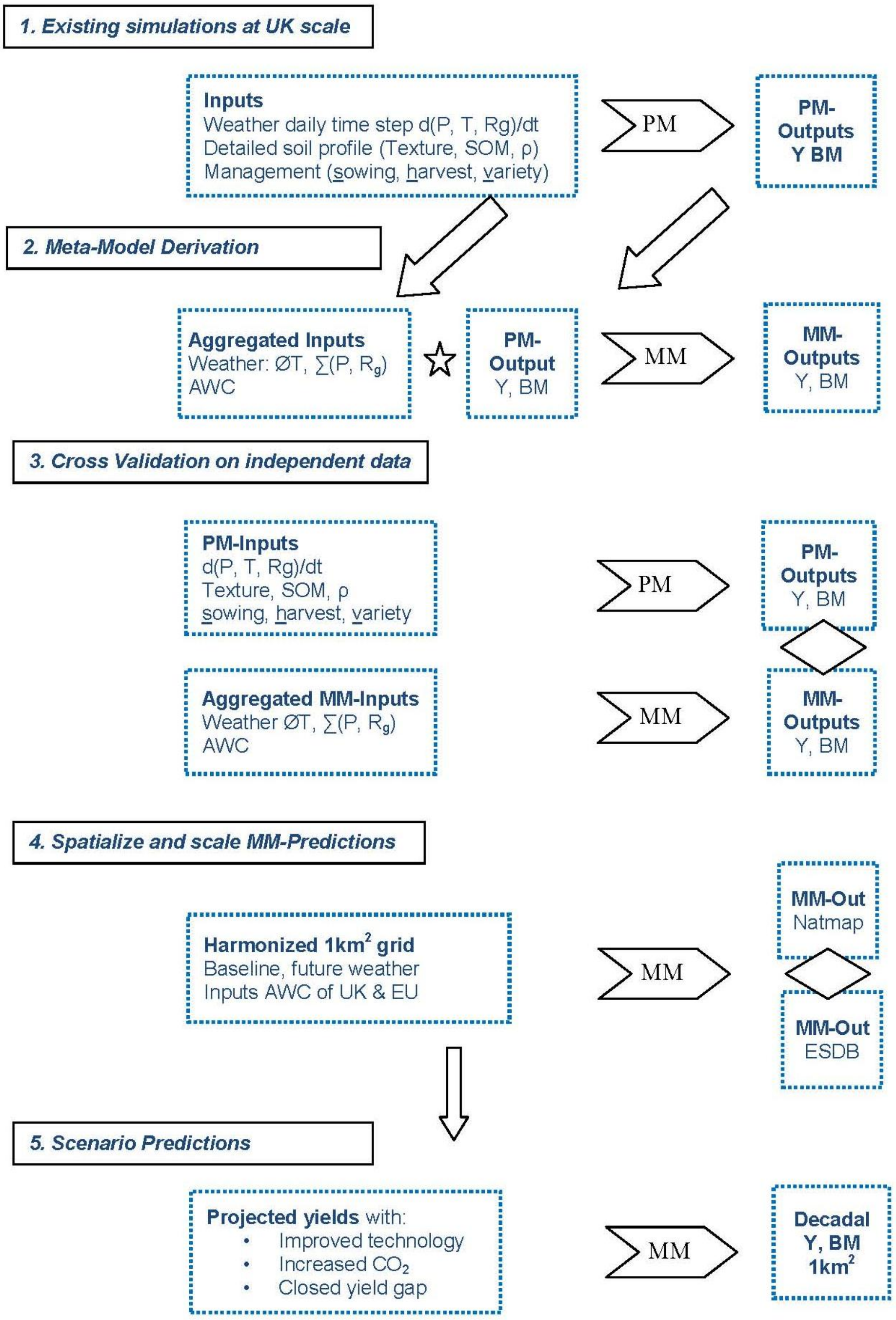

Figure 2-1 Inputs and outputs for process model (PM) and meta-model (MM) with regard to MM derivation, cross-validation and scaling to enable scenario applications using different geographic resources for weather and soil inputs (Natmap vs European Soil Data Base (ESDB) as well as technology variables

2.2 Wheat

2.2.1 Description of existing model/meta-model

Sirius is a wheat simulation model that was originally developed by Jamieson et al. (1998) using experimental data collected in a wide range of different environments. The model simulates the effect of variations in water and N supply on leaf area, biomass accumulation, grain growth, grain yield and N uptake and distribution. Simulations done by Richter and Semenov (2005) assumed adequate N-supply. As said above, it doesn't account for damage by diseases or pests, inadequate plant population or competition with weeds. The model has been used by farmers (Armour et al., 2002) and policy-makers to assess potential consequences of climate change in the UK (Semenov et al., 1996; Richter and Semenov, 2005). Phenological development is calculated from the main stem leaf appearance rate in thermal time and final leaf number, the latter being determined by responses to photoperiod and vernalisation. Sirius 2003 incorporates an improved description of leaf canopy (Lawless et al., 2005), and calculates daily above-ground biomass from intercepted photosynthetically active radiation (PAR) and radiation use efficiency (RUE). PAR interception is dictated by Leaf Area Index (LAI) according to Beer's Law, properties of the leaf canopy being integrated by an extinction coefficient. LAI is developed for a series of leaf layers determined by leaf appearance and nitrogen (N) sub-models but N-limitations are not included in this study data base. Effects of water deficits are calculated through their influences on LAI development and radiation-use efficiency (RUE). The model treats the crop as spatially amorphous; it does not describe individual plants or shoots. Grain growth and yield are calculated according to rules for internal partitioning and translocation of assimilates.

This model was used to simulate the response of winter wheat to different weather scenarios: Baseline (1961-1990); low, B2 and high, A2 emission scenarios for different time horizons (2020s, 2050s and 2080s). 50 years of daily weather were generated with LARS-WG based on the baseline weather from the thirty year period for each time slice (Semenov, 2007).

2.2.2 Description of the applied methodology

Robust and significant relationships were found between average baseline and future yields and classes of soil available water capacity (AWC) which depends largely on soil texture (Richter and Semenov, 2005). A simple empirical model, using soil AWC and meteorological data as independent variables is postulated to explain the regionally observed variation, similar to that for Miscanthus (Richter et al., 2008).

We therefore, propose to derive an empirical meta-model from the simulated annual outputs (wheat yield or biomass), which we treat as observations, and the related inputs, which we treat as independent variables (see Figure 2-1). To maintain the biophysical relevance, only those input variables will be included in this regression analysis, which have shown impact on the crop development and dry matter production and yield. The derived meta-models will be tested by independent data sets from outputs of the simulation models and/or observations from variety trials if they can be found. In the following we sketch the derivation of such META-MODEL as a proof of principle.

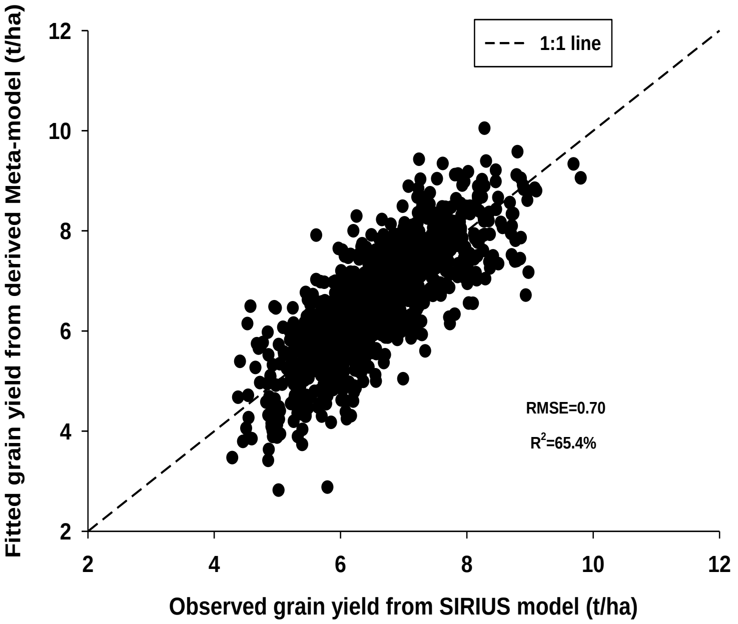

Figure 2-2 Relationship between grain yields estimated using meta-model and simulated grain yields using the process-based model Sirius

In order to derive the most appropriate meta-model for wheat yield and biomass, we defined the soil AWC (mm) within the rooting depth for each soil type series and aggregated various monthly weather variables and their particular combination across various months: The average daily air temperature per month, $T_a()$, sum of monthly precipitation, P(), and sum of global radiation, $R_g()$. The selection was based on correlation coefficients (*r*) between biomass/grain yield and the respective variables (Appendix 9). It is obvious that soil AWC, the precipitation in April, May and June, P(AMJ) and the air temperature in July, $T_a(Jy)$ have the greatest impact on the grain yield. Much to our surprise, solar radiation is much less and negatively related to grain yield.

When we determine the meta model to estimate the grain yield, we found that the presence of quadratic terms for the soil AWC and P(AMJ) significantly improved the variance accounted for and so these terms are included in the fitted meta model. Intuitively, it is likely that water availability beyond a certain level should not improve yield any further. The significance of the quadratic term for soil AWC in combination with the linear term reflects the fact that the rate of yield increase diminishes as the soil AWC increases (Richter et al. 2002). As with any empirical regression model, one needs being cautious of extrapolating beyond the data range from which the models were derived. The significance of the additional quadratic term for P(AMJ) may also indicate the diminishing yield increase as P(AMP) increases, reflecting the negative water-logging effects under extreme wet conditions. No further variable selection in addition to total radiation in April, May and June improved the variance accounted for:

$$Y_G = 6.6 + 2.3\times10^{-2}\times AWC - 3.3\times10^{-5}\times AWC^2 + 2.13\times10^{-2}\times P(AMJ) - 2.93\times10^{-5}\times P(AMJ)^2 - 0.25\times T_a(Jy) - 1.08\times10^{-3}\times R_g(AMJ)$$

A similar model will be derive for the biomass yield of winter wheat, $Y_{B(WW)}$, from which the straw yield, Y_S, can be calculated.

It is apparent that Nitrogen (N) is not included as an independent variable in the meta-model to account for the significant effects of varied N application rates on the grain yield of winter wheat. Soil pH values are not considered here, either. This is because that firstly the simulated outputs are based on crops grown on adapted soils and under optimal levels of nutrient inputs which include N. For the future yield estimates, we also assume that crop nutrition should not be a limiting factor.

Such an approach deriving an imperfect (statistical) from a perfect model treating simulated yields as “observed” dependent variables (see Figure 2-2) has recently been discussed with regard to maize yields (Lobell and Burke, 2010). They used much less disaggregated weather variables and did not account for soil AWC, effects which they accounted for in a site-specific empirical constant.

2.2.3 Functionality

The future Crop productivity (both in biomass and in crop yield) will be mainly affected by advancement in technology, part of which is closing the yield gap, increased CO_2 concentration in the atmosphere and climate change in the future. For the extrapolation into the different future time spans we follow the approach outlined by Ewert et al. (2005) for which details are given in section 2.3.3.

The derived equation can be used with aggregated data for any future climate scenario, provided that the yield response to CO_2 concentration (Carbon Fertilisation Effect, CFE) is known. The effects of CO_2 will be accounted by focusing on a single and positive effect on crop growth and yield. We are not going to allow for any other negative biotic effects from diseases, pests and weeds, related to climate change. We assume that chemical controls will be available and adapt to changes to cope with these negative effects. In the wheat model *Sirius*, it is assumed that doubling of the atmospheric CO_2 concentration causes yield to increase by 30% (Amthor, 2001). This corresponds to a yield increase of 0.08% per ppm CO_2 (Ewert et al., 2005).

This is in the range of experimental results and other models, like CERES, but larger than empirical field data in free air CO_2 enrichment studies (Long et al., 2005) which may include also other effects. The average response of simulated yield of arable crops is in a similar range (Figure 2-3) which corresponds to a CFE 7 kg/ha/ppm, which is very similar to the value given by Ewert et al. (2005).

The relationships shown in Figure 2-3 shows the overall effects of increased atmospheric CO_2 concentration on yields also taking into account the changes in temperature and rainfall in the future, so it implicitly accounts for changes in temperature and rainfall caused by rising CO_2 concentrations.

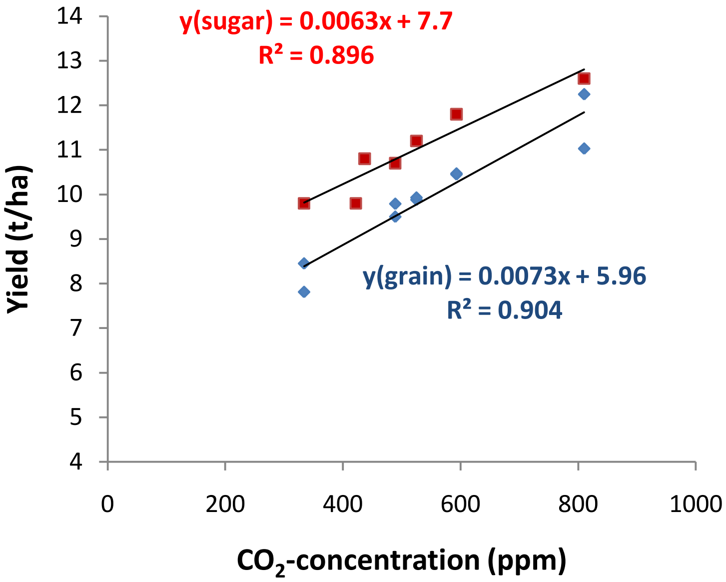

Figure 2-3 Mean yield response to increasing [CO_2] derived from simulation for crops grown under low water stress in England and Wales (Richter et al., 2004)

There will be a need to implement a factor to account for the technological yield progress, which comes from breeding, crop and pest/disease management and harvest technology. The long-standing research (Jaggard et al., 2007; 2010), and monitoring of regional yields national statistics, and other resources (Ewert et al., 2005) will enable the consortium to derive and implement well-founded technology and yield progress scenarios.

According to Ewert et al. (2005) technology effects alone were estimated to increase wheat yields within the next 80 years to between 7 and 13 t ha^{-1} depending on the scenario. Relative annual yield change is likely to decline from about 1.75% in 2000 to 1.13, 0.9 and 0.68% in 2020, 2050 and 2080, respectively, in the A1FI scenario. Their reference provides a good compilation of the relative contribution towards yield change from climate, [CO_2] and technology under different emission scenarios tabulated for wheat but also discussed for other crops across Europe.

2.2.4 Input data requirements

Input requirements need distinguishing between those to run the process-based model for the scenario analysis and those to estimate regional decadal yield estimates for the future to produce yield maps. Process-models are run on a daily time step and daily input data were generated using a weather generator (Semenov, 2007). Yield maps are generated from meta-models using weather variables aggregated over monthly time spans, which are summed or averaged over critical growth phases.

Weather and soil data:

Generated weather items included minimum and maximum air temperature (Tmin, Tmax; °C), precipitation (P; mm) and global radiation (R_g; MJ m^{-2}). Originally, representative weather stations for each region were chosen to represent a wide range of the geographic areas and weather. For each chosen region, different major soil series were selected to represent a range of soil AWC. For example, the Meta-Model was developed across five different locations with long-term average climate ranging from wet/dry-warm to wet/dry-cold (see Richter et al., 2004). In each of these locations, at least three different soils were included for the simulation. In total, there were 14 different soil series included, for which the AWC ranged from 98 to 313 mm of plant available water in the root zone.

For future regionalisation monthly aggregated weather data will be used as outlined and defined above. These will be provided from the different climate scenarios extracted from UKCP09.

2.2.5 Model output

The analysis will define meta-models for biomass, Y_B, and grain yield, Y_G, expressed as t ha^{-1}, for which different empirical parameters (coefficients) are given for the effects of potential water availability in the soil and climatic variables. The model will also provide an uncertainty measure for each time slice. Strictly, these values are valid for the mid-point of the scenario time slice, and decadal average yields will be estimated using a simple linear interpolation technique. The models will also allow estimating technological and [CO_2] effects on yields when combined with weather variables derived from future climate scenarios.

Here, as an example for all arable crops, the effects of scale and temporal variability will be considered with regard to uncertainty of the yield estimate of winter wheat. First, the HWSD and local soil survey data (NATMAP) for England and Wales have a different resolution and it is, therefore, important to check whether and how much the input variables agree or differ at each grid point and how this affects the biomass and yield estimates. Second, the climate scenarios are strictly probabilistic, and it is therefore necessary to represent average yields with respective variability and uncertainty. The respective runs using process-based model generate 10 year variability which would be therefore a natural by-product.

2.3 Sugar beet

Biomass dry matter and sugar yield of sugar beet is affected by various abiotic and biotic factors (Werker and Jaggard, 1998; Jaggard and Werker, 1999). The model simulations, however, assume that crops are grown with sufficient planting density, have adequate nutrition and are free from diseases, pests, and weeds. The most important difference between Sirius wheat and Broom's Barn sugar beet growth model is that the range of variety characteristics is much smaller for sugar beet than for wheat so that genetic coefficients are not required as input variables. These would be represented in the coefficients for the projected technical progress.

2.3.1 Description of existing model/meta-model

The Broom's Barn sugar beet model is a process-based growth simulation model. It has gone through several refinements (Jaggard and Werker 1999, Richter et al., 2001, 2006, Qi et al., 2005). In its approach to growth, the Broom's Barn sugar beet model is largely similar to Sirius: it calculates daily values of foliage cover, solar radiation intercepted by the canopy and total dry matter produced, based upon potential RUE, with a proportion of dry matter growth being partitioned to sugar yield. Differences from Sirius are that potential RUE decreases as total dry matter increases and the canopy ages; potential RUE also changes according to the proportion of daily radiation which is diffuse, and potential RUE is reduced by water stress, which is expressed as the ratio of actual over potential crop evapotranspiration. Actual evapotranspiration decreases according to the daily amounts of soil water available within the rooting zone, estimated through a simple soil water balance sub-model for a freely draining soil. Input requirements and parameterization of the Broom's Barn growth model can be found in the references given above.

Sugar yield is strongly influenced by sowing date and harvesting date. The UK 50% crop sowing date has been around the beginning of April in the past. For the scenario analysis the mean sowing date was fixed on 1 April; the harvesting date was fixed on 31 October, by which time most weather variations cease to affect yield. The effects of sowing date and seasonal length were analysed earlier (Richter et al., 2006)

2.3.2 Description of the applied methodology

The method to derive meta-models for sugar beet follows very much the procedure outlined above for winter wheat (Figure 2-1 of Section 2.1). This can be repeated here for the sake of displaying any differences. Two different models were derived, for total biomass yield (Y_b) and sugar yield (Y_s)

As with winter wheat, the section of most influential environmental variables to be included in the meta-model is based on the correlation coefficient (*r*) between biomass/sugar yield and the respective variables (Appendix 10). Apparently, the soil available water capacity within rooting depth, AWC (Richter et al., 2006), the amount of precipitation in June, July and August, P(JJA) and the mean air temperature in April, T_a(A), and May and June, , T_a(MJ), and the total global radiation in September and October, R_g(SO) were the most related variables to the biomass and sugar yield.

We also found that the presence of quadratic terms for the soil AWC and P(JJA) significantly improved the variance accounted for and so these terms should be included in the final meta model. Like winter wheat, the significance of the quadratic term for soil AWC reflects the fact that the rate of increase in yield diminishes as the soil AWC increases (Richter et al. 2004). The significance of the quadratic term for P(JJA) may also indicate the diminishing increases in yield as P(JJA) increases or the negative water-logging effects under extreme wet conditions. As with any empirical regression models, it needs to be cautious when extrapolation is applied beyond the data range from which the models are derived. Addition of any other variables has not further improved the variance accounted for. So, the following fitted meta-model can be used to estimate sugar beet biomass productivity, Y_b (t/ha):

$$Y_b = -5.375+10^{-2}\times 5.62\times \mathrm{AWC}-1.046\times 10^{-5}\times \mathrm{AWC}^2+ 6.167\times 10^{-2}\times \mathrm{P(JJA)}- 1.066\times 10^{-4}\times \mathrm{P(JJA)}^2+0.373\times T_a(\mathrm{A})+0.452\times T_a(\mathrm{MJ})+ 7.159\times 10^{-3}\times R_g(\mathrm{SO})$$

This meta-model accounted for 68.6% of the variations of the simulated total biomass root mean square error (RMSE) = 1.31t/ha. For sugar yield estimation, a very similar meta-model could be fitted, the specifications of variables being the same as in the total biomass estimate. The meta-model accounted for 68.7% of the variations in the simulated sugar yields, Y_s (root mean square error (RMSE) = 0.95t/ha).

2.3.3 Functionality

The derived equations can be used in the GIS environment based on NATMAP or similar soil data (see Section D) that allow estimating the AWC in the root zone. The inputs at the regional scale are defined below.

For the extrapolation into the different future time spans we follow the approach outlined by Ewert et al. (2005). Crop productivity (both in biomass and economic yield) will be mainly affected by advancement in technology, but also increasing CO_2 concentration in the atmosphere [CO_2] and climate change impacts in the future, affected by average temperature and cumulative precipitation in defined periods, t, (T_a(t); P(t)).

$$P_t=P_{t0}*(1+(P_{t,T}/P_{t0}\ -1)+(P_{t,CO2}/P_{t0}\ -1)+(P_{t,CL}/P_{t0}\ -1))$$

where P_{t0} represents the baseline crop productivity, $P_{t,T}$, $P_{t,CO2}$, and $P_{t,CL}$ represent future crop productivity as affected by technology development, increasing CO_2 concentration and climate change, respectively. The respective future relative change in crop productivity is represented by $P_{t,T}/P_{t0}$, $P_{t,CO2}/P_{t0}$ and $P_{t,CL}/P_{t0}$.

The technology effects on the relative change on future crop productivity ($P_{t,T}/P_{t0}$) were estimated based on historic yield trends and the correction for the effects of technology on potential yield and the yield gap. The relative yield change at t_0 was calculated from the fitted linear regression line at the end of the baseline period (1961-1990). So, the total effects of technology development are calculated as below:

$$P_{t,T}/P_{t0}=Y_{r(t0)}\ +\Sigma[(Y_{r,a}*f_{T,Pr(t)}*f_{T,Gr(t)}/f_{T,P(t0)}*f_{T,Gr(t0)})$$

in which Σ means to integrate years from the end of baseline year to the required year in the future. $Y_{rt(0)}$ is the relative yield change at the end of baseline year (i.e. $Y_{(1990)}/Y_{(1989)}$), $Y_{r,a}$ is the annual increment in the relative yield change with reference to the baseline year (t_0). $f_{T,Pr(t)}$ and $f_{T,Gr(t)}$ are the changes in future the potential yield and yield gap (i.e. actual yield as relative fraction of the potential yield) of the relative yield change. $f_{T,P(t0)}$ and $f_{T,Gr(t0)}$ are the baseline changes in potential yield and yield gap over the baseline period

2.3.4 Input data requirements

The data requirements are the same as for the winter wheat process-based model and regression-type meta-model, however, weather data are differently aggregated, as listed above. For the future scenarios estimates, data from the FAO yield statistics (FAO: http://www.fao.org) were taken. The calculated relative yield increase by the end baseline period (1961-1990) in UK was 1.2% for sugar beet, which will be extrapolated. However, the yield gap for sugar beet, $f_{T,Gr(t0)}$, is likely to be changing from 0.75 to 0.85, from the baseline to the 2050 scenario (Jaggard et al., 2010).

2.3.5 Model output

Meta-models for biomass, Y_b, and sugar yield, Y_s, expressed as t ha^{-1}, will be defined for which different empirical parameters (coefficients) are given for the effects of potential water availability in the soil and climatic variables as specified above. The model will also provide an uncertainty measure for each time slice. Decadal average yields will be estimated using a simple linear interpolation technique. The models will also allow estimating technological and [CO_2] effects on yields when combined with weather variables derived from future climate scenarios.

2.4 Oil seed rape

For oil seed rape (OSR), process-based models exist and have been calibrated on a rather small number of experiments (Gabrielle et al., 1998; Richter et al., 2006b). Average national and regional yields (2.5 to 3.5 t/ha) vary very little (Defra, https://statistics.defra.gov.uk/esg/ace/b11_chart.htm) and were, therefore, hardly differentiated in past studies on GHG emission (Hillier et al., 2009). The yield gap is larger than in continental Europe, possibly due to negative effects of weather during grain filling and pre-harvest maturity. In this project, therefore, it will need careful statistical analysis of the numerous experimental data available in-house (RRES), from ADAS and in the Brassica network to project further productivity closure of the yield gap. At optimum N grain yields may vary between 3.2 and 5 t/ha (Berry and Spink, 2009). Long-term analysis is being made available (Berry and Spink, 2006).

2.4.1 Description of existing model/meta-model

The software simulating crop growth and development of OSR is a generic process-based model that was calibrated for a series of different crops under various climatic conditions (Richter et al., 2006b, Ferrara et al., 2010; Richter et al., 2010). This tool belongs to the “School of de Wit” crop models (van Ittersum et al., 2003), like SUCROS or WOFOST. The crop development is based on accumulated thermal time scaled to a decimal scale called BBCH (Lancashire et al., 1991). Photosynthesis and net carbon assimilation are estimated from gross assimilation of CO_2, maintenance and growth respiration. Maximum potential photosynthetic rate is a function of CO_2 concentration in the atmosphere. Water stress affects growth rate via photosynthesis and root-shoot partitioning. The water stress factor is derived from relative soil water content using a simple logistic function (Richter et al., 2001). Details are given in Richter et al. (2006b).

Calibration was done on a very detailed French data set (Gabrielle et al., 1998), which resembles very much the conditions of north-west Europe; data were directly retrieved from the data base[1].

The dynamics of Green Leaf Area Index (GLAI) were well matched and so were the dynamics of total biomass and storage compartment (Richter et al., 2006b), however, the crop matured too early and the yield was underestimated (1 t ha^{-1}). The observed dry matter production (16 t ha^{-1}) and yield (5.1 t ha^{-1}) were higher than those measured in the UK. All growth indicators were simulated with high significance without adjustment of any of the parameters taken from the literature. It appears that the underestimated rate of increase in Above Ground Biomass (AGB) and yield - while LAI is slightly overestimated – may be due to the fact that the values for the initial light use efficiency and photosynthetic rate at light saturation were too small (LUE_0 = 17 µg CO_2 J^{-1}; pCO_2 ~ 0,00165 g CO_2 m^{-2} s^{-1}).

The crucial points of phenology are the beginning of flowering and grain filling. The French data set did not provide these data and we had to make some assumptions. For

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[1] Extraction from Chalons Oilseed Rape DataBase; Copyright INRA; http://www-bioclim.grignon.inra.fr/ecobilan/base/welcome.html.

vernalization requirement we assumed in this simulation a temperature window between 0 and 10 (±3) degrees and a cumulative requirement of 15 days starting after emergence. Most parameters for crop development and partitioning were taken from the HGCA-reports: For germination and emergence a base temperature of 3 °C had been calculated (Lunn et al., 2003). Emergence (50%) from 2 cm at 25 °C occurred after 110 hrs (1650 °Chrs; 69 °Cd). The thermal time until emergence was higher under field conditions: Emergence in the field can be affected by temperature and bulk density of the soil (and sowing depth). 130 and 160 °Cd were measured for 50 % emergence at optimal sowing depth (2-3 cm) in lab and field conditions, respectively. For anthesis 810 Growing Degree Days (GDD) was calibrated and for the beginning of grain filling we set another 280 GDD. Maturing was reached after another 400 GDD.

Partitioning (see Fig. 2, OS49 Lunn et al., 2001): Leaf growth is finalised by end of March to mid April (2 – 2.2 t/ha); stem growth increases until mid May (5 t/ha); hull is growing until end of June (max. 4 t/ha); grain filling occurs from mid June to mid July (4 t/ha). Translocation occurs from leaves and hull but not from stem, senescence of leaves starts after flowering (mid May) – translocation to hull, hull looses about 1 t/ha later on until harvest/maturity. Total above ground biomass (AGB) reaches 13 t/ha in low density crops, 15 t/ha in high-density crops. Crop dry weight at flowering can vary from 2 to 8 t/ha (Lunn et al., 2001), 5 t/ha was thought to be critical AGB but the analysis of Lunn et al (2001) shows that yields of 4 t/ha are possible at 3t/ha AGB at flowering.

Overall, when tested using local data, modelled yields were similar to those observed in experiments at the Rothamsted and Woburn sites using this parameter set and the regional simulation showed good performance for a multi-annual (1961-1990) data set (Richter et al., 2006b).

2.4.2 Description of the applied methodology

There is a two step approach to be followed: (a) Re-calibration of the process-based model and evaluation of the model at various sites and (b) extrapolation of the model by running the model for baseline (and future) scenario weather for a range of soils. These results are then in a final step (c) used to generate an empirical meta-model based on soil and various climatic variables.

Re-Calibration and regional up-scaling of the OSR process model

It is essential to re-calibrate the existing parameter set for UK conditions using high resolution growth curves from dedicated experiments run by ADAS and then use historical data to evaluate any effects which are not recognised by the process-based model. Data sets have been made available by ADAS (Berry and Spink, 2006; 2009) at different resolutions, which were being provided in easy to understand Excel spreadsheets.

(1) Growth analysis data for the parameterization of the model (3 sites x 5 seasons) for Biomass and partitioning between leaf, stem, pod, and seed measured at start of stem extension, mid flowering and combine harvest yields, daily weather data, soil series, texture, soil nutrients, pH, Nitrogen fertiliser rate.

(2) Historic yield data at 4 sites and probably at least 10 seasons from 2007 backwards. We can probably get 5 sites of data here. Yield data will be provided, (some of this information is still on paper and needs transferring to digital format), together with daily weather data and soil descriptions

It is essential to run simulation scenarios for OSR yields very much like this has been done for winter wheat and sugar beet (Richter et al., 2004) to enable us to see the overall biomass and yield response to agro-meteorological input data (T_a, P, R_g) to lay down the basis for the OSR-meta-model.

Development of a meta-model for OSR

For the Meta-Model it is planned to regionally disaggregate yield data across the country based on relationships between yield and soil, climate data. In analogy to the WW and SBt meta-models, an empirical relationship will be derived between simulated yields and aggregated input variables from the soil available water and weather data. In contrast to the wheat and beet model no meta-model for total OSR biomass is anticipated because there is no technology for its use.

The aggregation of these agro-meteorological input data cannot be decided and biased until the process-based model was re-evaluated and used to run a scenario analysis on various sites characterised by temperature and precipitation profiles. Then monthly aggregated input data will be tested and selected in a stepwise variable selection multiple regression analyses.

It is likely, that after crop establishment before winter the moisture regime/water balance before flowering and the temperature during grain filling will be important. Rainfall after maturation and before harvest may be detrimental (pod shatter).

2.4.3 Functionality

Eventually, the model will have the same functionality as the models for wheat and sugar beet. That is, it is spatially explicit (maps) and allows to recapture the response to new inputs with regard to meteorological variables and technological progress coefficients.

A recent climate impact simulation scenario used a process-based model, which showed a north-south and east-west divide of OSR yields, aggravating in the future (Butterworth et al., 2010). These yield maps could be used for cross-validation but they do not include a differentiation with regard to soil quality. A test with respect to the effect of different soil types, response to water availability (AWC) in interaction with climatic impacts is absolutely necessary.

This work needs further research at what resolution it is meaningful in terms of soil and soil water availability and how we can down-scale such climate impact maps for yield gap analysis due to pests and diseases affecting OSR productivity. Here, we will also refer to the most recent report on future UK winter oilseed rape production compiled by ADAS consultants (Clarke et al., 2009).

2.4.4 Input data requirements

The process-based model will use the existing daily weather data supplied for the Defra-project CC0368, based on the HadCM3 and documented in the UKCIP02-report, which were documented in Semenov (2007).

Data requirements will be the same as for winter wheat and sugar beet. Data about technological progress comes from Food and Agriculture Organization (FAO: http://www.fao.org), the calculated relative yield increase by the end baseline period (1961-1990) in UK was 0.7% for oil seed rape. The oilseed rape yield gap $f_{T,Gr(t0)}$ is based on Jaggard et al. (2010) and 0.75 and 0.85 under baseline and future scenario (2050), respectively (Jaggard et al. 2010). Recent report by Spink et al. (2009) to the Governments Chief Scientist will be consulted as well.

2.4.5 Model output

The model will generate obtainable grain yields of oilseed rape (OSR) on the basis of the provided soil AWC data and aggregated weather variables climate scenarios (UKCP09, see Section D). These outputs will be provided as maps and functions.

3 Second Generation Crops

3.1 Introduction

At a global level, a number of dedicated bioenergy crops (with no food value) have been identified for future deployment and harvest of lignocellulosic resource (Somerville et al., 2010). These include grasses such as switch grass, agave and trees such as poplar, but for the UK, the two front runners for commercial deployment are currently Miscanthus and SRC-willow. For these crops, detailed maps for potential yield have been generated in the past. For example, Aylott et al. (2008), Aylott (2011) and Richter et al. (2008) developed empirical yield maps for SRC and Miscanthus, respectively. These models are based on few, but physically meaningful climatic and soil variables, which allow a prediction of local yield potential. Crucially, at the regional and national scale input data become more uncertain, and, uncertainty caused by soil inputs may exceed the model error (Richter et al., 2008; Lovett et al., 2009).

Process-based models are available to estimate future yields of SRC (Aylott et al., 2010; Aylott 2011; Tallis et al., 2011) and Miscanthus (Richter et al., 2008b; ~ 2010), which however, have limited validation on a set number of sites across the UK for example, a minimum of 6 for SRC willow. Despite this, process-based approaches offer one ‘best possible’ solution to predict yields outside the current climatic envelope, although limited by the availability of field-based estimates of yield.

In conclusion, these second generation crops are less well-studied than food crops. Although a detailed process model exists for Miscanthus which has been evaluated for other sites we propose to use a well-established empirical model (Richter et al., 2008) to estimate future yields by applying average changes to the climatic input variables. For SRC willow, the process based model will be applied to climate change scenarios (described below).

3.2 Miscanthus

Maps of Miscanthus yield covering the UK were developed on potential rather than obtainable yield, either implying that all biomass can be harvested (Price et al., 2004) or ignoring water availability constraints in England (Clifton-Brown et al., 2004). More recent findings and discussions, however, show that Miscanthus in the UK can be water-stressed even on deep soils, probably due to interception losses and insufficient soil water recharge during the winter (Finch and Riche, 2010).

3.2.1 Description of existing model/meta-model

An empirical yield model was developed from harvestable dry matter yields at 14 field trials in the UK to estimate site specific and regional yields derived from meteorological variables and soil available water (Richter et al., 2008). Harvestable *Miscanthus* yields on 14 arable sites across the UK ranged from 5 to 18 t ha^{-1} (mean of 12.8 (±2.9) t ha^{-1}). Variables considered to affect yield were temperature, global solar radiation, precipitation, and potential evapotranspiration during the season, and soil available water capacity (*AWC*). At a single site (Rothamsted), *AWC* and the relative average potential soil moisture deficit during the main growing season explained 70% of annual yield variation (RMSE=1.38 t ha^{-1}, p<0.001). In the complete UK dataset (n=67), yield variation was related to *AWC*, temperature and precipitation during the main growing season and negatively affected by post-maturity, winter precipitation (RMSE=2.1 t ha^{-1}, p<0.01). This model was combined with AWC values estimated from a pedotransfer function (PTF) using primary data for mineral soils and accounted for water available from shallow groundwater or underlying porous rock (Lovett et al., 2009). AWC data taken from the NATMAP database (see Section D) were on average 20 mm lower than these, did not relate well with observed yields and underestimated yields (Richter et al., 2008).

$$Y_M = -15.2 + 0.0555\times AWC(PTF) + 0.0129\times P(AMJJAS) + 1.039 \times Ta(AMJJAS) - 0.0075 \times P(ONDJF)$$

Unlike winter wheat and sugar beet, the quadratic term of soil AWC(PTF) is not needed because the dry biomass production has not shown a diminishing increase as the soil AWC(PTF) increases (Figure 3-1).

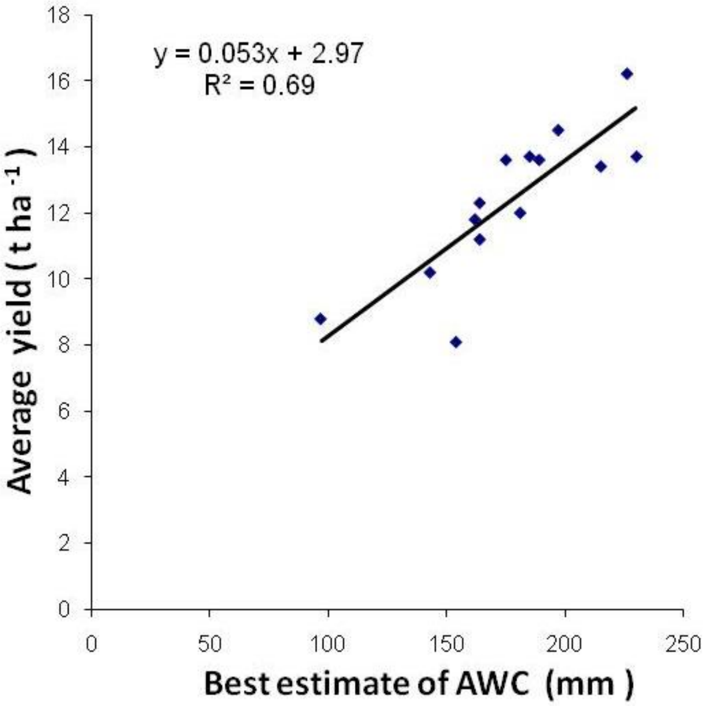


Figure 3-1 Relationship between dry biomass yield and PTF-estimated soil available water content (AWC) in Miscanthus.

3.2.2 Description of the applied methodology

This model will be combined with new weather variables and soil AWC data which will be generated as described below. The choice of emission scenario may impact on the climate warming effect. There is no need to account for an increase in CO_2-concentration (see below).

3.2.3 Functionality

A map of harvestable Miscanthus yield (oven dried tonnes, odt) will be generated by implementing a map algebra analysis (Berry, 1993) in ArcGIS. This involves combining coefficients from the multiple regression equation (see above) with 1 km resolution variables derived from the climate database and the equivalent of the NSRI NatMap 1 km soil database (see Section D; or lower in case of the farming community)..

The future scenarios for carbon fertilisation effects (CFE) and technological advancement will follow the procedure proposed by Ewert et al., 2005) while climatic impacts from changes in temperature and precipitation will directly be accounted for by inputs derived and aggregated from the UKCP09 data (see Section D).

There is,a dispute whether there effectively is a CFE in C4-crops at all. Analysing several FACE experiments for maize and sorghum Long et al. (2005) could not find any significant effect of [CO_2] on productivity, while Lobell and Burke (2010) presented the impact considered in CERES to be approximately 10% CFE when [CO_2] doubled.

Effect of technological advancement on the yield gap is unknown territory. One could, however, follow the philosophy that an unexplored, fairly unsophisticated crop like Miscanthus has a large future gain in crop development, currently experiencing a large yield gap but closing it more effectively with longer experience

3.2.4 Input data requirements

Inputs to estimate soil water availability, AWC, in the profile were derived by using a PTF (Woesten et al*.,* 1999) from soil texture, bulk density and organic matter. We assumed a maximum rooting depth of 1.5m unless otherwise stated (e.g. depth to rock in NATMAP). The set of rules considered four different soil groups: deep non-gleysols, shallow non-gleysols overlying porous rock, and deep gleysols and shallow gleysols above hard rock and sediments. AWC is the water retention between field capacity (FC) and wilting point (WP, -1500 kPa), and water content at FC was estimated at -10kPa for gleysols, and -33 kPa for any other soil. AWC is the sum of horizon-specific AWC(z) up to depth of rock, and water from porous rock was approximated for those soils classified as HOST classes 1 to 3 (Boorman et al., 1995). AWC of porous rock was assumed to be between 10 vol% (chalk) and 5 vol% (oolitic limestone, sandstone) and was estimated for the layers exceeding depth of rock to the maximum profile depth. For shallow gleysols the PTF was extended to the depth of profile of the porous sediments recorded in the database (Lovett et al., 2009).

The agro-climatic variables used to predict harvestable Miscanthus yield were derived from the weather/scenario data by annually aggregation over periods of the growing season as defined earlier (Richter et al., 2008; Lovett et al., 2009): (1) precipitation during the April to October growing season (positive effect); (2) precipitation during the October to February post-maturity and pre-harvest period (negative effect); and (3) mean temperature during the April to September growing season (positive effect).

3.2.5 Model output

Yield of biomass in oven dry tonnes per hectare as maps. In combination with variable inputs from UKCP09 scenarios average yields per scenario and decade will be calculated.

3.3 SRC-Willow

3.3.1 Description of existing model/meta-model

ForestGrowth-SRC is a process-based model representing the current understanding of the physiological, biophysical and physical processes underlying growth, development and yield of short rotation coppice (SRC) crops. ForestGrowth-SRC is a modular, fully coupled, daily timestep soil–vegetation–atmosphere transfer (SVAT) model developed from Forest ETp (Evans et al., 2003) and including the wood development principles of refined pipe theory (Deckman et al., 2006) adapted for SRC (Aylott, 2011). The seven modules of ForestGrowth-SRC are described in detail in Aylott (2011). The model is driven by local climate and soils data and runs at site / field scale, considering a user defined per hectare stocking density, and at a daily time step summating an annual yield across a user defined time period and rotation length. The model was originally parameterised to simulate poplar SRC yield and has now been re-parameterised for willow and validated simulated yields have been evaluated (Tallis et al., 2011) for willow using site specific yield data currently from six sites of the Forestry Commission SRC field trials network (Aylott et al., 2008).

Processes within ForestGrowth-SRC directly impacted by the applied methodology (section 3.3.2) will be briefly described. Within the climate module the internal weather generator generates daily time series from monthly summary data (Evans et al., 2003.), thus allowing use of the most current predictions of future climates for the UK (e.g UKCP09 spatially coherent data). The photosynthesis module developed by Farquhar et al. (1980) and von Caemmerer and Farquhar (1981) includes modifications by Long (1991), McMurtrie and Wang (1993) and Friend (1995). This modified C3 photosynthesis model is tightly coupled with the C3 version of the Ball-Berry model of stomatal conductance, Ball et al. (1987) thus allowing explicit responses to environmental variables to be modelled (i.e. increasing atmospheric CO_2 concentrations ([CO_2]) the CFE). ForestGrowth-SRC has been evaluated against experimental data for poplar SRC growth in high atmospheric CO_2 (enriched by ~ 40% of the current concentration, which is within the range predicted out to 2050, (IPCC, 2007). The yield enhancements of ~ 20 % (Liberloo et al., 2009) under such conditions were well simulated by ForestGrowth-SRC (Tallis et al., 2011). Carbon allocation to the biomass pools of leaf, stem, branch, coarse root and fine root has been calibrated and evaluated using data from two three year coppice rotations (Tallis et al., 2011). During the end of the growing season any additional carbon can be allocated as a user defined ratio between stem and coarse root to account for genotypic variations observed in SRC (Nelson and Isebrands, 1983).

3.3.2 Description of the applied methodology

ForestGrowth-SRC will be used to predict SRC willow yield across the UK and out to 2050. The process model will be run for each decade 2010 – 2050 (incorporating an establishment year that is cut back followed by three, three year coppice cycles) and accounting for future predicted climates (UKCP09) and atmospheric [CO_2]. Yield output will be annualised for each 1 km² of the UK and on a decadal basis (oven dried tonnes hectare^{-1} year^{-1} for each decade) using the sum of the three harvestable yields. The work flow is detailed in Figure 3-2 detailing the approach and temporal and spatial resolution.

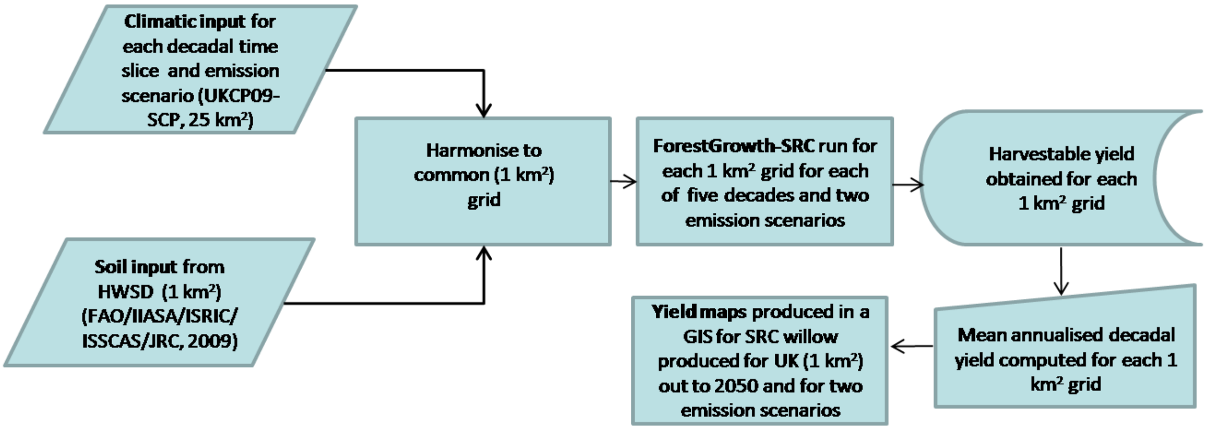


Figure 3-2 A flow chart representing the work flow envisaged to produce simulations of SRC willow yield within the UK out to 2050.

SRC yield is dependent on soil conditions, climate and [CO_2], all of which are handled by utilisation of the process-based model with discontinuous scenario analysis. The predicted [CO_2] changes during the time-period specific to BVCM, interacts with these C3 crops to positively influence yield by an enhancement of 20-40 % as measured across a network of field scale CO_2 enrichment experiments (e.g. Karnosky et al., 2007; Liberloo et al., 2009; Long et al., 2004). Plant level water-use efficiency as a consequence of reduced stomatal conductance of ~ 20% (e.g. Tricker et al., 2005; Oliver et al., 2009), may be improved at leaf level, but reduced at canopy scale as a consequence of enhanced leaf area (Tricker et al., 2009). The magnitude of these influences and interactions between them is largely dependent on soil conditions and climate which will vary spatially and temporally and suggests that process-model runs (for example the > 100 equations handling > 100 parameters in ForestGrowth-SRC) are essential to gain meaningful insight into the productivity of SRC for the UK in future climates. Furthermore, yield in an SRC system can also be influenced by inter-annual carry over effects from the previous year's growth which is accounted for in ForestGrowth-SRC. It is therefore considered that the most reliable approach to simulate SRC willow yield across the UK out to 2050 is to run ForestGrowth-SRC for the chosen climate scenarios. This approach allows predictions of yield outside of the climatic envelope of any current yield studies from which it was developed, e.g. the yield enhancement in elevated [CO_2] which is well matched with measured data (Tallis et al., 2011) and integrates inter-annual influences affecting yield. It is considered that up-scaling all the processes modelled by ForestGrowth-SRC to a simple equation or meta-model relating inputs with outputs would substantially reduce the ability of such yield simulations to account for the biological processes responding in a multi-variate way to the multi-variate inputs apparent across the UK and out to 2050. For example, the mathematical relationships between inputs and outputs that best accounted for observed yield and formed the empirical model for SRC in the UK (Aylott et al., 2008) are rotation specific. The ranking of importance, type of input variable and mathematical function of each variable determining yield for the same willow genotype differed between two rotations (Aylott et al., 2008; Aylott, 2011). This suggests that a meta-model approach of simplified equations is likely at this stage, to be less accurate for predicting future UK SRC yield in willow than for arable crops such as wheat. This justifies the use of a process-based model approach alongside a number of discrete model runs for pre-define scenarios as proposed for SRC in the original specification.

3.3.3 Functionality

No additional functionality has been specifically developed for this project. Rather, the contract is utilising on-going developmental work of the model within the laboratory of Gail Taylor.

3.3.4 Input data requirements

ForestGrowth-SRC is driven by inputs that describe the local soil and climate to a specified grid reference and time period. These can be obtained by the latest spatially coherent climate predictions for the UK (UKCP09-SCP). The monthly variables are mean maximum temperature, mean minimum temperature, mean precipitation, mean wind speed, a deviation from the mean of each variable is also required, and all are available via UKCP09-SCP. A monthly value for number of wet days is also required; this can be derived from the UKCIP02 baseline data (1961-1990). The mean [CO_2] for each decade will be estimated according to the emission scenario used to drive the climate predictions. The soil variables required for the BVCM are bulk density, horizon depth and the percentage content of sand, silt, clay and organic matter for each horizon and an estimate of permanent water table depth, provided by the Harmonized world soils data (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009). Although in the past we have been working with the UK NATMAP soil data set, we have now moved to the HWSD since HWSD provides soil input data that is coherent for the whole UK (including Scotland and Northern Ireland) - a feature absent from NATMAP (providing only for England and Wales). This attribute combined with the up-scaling of yield to a 10 km resolution for the value chain model strongly suggests HWSD as a suitable soils dataset. In other projects NATMAP may be more suited to down-scaling of yield (to less than 1 km resolution) and soil processes to a tighter spatial resolution, but here we can find no justification for that approach.

3.3.5 Model output

ForestGrowth-SRC outputs up to 60 variables concerned with SRC production covering the movements of water, radiation and carbon. For the BVCM ForestGrowth-SRC will output geo-referenced values of above ground biomass in oven dried tonnes (ODT). Specifically these will be ODT hectare^{-1} year^{-1} for each decade and km^2 grid cell for 2020, 2030, 2040 and 2050 medium and high climate scenarios and for a ‘business as usual’ management regime – three year rotation with limited management input. These data will feed forward to the value chain model.

4 Forest Based Wood Resources

The Forest Research CARBINE model is used to model outputs from forestry, specifically from short rotation forestry (SRF), high forest stemwood (HFSW) and high forest branchwood (HFBW). These three components are effectively elements of the same resource.

4.1 Introduction

Models available to estimate potential production are relatively simple in terms of process representation but have proved effective for national and regional production forecasting and planning. The principal model to be used in this project for forecasting potential biomass production is the CARBINE model. The primary purpose of the CARBINE model is to simulate forest sector carbon balances for a wide range of tree species, growth rates and management prescriptions at the regional and national scales. However, the model can produce estimates of biomass production (of primary relevance to this project) as an additional output. For the purposes of this project, CARBINE will require spatially explicit input data on forest composition, growth rates and management. Information on forest composition and management will be derived through analysis of inventory data from the National Inventory of Woodland and Trees (NIWT, Smith and Gilbert, 2003) and the Forestry Commission sub-compartment database (SCDB) maintained as part of the management of publicly-owned woodlands.

Initial estimates of growth rate can also be obtained from the sub-compartment database but, to enable projection of biomass forecasts under certain scenarios, it will be necessary to construct meta-models of tree growth rates with respect to environmental variables. The CARBINE model uses General Yield Class which is the forest industry standard index of tree species productivity See Appendix 7 for a description of General Yield Class. There has been some research on developing relationships between General Yield Class and agroclimatic data including some integration into a knowledge-based model, the Ecological Site Classification, ESC (Pyatt et al., 2001; Ray, 2001). It is proposed to use ESC and (to the extent feasible within the project timescale) its extended form currently under development, ESC climate-change, supplemented by less extensive research studies to develop yield class maps, for use as inputs to CARBINE. Estimates of General Yield Class for high forest derived from ESC are expected to be accurate but are likely to be imprecise at the scale of individual stands. On average, for a population of stands at a scale larger than 10,000 hectares, precision is likely to be ± 20 % (Matthews et al., 1996).

The following discussion outlines the principles of the CARBINE model, how its outputs can be adapted for the purposes of this study, and how meta-models may be developed using ESC as a framework to provide the essential input data. Limitations to the development of meta-models, mainly due to the highly discontinuous nature of biomass production from forest stands, are also explained.

4.2 The CARBINE and ESC models

4.2.1 Description of existing model/meta-model

THE CARBINE FOREST CARBON ACCOUNTING MODEL

CARBINE was first developed by the then Research Division of the Forestry Commission in 1988 (Thompson and Matthews, 1989). Essentially it is an analytical model of the exchanges of carbon that take place between the atmosphere, forest ecosystems (trees, deadwood, litter and soil) and the wider forestry sector (harvested wood products) as a result of tree growth, mortality and harvesting (Thompson and Matthews, 1989; Matthews, 1991). Other land uses are represented in CARBINE 'at the margin', i.e. to the extent necessary to represent land use transformations involving forests such as afforestation of cropland or grassland or conversion of forest to other land uses (deforestation). CARBINE also represents other economic sectors 'at the margin', notably the Energy and Construction sectors, in order to estimate the impacts of changes in patterns of timber harvesting and utilization on consumption of fossil fuels and alternative materials, and consequent changes in greenhouse gas emissions (Matthews, 1994, 1996).

The CARBINE model has common features of structure and functionality with other analytical forest carbon accounting models, notably C-Flow (Dewar, 1990, 1991; Dewar and Cannell, 1992), CO2FIX (Mohren and Klein Goldewijk, 1990; Nabuurs, 1996; Mohren et al., 1999), CBM-CFS3 (Kurz et al., 2009), C-change (Beets et al., 1999) and GORCAM (Marland and Schlamadinger, 1995, 1999; Schlamadinger and Marland, 1996). A comparison of CARBINE and C-Flow (the other main forest carbon accounting model relevant to UK conditions) revealed many similarities and consistencies in the functioning and results produced by the two models (Robertson et al., 2003).

Initial versions of CARBINE produced per-hectare scale estimates of carbon exchanges associated with individual stands of trees (Thompson and Matthews, 1989; Matthews, 1994). Subsequently CARBINE was further developed into a national-scale scenario analysis tool and has been used to assess the impacts of current and alternative forestry practices on greenhouse gas balances in Great Britain and the United Kingdom (Matthews, 1991, 1996; Matthews and Broadmeadow, 2009).

A schematic diagram of the structure of the CARBINE model is given in Figure 4-1.

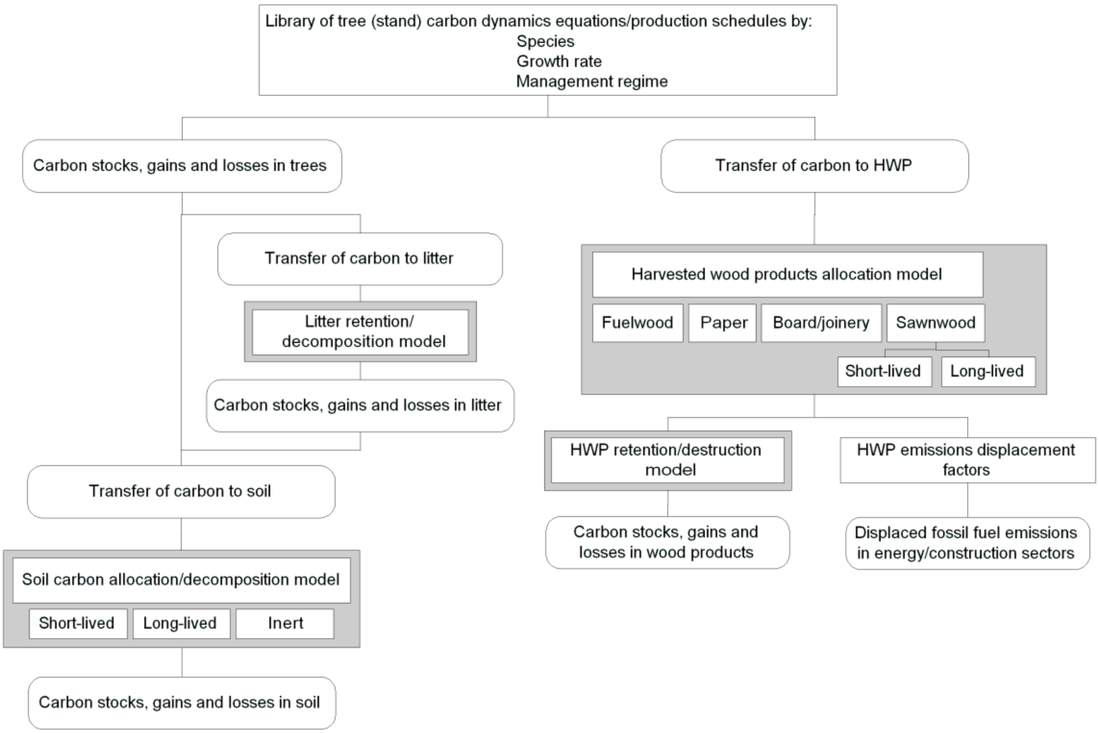


Figure 4-1 Schematic illustration of structure of CARBINE model.

The CARBINE model also has the capacity to produce estimates of other variables not directly to do with forest carbon but of great relevance to decisions about forest management, for example:

- Levels of wood and timber production (which can be broken down into specific wood product categories if required);
- The development of forest age class structure over time;
- Changes in the species composition of forests in response to management interventions (where relevant).

Predictions of wood and timber production can be provided as outputs expressed in units of oven dry tonnes, which are likely to be of most relevance to this project.

CARBINE cannot represent changes in carbon dynamics due to increased atmospheric CO2 or climatic change, although it is possible to specify progressive changes to yield classes of different tree species so as to partially describe the impacts of long term environmental change. This is implicit in the approach which is adopted to longer term projections relevant to this project.

The modelling methodology behind the current version of CARBINE is based on long-established conventional Forestry Commission yield models (Edwards and Christie, 1981), coupled to models of tree carbon content, wood decomposition, soil carbon exchange, product utilisation and emissions factors for forestry operations, timber transport and timber processing. Emissions reductions factors describing different options for timber and wood fuel utilisation are applied in the estimation of interactions between the forest, energy and construction sectors, which may be relevant to estimation of GHG balances within this project.

BIOMASS IN GROWING TREES

The main driving module of CARBINE consists of a set of computerised mathematical functions and algorithms describing the accumulation (and loss) of tree biomass of different forestry systems at the per-hectare scale. Different functions and algorithms are used to represent distinct forestry systems, defined in terms of:

- Tree species composition
- Tree growth rate (yield class)
- Management regime applied to the stand.

The combinations of tree species, growth rates and management regimes represented in the ‘standard’ version of CARBINE are summarised in Table 4-1. The main management regimes covered in the current version of the model are for high forest and short rotation forestry systems (i.e. not short rotation coppice or non-forest vegetation).

Stem volume growth and yield are provided in Forestry Commission yield tables of Edwards and Christie (1981). For example, a stand of Scots pine may have an initial tree density on planting or regeneration of 2,500 trees per hectare. This example stand may have a maximum productive potential (over a rotation) of about 8 m^3 ha^{-1} yr^{-1}, and is managed with thinning operations every 5 years starting at stand age 31 years.

The basic tables of Edwards and Christie run from age 21 (10 years before the scheduled age of first thinning) to age 101 years (beyond the age of a typical rotation for this forest stand type in the UK), with entries every five years coincident with the thinnings. In the CARBINE model, the basic growth and yield tables are extended to later ages to enable the retention of stands on long rotations or without felling to be simulated. For each table entry, the tables give estimates of standing stem volume and also the volume removed in any scheduled thinnings in units of cubic metres over bark per hectare.

In CARBINE, stem biomass is estimated by multiplying the stem volumes in a standard yield table by a standard value for the basic density of wood for the relevant tree species, expressed as oven dry tonnes of mass per cubic metre of ‘green’ timber volume (Lavers, 1983). In the case of Scots pine this value is 0.42 odt m^{-3}.

Tree species	Growth rate[1] (m^3 ha^{-1} yr^{-1})		Management regimes[2,3]			Basic density[4] (odt m^{-3})	Allometric coefficients[5]	
	Lowest	Highest	Clearfell, thinned	Clearfell, unthinned	Continuous cover		f_R	f_B
Norway spruce	6	22				0.33	0.30	0.40
Sitka spruce	6	24				0.33	0.45	0.35
Corsican pine	6	20				0.40	0.20	0.20
Scots pine	2	14				0.42	0.35	0.40
Lodgepole pine	2	14				0.39	0.40	0.50
European larch	2	12		▨		0.45	0.30	0.20
Japanese/ hybrid larch	2	14				0.41	0.30	0.20
Douglas fir	8	24		▨		0.41	0.30	0.30
Grand fir	12	30		▨		0.30	0.25	0.30
Noble fir	10	22		▨		0.31	0.30	0.40
Red cedar/ leyland cypress	12	24		▨		0.38	0.30	0.30
Western hemlock	12	24		▨		0.36	0.30	0.30
Oak	2	8		▨		0.56	0.50	0.80
Beech	2	10		▨		0.55	0.50	0.80
Sycamore	2	12		▨		0.49	0.50	0.70
Ash	2	12		▨		0.49	0.50	0.65
Birch	2	12		▨		0.49	0.50	0.60
Nothofagus	10	18		▨		0.49	0.50	0.80
Poplar	2	14				0.35	0.50	0.50

Table 4-1 Tree species, growth rates and management regimes represented in the CARBINE model

[1] Growth rate is defined as the maximum average rate of cumulative volume production over a rotation. (The average rate of production will vary with the specified rotation.)

[2] Clearfell thinned and unthinned management regimes can be specified with any rotation in years, or can be specified for no clearfelling (i.e. indefinite retention of the stand).

[3] Cells shown with grey background indicate management options not available for the tree species in the CARBINE model.

[4] Basic density is defined here in units of oven dry mass per ‘green’ cubic metre.

[5] The allometric coefficient f_R is used to determine the quantity of root wood, whilst f_B is used to determine the quantity of branch wood and foliage combined.

These values are converted to equivalent estimates of carbon by multiplying by a standard value for wood carbon content of 0.5 tC odt^{-1} (Matthews, 1993).

The CARBINE model works at an annual timestep, therefore annual estimates of carbon in standing stem volume, biomass and carbon is also ‘extrapolated back’ to stand age zero (i.e. time of tree planting or regeneration). This is achieved by linear interpolation of periodic values for stem carbon and, assuming a notional value for standing carbon of zero at age zero, then constructing a curve that passes through this point and the entries for the first two periodic carbon estimates. The curve is assumed to be of an exponential form:

$CSTEM(t) = -\alpha + \alpha \times \exp(\beta \times t)$ (Equation 4-1)

where CSTEM(t) is the carbon in stem wood at stand age t years and α and β are constant model parameters selected to ensure the curve of Equation 4-1 passes through the first two observations of standing stem carbon for the relevant growth and yield table. Note that, by convention, tree stem volume is defined as having a minimum diameter of 7 cm over bark. Consequently, trees of smaller diameter (such as at young ages) strictly have zero stem volume. The small stem volume values at young ages produced by the ‘backwards extrapolation’ procedure are thus ‘theoretical’. Carbon and biomass (and volume, although of less relevance) in tree roots, branches and foliage are estimated by assuming simple allometric relationships with stem wood of the form

Root carbon or biomass = f_R × Stem carbon or biomass (Equation 4-2)

Branch+foliage carbon or biomass = f_B × Stem carbon or biomass (Equation 4-3)

where f_R and f_B are species-specific coefficients (see Table 4-1).

The coefficients f_R and f_B are assumed to be constant with respect to tree age, size and growth rate and the values assumed for different tree species are listed in Table 4-1. These values are based on interpretation of summary estimates of root, branch, foliage and stem biomass using the Forestry Commission BSORT forest stand biomass model (Matthews and Duckworth, 2005).

The assumption that f_R and f_B take constant values is an important simplification which permits more straightforward and robust implementation within CARBINE. In reality f_R and f_B vary systematically, in particular with stem diameter. (Generally roots and branches constitute a progressively smaller fraction of total tree biomass relative to stem wood as tree diameter increases, see Matthews et al., 1991; Matthews and Duckworth, 2005). The simplification will not affect the estimated long-term rate of carbon sequestration, for example over a typical rotation for a given tree species and yield class. However, the detailed timecourse of sequestration will be slightly ‘smoothed out’ over a typical rotation. The impacts of alternative assumptions about the form of f_R and f_B have been explored by Robertson et al. (2003).

Figure 4-2 shows the development of carbon in root, stem, branchwood and foliage biomass (the latter two quantities combined) with stand age for the example Scots pine stand, obtained by applying the allometric relationships defined in Equations 4-4 and 4-3 to partition coefficients for allocation of ‘raw’ harvested wood material to primary wood product categories, with parameter estimates for f_R and f_B, for Scots pine taken from Table 4-1. Outputs such as shown in Figure 4-2 represent the main results for carbon in growing trees generated by CARBINE for an individual forest stand. The results in the figure clearly show how the CARBINE model can represent changes in growth rate, potential production levels and rate of carbon sequestration which evidently evolve over decades. This has implications for the reporting of model outputs within the BVCM tool and for functionality, as discussed in section 4.2.2 (subsection on Bespoke output data sets) and section 4.2.3.

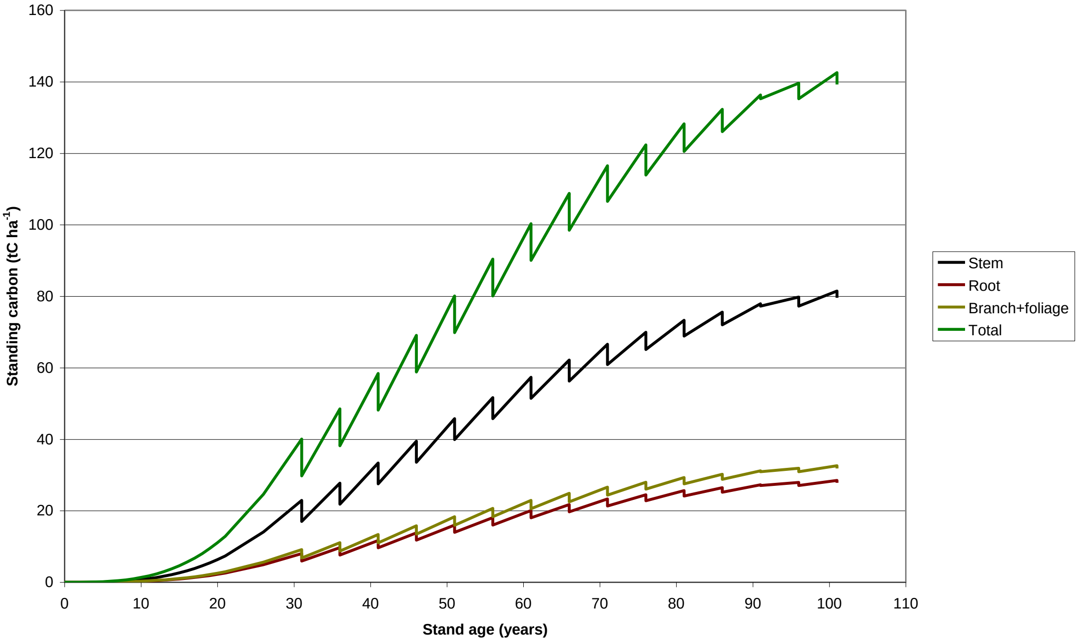
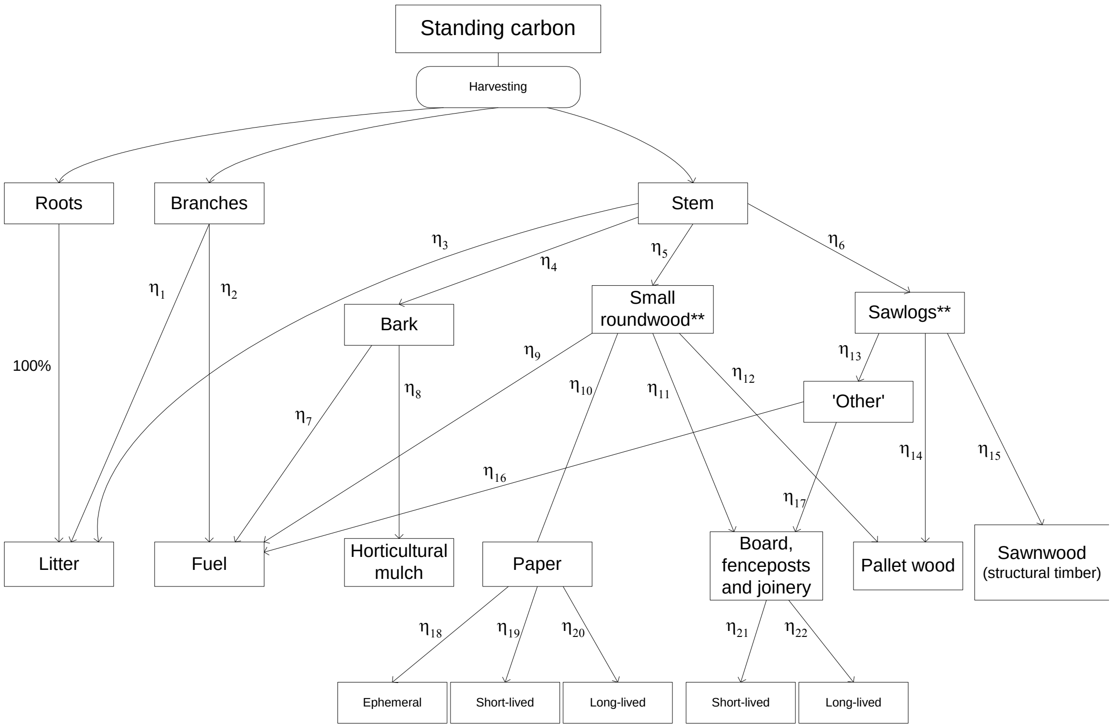


Figure 4-2 Estimates of the development of stem, root, branch (with foliage) and total carbon in living trees with stand age for a stand of Scots pine with maximum stem volume production of 8 m^3 ha^{-1} yr^{-1}.

ALLOCATION OF BIOMASS AT HARVEST

Figure 4-3 illustrates the approach to allocating harvested wood to litter in the forest and to primary products, as implemented in the current version of CARBINE. As already explained, carbon in roots of harvested trees is assumed to enter the litter pool in its entirety. (The option of harvesting some or all root biomass is not represented in the current version of CARBINE.)

Branchwood of harvested trees is assumed to be either harvested for use as wood fuel or left on site as part of the litter pool. The proportions allocated to be left on site or harvested for fuel are determined by simple partition coefficients, η1 and η2. These coefficients are both set to 50% on the basis of a broad assumption as described earlier. (Implicitly, the bulk foliage associated is assumed to remain on site as litter.)



* Proportion varies with tree size and shape

** (not including bark)

Figure 4-3 Schematic illustration of allocation of harvested wood material to primary wood products and litter as implemented in the standard version of CARBINE.

The first step in the ultimate allocation of harvested stem wood to primary products involves an initial allocation to waste wood left as litter in the forest and to three ‘raw’ stem wood categories of ‘bark’, ‘small roundwood’ and ‘sawlogs’. The proportion of stem wood allocated to litter is determined by a partition coefficient, η3, which is set to a standard value of 10% (see for example www.forestry.gov.uk/forestry/infd-7aqdgc). The allocation of the remaining stem material to bark, small roundwood and sawlogs (otherwise known as a product assortment) is determined respectively by the partition coefficients η4, η5 and η6, which depend on the size and shape of the harvested trees. In turn, tree size and shape depend on many factors but notably tree species, yield class and how the trees have been managed (Matthews and Mackie, 2006). The specific definitions used for small roundwood and sawlogs also influence these allocations.

In the CARBINE model, coniferous (softwood) sawlogs are defined as (individually or collectively) taking up the maximum available length in stem wood (as opposed to taking a specified fixed length), up to a minimum top diameter of 18 cm overbark, but with a minimum length constraint of 1.3 m, excluding that portion of stem wood allocated to litter. Broadleaf (hardwood) sawlogs are defined as (individually or collectively) taking up the maximum available length in stem wood (as opposed to taking a specified fixed length), up to a minimum top diameter of 24 cm overbark, but with a minimum length constraint of 1.3 m, excluding that portion of stem wood allocated to litter. The more conservative specification of sawlogs adopted for broadleaves compared to conifers reflects differences in the utiisation of the two broad types of timber, but also allows for the occurrence of significant branching and forking of tree stems in broadleaves (generally higher up the stem and at smaller top diameters), which limit the suitability of such material for utilisation as sawlogs.

Small roundwood is defined as the remaining portion of stem material (excluding any portion allocated to litter) to a minimum top diameter of 7 cm overbark. By convention in the forest industry, sawlog volume (or biomass or carbon) is expressed as an underbark quantity, whilst small roundwood is expressed as an overbark quantity (i.e. including any associated bark). In CARBINE, quantities of harvested sawlogs and small roundwood are both calculated on an underbark basis because this approach is more appropriate for the methodology used in the model for allocation of harvested carbon to raw and ultimately primary wood products. These relationships also depend on tree species (or species group) and whether the stand has been thinned or left unthinned.

THE ESC KNOWLEDGE-BASED MODEL

CARBINE requires yield class as a key input parameter for determining stand productivity (see Table 4-1). To obtain a spatially explicit estimate of yield class for different tree species, it is proposed to develop relationships for predicting yield class from agroclimatic variables using the ESC expert system as a framework.

The Ecological Site Classification (ESC, Pyatt et al., 2001) model allows the classification of sites in terms of climatic and soil characteristics (Figure 4-4). One of the desired outcomes is to give forest managers information on the relative suitability of different tree species to particular sites. Work on ESC began in 1992. The project was conceived by Graham Pyatt following a study tour of the Biogeoclimatic Ecosystem Classification (BEC) system, used to classify the natural forest types of British Columbia. Similar approaches have been suggested for use in Britain (Anderson, 1950) and the methodology is used fairly widely across Europe and North America (Cajander, 1926; Krajina, 1969; Kuusipalo, 1985; Klinka et al., 1989; Cleland et al., 1993). The ESC suitability model has been developed from a multi-criteria analysis approach (Ray et al. 1996), to a method using fuzzy-set theory (Ray et al. 1998) described by Zadeh (1992).

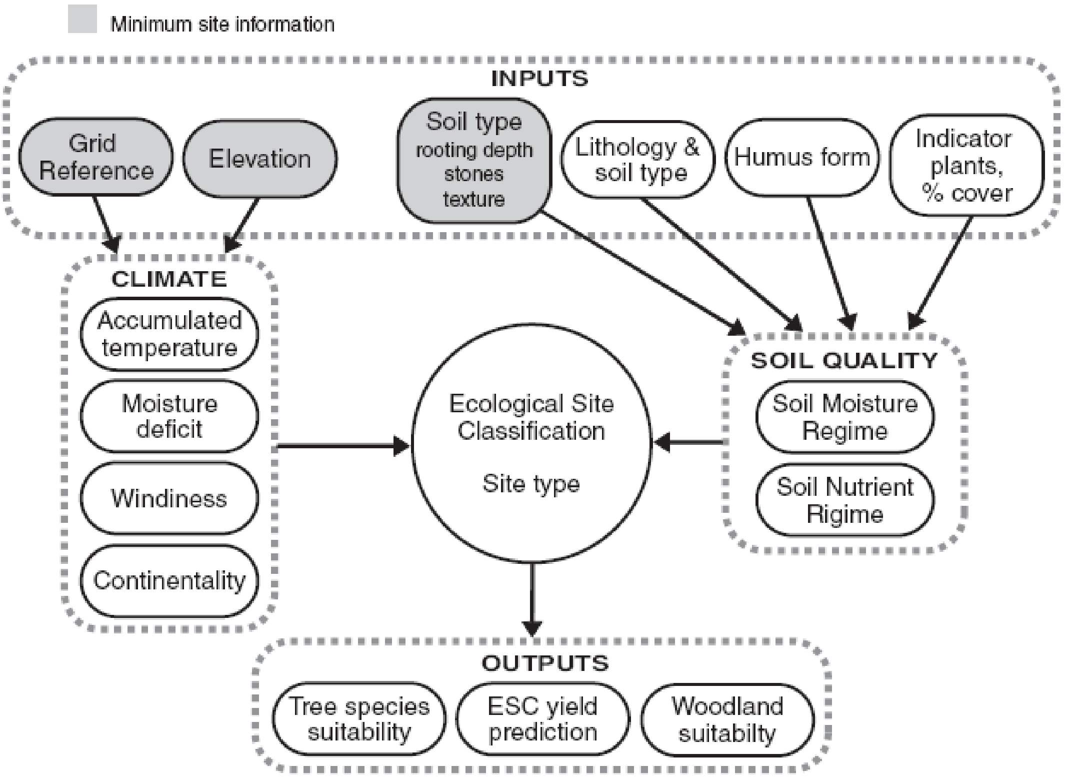


Figure 4-4 Schematic diagram of ESC model

The minimum site information required to be input for ESC is the grid reference, the elevation and the soil type. From these data the climatic factors (accumulated temperature - AT, moisture deficit - MD, windiness - DAMS and continentality) are calculated, but only approximate estimates of the soil quality (soil moisture regime - SMR, and soil nutrient regime - SNR) can be made. If more information is known about a site, e.g. rooting depth, soil texture and stoniness, a more precise estimate of the SMR can be made. If external estimates of accumulated temperature (AT) and moisture deficit (MD) are not available, ESC refers to internal estimates. The estimates of accumulated temperature were calculated for grid squares using the following equation (White et al., unpublished):

$$T_\alpha = \frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{M}\delta_{ij}D_j\left(t_{ij}-\alpha\right) \qquad \text{(Equation 4.4)}$$

where: T_α = accumulated temperature above 5.0°C,

N = number of years in period (index i),

M = number of months in year (index j),

D_j = number of days in month j (leap years accounted for),

t_{ij} = mean temperature (°C) for month j in year i,

δ_{ij} = 1 if $t_{ij} > 5.0$, zero otherwise,

α = temperature threshold (°C).

The estimates of moisture deficit were from the 188 grid squares each 40 x 40 km used by the Meteorological Office MORECS system. Values were provided for each year 1961-1990. The period mean value for each square was taken. A weather generator for future accumulated temperature and moisture deficit under UKCIP02 scenarios is available internally (see Broadmeadow et al., 2005 for an example). It would not be feasible to compute estimates of AT and MD based on UKCP09 during the timescale of this project.

ESC produces an output file (.csv or MS Excel) of the site information, calculated variables, and derived yield classes. Figure 4-5 shows an example of yield class predictions using ESC for stands of ash (*Fraxinus excelsior*) for Great Britain.

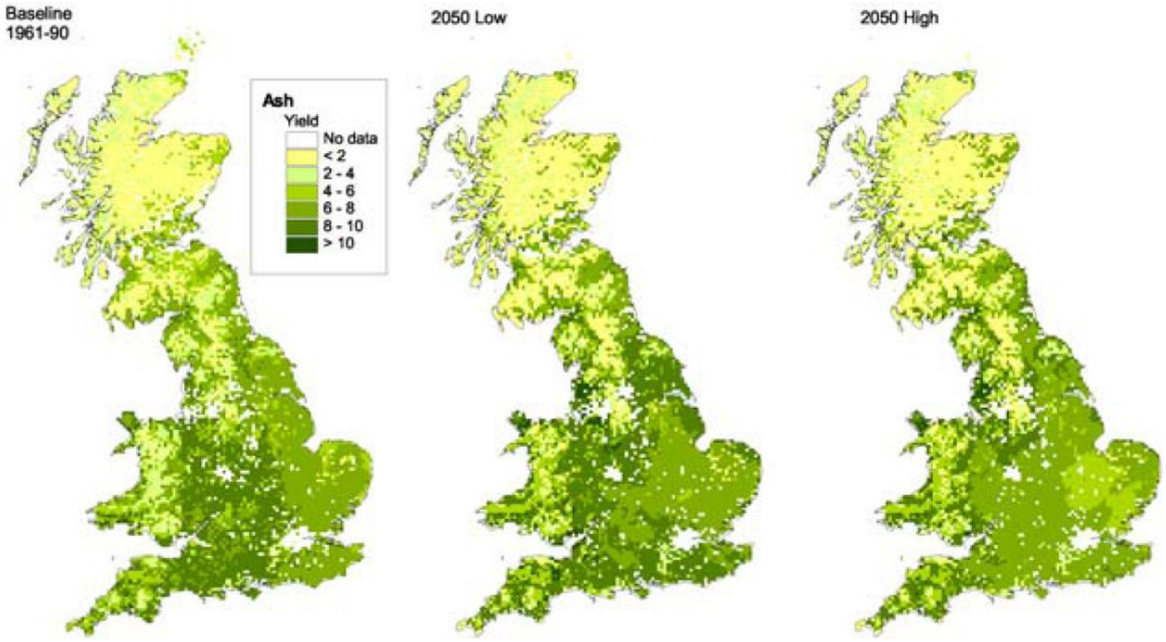


Figure 4-5 Example of ESC predictions of yield class for stands of ash (*Fraxinus excelsior*) under baseline climate change scenarios (see http://www.forestry.gov.uk/pdf/cchg_bihip_ash_beech.pdf/$FILE/cchg_bihip_ash_beech.pdf)

4.2.2 Description of the applied methodology

The development of the meta-model for estimating potential biomass production from SRF, HFSW and HFBW involves three main tasks:

- Development of spatially-explicit estimates of yield class for a range of tree species for use as input to the CARBINE model.
- Characterisation of other key input variables, including the extent, spatial disposition, composition and management of existing forest areas.
- Generation of bespoke output data sets of biomass potentials using the CARBINE

model.

With regard to the third task, a key decision to be made concerns whether outputs need to account for the strong time-dependence of biomass production in forest stands (as illustrated by the example in Figure 4.2), allowing for the age class structure of existing and newly-established forest stands, or whether outputs can be more simple, i.e. estimates of long-term average biomass production from forest stands. In the former case, it is not possible to express biomass potentials in the form of simple linear equations; instead it will be necessary to provide discontinuous estimates of biomass potential, in the form of spatially-referenced ‘lookup tables’. In the latter case, the possibility exists to construct a completely equation-based meta-model.

Spatially-explicit yield class estimates

It is proposed to adopt an incremental approach to the provision of spatially-explicit estimates of yield class for tree species relevant to UK conditions:

- Start by applying the yield class estimates already available in the ESC model
- Refine the existing yield class estimates in ESC using supplementary field data and expert knowledge
- Further improve the ESC yield class estimates by means of a ‘data fusion’ exercise, drawing on results from less extensive studies of relationships between yield class and site and climatic variables.

Such an approach should accelerate the development of a complete forestry component of the BVCM tool.

Existing ESC yield class estimates

The estimates of yield class currently available in ESC for selected tree species will be used initially in the construction of the forestry biomass meta-model(s). In the event that yield class estimates are not available for certain tree species (e.g. minor tree species) a ‘gap filling’ methodology will be developed by which estimates for the nearest available comparable tree species will be referred to. In this way a ‘first cut’ comprehensive set of yield class estimates covering the full range of tree species relevant to UK conditions can be provided within a short time scale.

Refined ESC yield class estimates

The initial set of yield class estimates available in ESC for a range of tree species will be verified by carrying out a “reality check” against expert knowledge of potential yield classes and datasets not referred to as part of the development of the existing ESC predictions. The main relevant supplementary datasets are the Forestry Commission subcompartment database (SCDB) and the permanent and temporary mensuration sample plot networks. This refinement stage will involve qualitative as much as quantitative analysis and any adjustments to ESC yield class estimates will involve largely graphical and manual techniques.

Further improved ESC yield class estimates

To the extent feasible within the project timescale, attempts will be made to further improve estimates of yield class available in ESC for various tree species through a true ‘meta-modelling' or 'data fusion' exercise in which the estimates of yield class available in ESC will be analysed in conjunction with supplementary, less extensive (but perhaps more locally applicable) estimates of yield class from a number of research studies carried out in regions of the UK (Allison et al., 1994; Macmillan and Towers, 1991; Macmillan et al., 1990; Matthews and Methley, 1996; Matthews et al., 1996; Tyler et al., 1995; 1996; Waring, 2000; White, 1982; Worrell and Malcom, 1990a; 1990b). An example of the types of results produced by these studies is shown in Figure 4-6 and Figure 4-7, which illustrate a relationship developed for predicting yield class in lowland England and Wales from accumulated temperature, moisture deficit and windiness (Matthews et al., 1996). A key principle that will be adopted in any such analysis will be to express any improved predictions of yield class primarily in terms of the principal variables referred to in the ESC model. Secondary site and climatic variables (e.g. oceanicity, windiness) will be referred to only if absolutely necessary, whilst options for predicting yield class without reference to such variables will also be provided. This approach has implications for the specification of input data as discussed in Section 4.2.4.

Depending on the state of development reached during the timescale of this project, the ESC climate change model may be used to adjust the yield classes applied to forest stands over time when making calculations for scenarios involving climate change.

$$SGYC = a_0 + a_1 N(AT56,MD) r^{WIND}$$

where

$$N(AT56,MD) = \exp\left[\frac{-1}{2(1-\rho^2)}(z_1^2 - 2\rho z_1 z_2 + z_2^2)\right]$$

$$z_2 = \frac{(MD - 97.77643)}{109.21281}$$

$$z_1 = \frac{(AT56 - 1920.019543)}{420.6191}$$

and

a_0 = 7.8962
a_1 = 20.45994
r = 0.93298

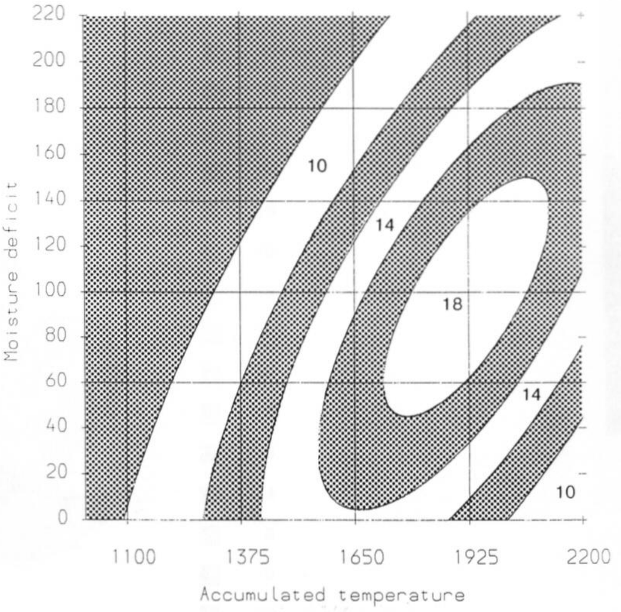


Figure 4-6 Description of model for predicting yield class of Douglas fir (Pseudotsuga menziesii) in lowland England and Wales from site factors of accumulated temperature, moisture deficit and windiness (from Matthews et al., 1996).

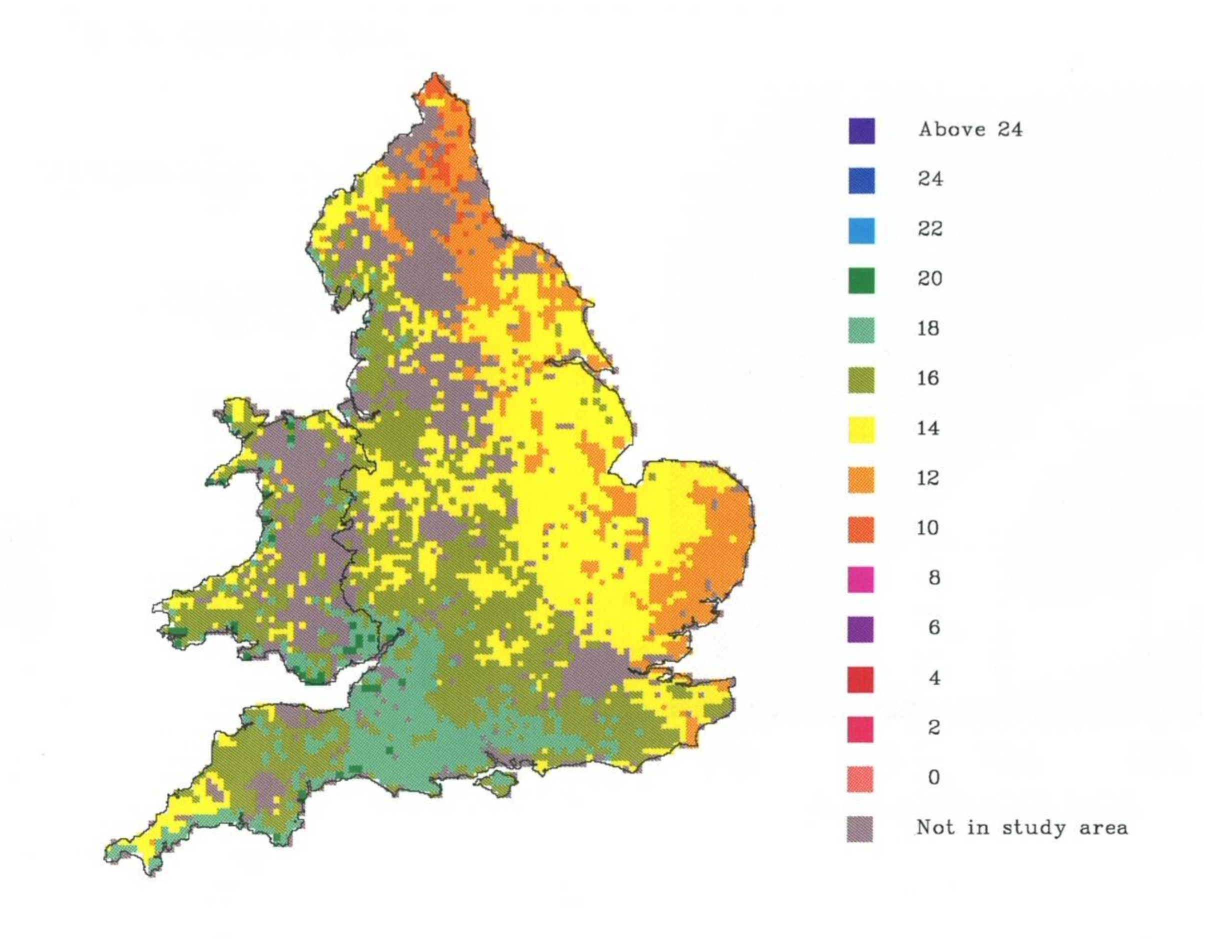


Figure 4-7 Map of yield class predicted for Douglas fir (Pseudotsuga menziesii) in lowland England and Wales from site factors of accumulated temperature, moisture deficit and windiness (from Matthews et al., 1996).

Other key input variables

Apart from the key input parameter of yield class for tree species, the CARBINE model requires information about a number of other variables as input data in order to calculate estimates of potential biomass production. Essentially, it is necessary to classify specified forest areas (expressed in hectares) in terms of:

- Tree species
- Year of planting
- Management type (unthinned, thinned, clearfelled, continuous cover)
- Rotation period in years (if managed according to a clearfell regime)

For newly created forest areas (i.e. arising from afforestation activities), these input parameters are entirely under user control and represent essential elements of the functionality of the BVCM tool. For existing forests, it is necessary to establish the proportions of forest area for which combinations of these parameters can be assumed to apply. As far as possible, the distribution of these parameters needs to be represented spatially. This is being achieved through the application of spatial data from the National Inventory of Woodland and Trees (Smith and Gilbert, 2003) and through analysis of detailed data on forest composition for public and private forest areas from national inventories (for Wales, England, Scotland and Northern Ireland) and the Forestry Commission SCDB (for England, Scotland and Wales).

National inventory data

The National Inventory of Woodland Tree survey (NIWT, see Smith and Gilbert, 2003) was carried out between 1994 and 2000. The area and composition of forest stands across the land area of Britain were characterised based for 100 x 100 km grid squares of the Ordnance Survey system. In order to achieve a finer resolution, further analysis and sub-sampling on the ground enabled each of the 100 km grid squares to be broken down into 25 tiles of 20 x 20 km resolution. All woodlands with an area greater than 2 ha were considered. Species composition in each 20 km square is represented in terms of the broad categories of ‘broadleaf’, ‘conifer’ or ‘mixed (broadleaf and conifer) woodland.

The 20 km x 20 km data set derived from the National Inventory represents the best spatially-explicit data set on the location and composition of existing forest areas available during the timescale of this project.

Detailed forest composition

An analysis is being undertaken on data on the species composition of forests and age classes of forest stands (equivalent to planting or restocking year) and management types being applied in Forestry Commission woodlands as represented in the SCDB. This analysis is being carried out separately for England, Wales and Scotland and a similar analysis will be carried out for forests in Northern Ireland, although without the detailed records from the SCDB. Table 4-2 shows how these data can be processed to obtain a breakdown of forest areas in terms of the key input parameters to CARBINE of tree species and management type (as defined in Table 4-1). Expert knowledge and information from the SCDB are used to assign rotations to stands according to tree species and yield class. Subsequent analysis involves allocating planting years to forest areas by tree species, yield class and rotation, through a complex reconciliation process against data on areas of new planting since 1920 and the age class distribution of forest reported as part of the NIWT. The end result of this detailed analysis is a breakdown of forest areas in England, Wales, Scotland and Northern Ireland in terms of combinations of tree species, yield class (from ESC), management type, rotation period (where relevant) and year of planting or restocking. These areas can be allocated on a pro-rata basis to the 20 km grid squares reported for the NIWT separately for conifer and broadleaf forests.

Species	Management type description			
	Clearfell, thinned	Clearfell, unthinned	Continuous cover	Not in production
Beech	1107.2	1976.4	1926.9	3190
Oak	11942.8	5487.1	2915.9	17746.2
Poplar	181	82	39.6	265.4
Nothofagus	15.3	2.5	26.1	10.8
Sycamore, Ash and Birch	11878.5	14723.4	3586	27162.9
Sitka spruce	43618.4	19722.7	7759.4	10214.5
Norway spruce	4823.9	2438.7	2669.4	1704.9
Corsican pine	985.3	391	1694.2	279.2
Scots pine	1142.8	1325.1	1388.1	666.8
Lodgepole pine	1174.8	3459.4	704.9	792
Douglas fir	5551.9	1089	2567.1	1607.2
Grand fir	484.3	123.6	199.8	142.1
Noble fir	359.6	216.2	162.6	166.6
Japanese/Hybrid larch	7689.7	4610.1	6103.4	3130.8
European larch	141.1	194.3	148.6	102.7
Western red cedar	255.4	310	186.9	103.1
Western hemlock	1217.4	1008.4	357.8	326.2

Table 4-2 Forest areas (ha) in Wales by tree species and applied management regime

Bespoke output data sets

The preparation of output data is likely to involve the repeated running of the CARBINE model (or the underpinning BSORT model) for a set of geographical grid squares and for a set of scenarios involving:

- Future management of existing forest areas
- Future programmes of new planting involving specified tree species
- Intended management of new forest areas (e.g. as SRF).

The number of potential combinations of these parameters is potentially very large, therefore it will be necessary to carefully scope and specify the scenarios of key relevance to the BVCM tool. In general, the complexity and strong time-dependence of the pattern of biomass production from forest stands may place significant constraints on the flexibility with which model outputs can be represented, hence limiting the functionality of the BVCM tool with regard to forestry systems. However, the extent to which these issues will be encountered depends strongly on the level of detail with which biomass production from forest areas needs to be represented in the BVCM tool.

If users of the BVCM are mainly interested in the long-term potential for biomass production, rather than the time-dependent profile with which biomass is likely to come ‘on stream’ under a certain scenario, then it may be possible to simplify the development of the forestry meta-model and even to express the outputs in terms of a relatively simple set of equations. To illustrate, Matthews et al. (2008) have demonstrated how it is possible to summarise the annualised production of biomass from forest stands over a ‘typical’ rotation period in terms of simple linear equations. Biomass yield tables were constructed, such as the example in Table 4-3, by applying the BSORT model (Matthews and Duckworth, 2005) to estimates of production from standard yield tables (Edwards and Christie, 1981). As shown in Table 4-3, results over typical rotations for forest stands of a given species and yield class were accumulated over time and then annualised to give estimates of the long term average level of biomass production for different tree components (e.g. stumps, sawlogs, roundwood etc.). These results were then subjected to an allocation procedure similar (but not identical) to that described in Figure 4-3 and then summed to obtain estimates of total annualised potential biomass production. The estimated biomass production for different tree species, yield classes and management regimes was then plotted against yield class to investigate whether a simple relationship could be established. Inspection of the results revealed that:

- Biomass production was strongly linearly correlated with yield class
- The linear relationship was very similar for many species, although distinct species groups could be identified.
- The relationship shifted depending on whether stands were thinned or not.

An example of the observed correlation between potential biomass production and yield class is illustrated in Figure 4-8.

Age	**Roots**	**Stump**	**Sawlog**	**Roundwood**	**Stem Tips**	**Branches**	**Foliage**
31	6.3852	0.5154	0.0000	9.1282	3.6049	4.7694	2.1983
36	5.5088	0.4355	0.0054	10.0862	2.1452	3.8596	1.7730
41	4.3187	0.3262	1.0310	9.79.5	1.0806	2.9167	1.3328
46	3.7945	0.2828	2.5961	8.2181	0.9293	2.5327	1.1491
51	3.5199	0.2575	4.3343	6.5380	0.7891	2.3620	1.0621
56	3.3441	0.2394	6.1860	4.9315	0.5159	2.2799	1.0141
61	35.8851	2.4970	83.1315	26.3761	3.2240	25.9701	11.1475
Total	62.7563	4.5538	97.2843	75.0686	12.289	44.6904	19.6769
[1]Annualised	0.9961	0.0723	1.5442	1.1916	0.1951	0.7094	0.3123

[1] Calculated from total biomass by dividing by 63 years (61 year rotation plus 2 fallow years).

Table 4-3 Example output from BSORT model for Scots pine, yield class 8. Biomasses are given at each thinning age and for the final felling in odt ha^{-1}

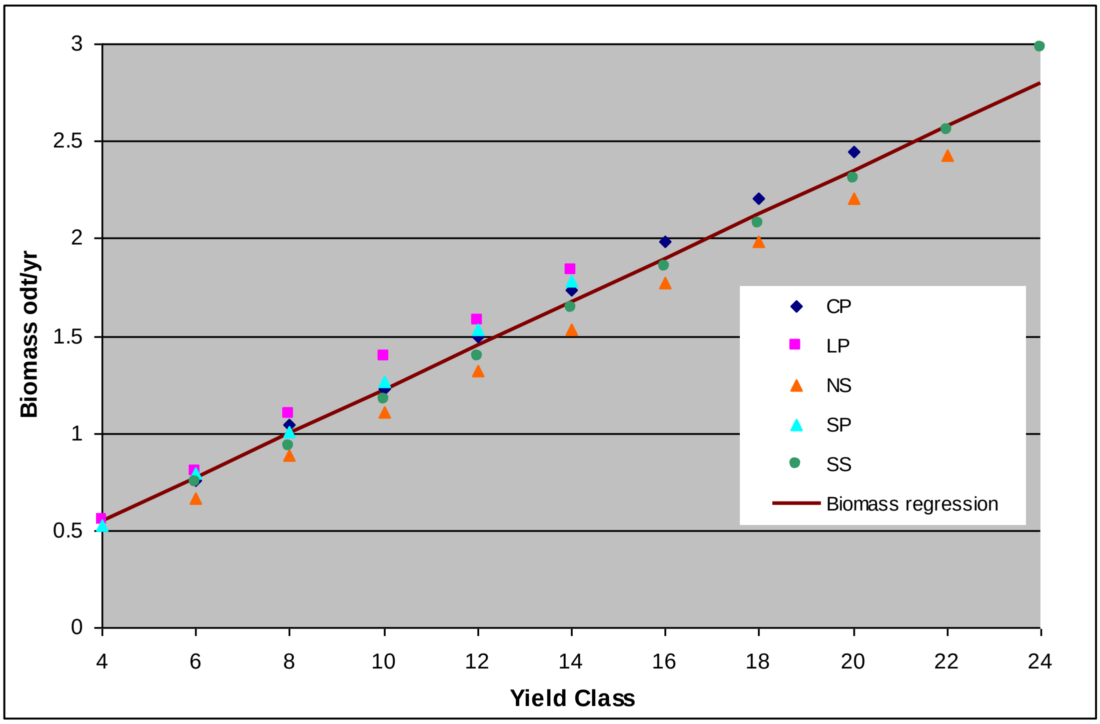


Figure 4-8 Relationship between estimated biomass production and yield class. An example based on results for spruces and pines is shown

From the above illustration, it follows that estimates of potential biomass production from forest areas can be expressed in relatively simple terms, if only relatively low resolution is required by users of the BVCM tool (particularly in terms of timing of production events). However, as discussed above and in Sections 4.2.3 and 4.2.5, higher resolution estimates will involve significant discontinuities over time and with respect to response variables, which may have implications for functionality.

4.2.3 Functionality

The existing functionality of the CARBINE and ESC models has been described implicitly in sections 4.2.1 and 4.2.2. The extent to which new functionality will be developed for this project will depend upon the level of complexity and detail with which biomass estimates for forestry systems need to be represented in the BVCM tool. As explained at the conclusion of section 4.2.2, if a relatively simplistic, time average representation of forest biomass production is all that is required, the possibility exists to calibrate sets of simple equations in terms of tree species (or species groups) yield class and management type which may be integrated directly into the BVCM tool to provide outputs that are fully dynamic with respect to climate and management scenarios, as originally envisioned. However, it may be equally important to understand the time-dependency of forest biomass production under a given scenario, e.g. due to the delays between planting of new forest areas and the first production event or the uneven age class structure of existing forests. If it is necessary to represent this complexity and detail in model outputs, then it is unlikely that results can be summarised as simple sets of continuous relationships. Rather, results will take the form of discontinuous levels of biomass production over time and across different scenarios which can only be represented as discrete tables of spatially-referenced 'lookup values'. Within the project scope, it will only be possible to construct a finite and limited selection of outputs for a set of specified cases, which would constitute the available functionality of the BVCM tool with regard to forestry systems. Due to the highly discontinuous nature of these individual ‘spot’ results, it will not be possible to consider scenarios not directly represented within the set of specified cases, e.g. interpolation between results for different cases would be inadvisable. In any event, some new functionality will be created within this project through the creation of improved linkages between the ESC and CARBINE models, and the provision of bespoke model outputs as required for the BVCM tool.

4.2.4 Input data requirements

The input data requirements for CARBINE have been discussed as part of the methodology description in Section 4.2.2. The ESC model will provide the key input parameters relevant to determining the yield classes of forest stands.

In turn, ESC models yield class with respect to a number of site and climatic variables. The essential variables referred to in the ESC framework are

- Accumulated temperature
- Moisture deficit
- Elevation
- Soil type.

Some of these data may be available as intrinsic estimates within the ESC model; others (or possibly all) may need to be provided externally. In addition to estimation of yield class for input to CARBINE, the BVCM tool may need to provide other input data relevant to scenarios representing different forest management decisions, e.g.

- Species mix (of new forests)
- Changes to species mix over time in existing forests
- Mix of management types practised in forest stands (clearfell, continuous cover, thinned or unthinned, rotation periods where relevant).

The extent to which these inputs will need to be specified will be strongly dependant on the level of functionality implemented for forestry systems in the BVCM tool (see Section 4.2.3).

4.2.5 Model output

In principle the CARBINE model can be configured to provide outputs in any format although simple formats (ASCII, .csv) are the easiest to implement. Additionally, outputs of both CARBINE and ESC have the potential to be produced at any spatial resolution, the limiting factors being the resolution of the inputs. However, for the existing forest resource, data will be produced at a 20km x 20 km scale, as this is the scale of the data of the National Forest Inventory. The highest resolution for the future potential production outputs is that of the soil dataset (the most coarse resolution agroclimatic input data) at 1km x 1km.

Estimates from forest biomass production comprise the principal output from CARBINE (or any derived meta-model) and these can be expressed in any of the obvious possible units e.g. oven dry metric tonnes for a period or per year, 'loose' cubic metres of material. Only limited information is available on the moisture content of wood (Matthews and Mackie,

2006) but this may be referred to as the best available data for estimating production in terms of fresh tonnes of material or for providing estimates of moisture content in conjunction with dry tonnages. Outputs of biomass production estimates can also be generated for a range of tree components, e.g. stemwood, roots, stumps and branches. As discussed in section 4.2.2, biomass estimates can be provided for these ‘raw’ products or for ‘primary’ products such as sawlogs or roundwood. The precise requirements for such output results needs to be confirmed before work on the forestry meta-model starts.

Unless agreed otherwise, estimates of biomass production for all tree components will not include any ‘mark-downs’ to take account of existing consumption of woody material for competing end uses (e.g. for paper, board products or sawn timber). However, the great strategic and economic importance of the provision of woody biomass to these end uses needs to be recognised at some stage within the BVCM methodology.

Output estimates of woody biomass production will need to be time-dependent, if only to allow for possible changes in forest productivity in response to climate change or other environmental factors. Clearly such an approach to presentation of results will also be essential if the time-dependent nature of production events in forest stands needs to be represented (see sections 4.2.2 and 4.2.3). The CARBINE model can easily provide such estimates at decadal time step or for any annual or greater reporting period. The important implications of the level of detail required in biomass output results for methodology development and meta-model functionality, particularly representation of time-dependent fluctuations in supply, has already been highlighted in sections 4.2.2 and 4.2.3.

Section B: Cost Calculation

5 Cost of First Generation, Second Generation Crops and Forest Based Wood Resources

5.1 Introduction

The extent to which first and second generation biomass and forest based wood will be produced for energy production going forward will in the main depend on the cost of producing these bioenergy resources as well as the relative economics of producing these resources vis-à-vis other competing uses of land. This Section details our approach to estimating the regional cost of production and opportunity cost of a number of first and second generation biomass and forest based wood resources within the UK.

5.2 Review of existing studies and cost approaches

Although considerable research has already been carried out on the spatially explicit supply of first and second generation biomass and forest based wood resources within the UK (e.g. Richter and Semenov, 2005; Richter et al., 2006; Ferrara et al., 2010; Aylott et al., 2008; Richter et al., 2008), spatially explicit modelling of the cost of producing such resources is generally absent or only carried out at a high level. The cost of producing first and second generation biomass and forest based wood resources within the UK has been analysed previously in some national (e.g. Bell et al., 2007) and European-wide studies (e.g. VIEWLS, 2005; Nikolaou, 2003), but such studies are relatively limited in their geographical breakdown, their coverage of different biomass resources and their approach; most studies assessing the cost of bioenergy resources in the UK tend to focus on estimating the cost of production, with few assessing the opportunity cost of production. Furthermore, it is generally difficult to compare the results between studies due to the use of different cost methods, assumptions and delimitations (Ericsson et al., 2009), which makes the possibility of disaggregation to the regional or spatially explicit level difficult.

This research builds on existing data sources and cost methodologies to produce a comprehensive spatially explicit estimate of the per unit cost of producing, and opportunity cost of, a number of first generation bioenergy crops (wheat, sugar beet and oilseed rape) and their by-products (straw), second generation biomass (Miscanthus, SRC willow) and forest based wood (SRF) resources using spatially explicit yield data.

5.3 Production cost

This section describes the method used and general considerations made when calculating the costs associated with the production of bioenergy resources.

5.3.1 Input data requirements

For each bioenergy resource (with the exception of straw), we will distinguish between four main production cost categories (to the extent that it is possible to disaggregate the available cost data to the specific regional level), namely:

- pre-planting costs
- establishment costs
- operational costs

- risk margin cost

In the case of straw, we will not consider pre-planting costs or establishment costs as it is a by-product of wheat production.

The costs associated with pre-planting, crop establishment and field operations (including basic on-farm processing costs associated with the harvesting operation) are tangible in nature and relate to the actual cost of inputs used in the production of each bioenergy resource, expressed on a per hectare of land basis. In contrast, the cost associated with risk is intangible and represents a notional economic value to reflect the necessary income required to compensate farmers for the changed risk associated with the production of the different bioenergy resources.

Typical production costs associated with pre-planting, crop establishment and field operations for three example bioenergy resources are set out in Figure 5-1. It should be noted that such a detailed breakdown at a regional level is unlikely to be achievable given data limitations and the need to disaggregate the data to the required geographical level.

Wheat	Miscanthus	SRC
Operational costs	**Pre-planting costs**	**Pre-planting costs**
Seeds	Vegetation removal/cutting	Vegetation removal/cutting
Fertilisers	Ploughing	Ploughing
Herbicides	Sub-soiling	Sub-soiling
Fungicides	Cost of rhizomes	Cost of cuttings
Other sprays	Herbicide farmer application cost	Farmer cost per herbicide application
Disc harrowing	Herbicide cost	Herbicide cost
Power harrowing	Total cost of herbicide	Total cost of herbicide
Drilling	Fertiliser costs	**Establishment costs**
Rolling	**Establishment costs**	Power harrowing
Combine harvest	Power harrowing	Planting contractor
Baling	Planting contractor	Farmer cost per herbicide application
Haulage	Farmer cost per herbicide application	Herbicide cost
Drying costs	Herbicde cost	Total cost of herbicides
Miscellaneous	Total cost of herbicides	Farmer cost per fertiliser application
	Topping	Fertiliser cost
	Fencing	Total cost of fertiliser
	Operational Costs	Gapping up
	Mowing	Fencing
	Baling costs	**Operational Costs**
	Carting	Harvesting/carting
	Haulage	Haulage
	Fertiliser application	Fertiliser application
	Fertilisers	Fertilisers
	Total cost of fertiliser	Total cost of fertiliser
	Drying costs	Drying costs
	Stock removal	Stock removal
	Miscellaneous	Miscellaneous

Figure 5-1 Typical resource production cost categories

The production costs associated with pre-planting, crop establishment and field operations will be sourced from a combination of secondary data sources, including published farm survey data of actual input use and costs (including regional Farm Business Survey[2] data,

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[2] Under Council Regulation 79/65/EEC (as amended), all EU Member States have to collect farm level financial and economic data for the purpose of monitoring and formulating European agricultural policy. In the UK, regional annual surveys of farm businesses are commissioned by the government, under which a range of management accounting information on all aspects of farmer's and grower's businesses is collected. The survey uses a sample of farms that is representative of the national population of farms in terms of farm type, farm size and regional location. Primarily, this survey data is used to provide information on the financial position and physical and economic performance of farm businesses regionally throughout the UK (with England broken down into between 3 and 7 sub-regions (depending on data requirements) and Scotland broken down into between 1 and 4 sub-regions (depending on data requirements), and Northern Ireland and Wales (both treated as a single region), to inform policy decisions on matters affecting farm businesses and to enable analysis of impacts of policy options.

Survey of Fertiliser Practice[3] data and Survey of Pesticide Use[4] data) as well as typical crop and bioenergy specific (regional) production cost data published by the industry and various academic and research institutions.

In addition, the Defra Fertiliser Manual (Defra 2010) will be used to disaggregate fertiliser costs to the appropriate geographical level. To estimate the cost of nitrogen used for the production of each bioenergy crop, spatially explicit data on soil type and rainfall will be used (consistent with that used in the GHG Emission Model as discussed in Section C) as well as data on the most likely crop rotation within the geographic area. Typical regional crop rotations will be identified based on cropping statistics from the Defra Agricultural Survey data[5]. For phosphorus and potassium, the cost associated with producing each bioenergy resource will be based on spatially explicit data on yields (consistent with that used in the GHG Emission Model as discussed in Section C).

Production cost extrapolations will in part be based on long term global oil price projections produced by organisations such as the US Energy Information Administration, or any other provided/suggested by the ETI. These extrapolated production cost assumptions will be validated in the context of the UK based on expert opinion

Estimating the risk margin cost is subjective and depends on the degree of risk aversion of the individual farmers and the perceived risk of producing each bioenergy resource. In general, farmers assign a higher cost of risk to less developed and perennial bioenergy crops than they do to the more traditional annual crops. This is due to their more limited knowledge and experience in producing such crops as well as the longer term nature of perennial crops production (Ericsson et al., 2007). Since the empirical basis for quantifying the risk margin cost of bioenergy resource production is rather weak and not comprehensive (Ericsson et al., 2009), estimates will be based on those used in other studies (e.g. Rosenqvist and Nilsson, 2006) and validated in the context of the UK based on expert opinion.

It should be noted that the cost of land is not taken into consideration in the production cost calculation for each bioenergy resources as this cost is the same irrespective of what crop is produced and land is the limiting factor in the production of additional bioenergy resources. However, the impact on land values of producing perennial second generation biomass and forest based wood resources that have longer production cycles, compared to annual first generation biomass crops, will be considered as part of the assessment of opportunity costs in Chapter 5.4.

5.3.2 Description of the applied methodology

To produce consistent and comparable regionally explicit production cost estimates for the

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[3] The Survey of Fertiliser Practice is the primary source of data on organic and inorganic fertiliser use in Great Britain. The main purpose of the survey is to estimate average application rates of nitrogen, phosphate and potash used for agricultural crops and grassland. The results from the Survey are used by the British fertiliser industry, by Government and by the wider agricultural community. Similar survey data is available for Northern Ireland.

[4] The Survey of Pesticide Use is the primary source of all aspects of pesticide usage on individual crops grown in Great Britain. The results from the Survey are used by the British pesticide industry, by Government and by the wider agricultural community. Similar survey data is available for Northern Ireland.

[5] The Agricultural Survey is the primary source of data on farm size, cropping, stocking and employment in the Great Britain. The survey is undertaken from the population of agricultural holdings. The results from the Survey are used by the industry, by Government and by the wider agricultural community. Similar survey data is available for Northern Ireland.

different bioenergy crops over time, a five stage methodology will be employed (Figure 5-2).

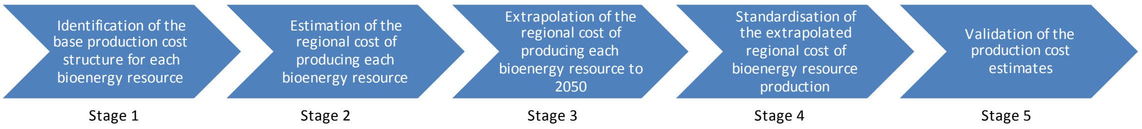

Figure 5-2 Five stage production cost estimation methodology

Identification of the base production cost structure for each bioenergy resource

The base production cost structure, detailing the cost components to be included, for each bioenergy crop will be dependent on the management regime assumption used to produce the resource models and yield estimates (as discussed in Section A). This will ensure that not only will the production cost estimates be consistent and comparable between regions, but also ensure consistency within all the modelling work within WP1.

Estimation of the current regional cost of producing each bioenergy resource

Having established the base production cost structure, current production costs will be estimated for each bioenergy crop within the appropriate region. In all cases, 'typical' (i.e. excluding the large cost swings that we have experienced in recent years) average production cost data for the range of bioenergy crops will be computed based on available time series of production cost data.

The input data required to calculate the cost of producing first and second generation biomass and forest based wood resources, and the secondary data sources, were discussed in Chapter 5.3.1. While extensive and comprehensive in nature, one of the general limitations of the Farm Business Survey, amongst others, is that the production cost data is typically collected on a 'per farm hectare basis' or a 'per broad enterprise (such as 'mainly cereals' farms or 'mixed cropping' farms) hectare basis' rather than on a 'per crop hectare basis'. This means that although regional production cost data is available for typical farms in the region, it is not necessarily available by individual crop. Accordingly, assumptions need to be made as to the typical cropping land use for farms or enterprises in each region to disaggregate the cost data from a 'per farm/enterprise hectare basis' to a 'per crop hectare basis'. This will be undertaken based on typical regional cropping land use data which is collected from another regional survey, the Agricultural Survey, commissioned by the government and administered in June and December each year.

The resulting regional estimates will be validated against regional crop and bioenergy specific production use and cost data, published by the government, industry and various academic and research institutions, where available for the individual bioenergy resources and regions. In general, while such data is more widely available for first generation bioenergy crops (wheat, sugar beet and oilseed rape) and their by-products (straw), data is less widely available for second generation biomass (Miscanthus, SRC willow) and forest based wood (SRF) resources.

Extrapolation of the regional cost of producing each bioenergy resource to 2050

The estimated regional cost of producing each bioenergy crop will be extrapolated forward to estimate the cost of producing each resource in each decade to 2050. The production cost extrapolations will be based on historic trends and expectations on the likely future evolution in costs. Such assumptions will be linked to the typical drivers of agricultural input costs including, inter alia, the oil price; long term global oil price projections from the US Energy Information Administration and International Energy Agency will be used in association with guidance from the ETI.

Standardisation of the extrapolated regional cost of bioenergy resource production

When comparing the production costs of bioenergy resources, the process is complicated by the perennial nature of some second generation biomass and forest based wood resources. Compared to annual crops, there are significant cash flow and interest charge implications when producing perennial bioenergy resources as the production cycle takes place over more than one year with payments and disbursements unevenly distributed over this period. To account for this, the production cost data for each bioenergy crop will be annualised using discounted cash flow analysis to allow the calculation of a discounted cash flow for each decade to 2050.

Validation of the production cost estimates

The production cost data used in this study is based on secondary data sources, from industry surveys carried out for Defra, academic sources or respected industry data (as discussed above). The applicability of the production cost data will be validated through discussion with industry stakeholders. A four stage iterative validation process is proposed and presented in Figure 5-3.

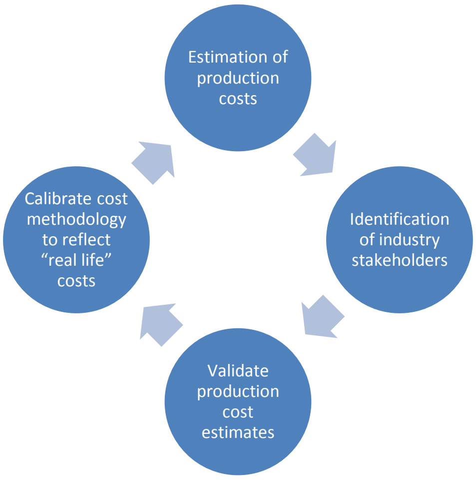

Figure 5-3 Iterative four stage validation process

Firstly, industry stakeholders have been identified to whom the methodology and production cost data will be presented, and feedback received will be used to assess whether the industry agree that the production cost estimates are likely to reflect the true cost of production in general for the industry. Any significant deviations will be used to recalibrate our cost methodology to ensure that the final production cost dataset reflects “real life” costs.

Three sets of stakeholders have been proposed for use in this validation process:

1. **University/government regional Rural Business Research Units**. These units conduct annual farm business surveys on behalf of the Department for Environment, Food and Rural Affairs in England, the Welsh Assembly, the Scottish Executive and the Department for Agriculture and Rural Development in Northern Ireland. They are responsible for providing information on the physical and economic performance of farm businesses throughout the UK, to inform policy decisions on matters affecting the rural economy and as such have a significant knowledge of production costs within their UK region.

   This knowledge will be consulted, during stage II of the production cost estimation methodology, in estimating the regional cost of producing each biomass resource.

   Regional rural business research units are located: in England at the University of Cambridge, University of Nottingham, University of Newcastle upon Tyne, Askham Bryan College, University of Reading and University of Exeter; in Wales at Aberystwyth University; in Scotland at the Scottish Agricultural Colleges; and in Northern Ireland at the Department of Agriculture and Rural Development. The rural business research consortium have already been contacted as part of the initial cost data collection process and further contact will be made during the cost estimation process to seek advice in validation.

2. **Industry bodies**. Within the UK, there are a number of bodies that represent the interests of the rural business sector. They are responsible for representing the interests of and/or providing services to their members and/or the industry. As such they have a significant knowledge of what is happening at the farm level.

   This knowledge will be consulted, during stages III and V of the production cost estimation methodology, in validating the assumptions used in the extrapolation of the regional cost estimates (stage III) as well as in the validation of the regional production cost estimates (stage V).

   The core industry bodies that have been contacted to help steer this research will include the National Farmers Union (NFU), the Country Land and Business Association (CLA), the Home Grown Cereals Association (HGCA) and the National Centre for Biorenewable Energy, Fuels and Materials (NNFCC). Within these industry bodies, key individuals[6] have been identified to ensure representation of each of the different biomass resource types (agricultural crops, second generation crops and forestry).

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[6] Clare Rowntree (Economist), Ruth Digby (Non-Food Crops Adviser), Mike Seville (Forestry and Woodlands Adviser) and Charlotte Garbutt (Cereals Market Intelligence).

In addition, other industry bodies will be kept in contact and be given the opportunity to validate and comment on the production cost estimates and assumptions used to generate them. These other industry bodies will include the: NFU Cymru, NFU Scotland, Ulster Farmers Union, Scottish Landowners Federation (SLF) and Farm Tenants' Association. At this stage, these organisations have been contacted and made aware of the research.

3. **Farmers**. In association with the aforementioned core industry bodies, representative or typical farmers in the UK (a small number, with sufficient geographic distribution and type/size of farms representation) will be consulted during stages III and V of the production cost estimation methodology, in validating the assumptions used in the extrapolation of the regional cost estimates (stage III) as well as in the validation of the regional production cost estimates (stage V).

   Given that the delayed start of this research has fallen in the busiest time of the year for farmers, i.e. during the harvest and autumn cultivation period, it has not been possible *a priori* to elicit support in advance. However, as soon as the production cost estimates and assumptions have been agreed and ready for validation, representative or typical farmers will be sought and consulted.

Figure 5-4 summarises how the validation process operates within the five stage production cost estimation methodology. Stakeholder consultation is already underway as part of the methodological stage II. Stakeholders will be consulted as part of methodological stages III and V as soon as the production cost data and assumptions are ready (and only after the spatially explicit yield data has been generated) using the most appropriate means depending on timing/availability.

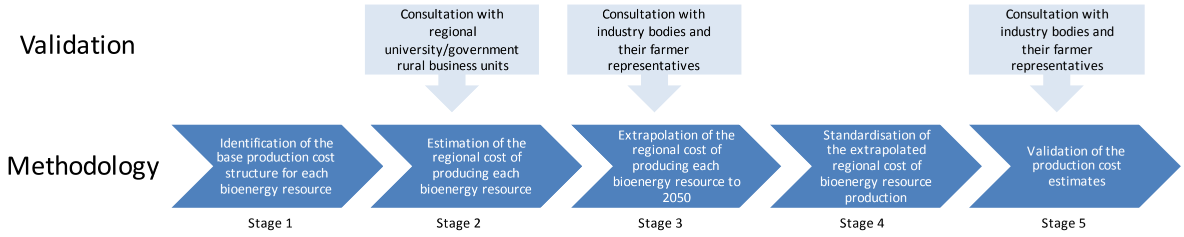


Figure 5-4 Five stage production cost estimation methodology and stages of validation.

5.3.3 Functionality

The proposed production cost calculations will feature the added functionality, when compared to existing estimates of production costs, of being spatially explicit for first generation resources. Production cost calculations for Miscanthus, SRC Willow and forestry will also be spatially explicit to the extent that existing data is available and allows.

The cost calculations will be developed in MS Excel. Spatially explicit inputs will be based on secondary data from a combination of published farm survey data of actual input use and costs, and crop and bioenergy specific production cost data published by the industry and various academic and research institutions (as discussed in Section 5.3.1 and 5.3.2). Outputs will be Excel datasets, available for further GIS visualisation and manipulation as described in Section 5.3.4.

5.3.4 Model output

The key output of the production cost modelling, which will feed into WP2, will be:

- Total production cost of each biomass resource, in each decade to 2050, in each UK region
- Total establishment cost of each biomass resource, in each decade to 2050, in each UK region

Model output will be included in the GIS for creation of maps.

5.4 Opportunity cost

This section describes the method used and general considerations made when calculating the opportunity cost associated with the production of bioenergy resources.

5.4.1 Input data requirements

The cost data associated with the cost of producing competing agricultural crops will be sourced from the combination of secondary data sources, including published farm survey data of actual input use and costs as well as typical crop specific (regional) production cost data published by the industry and various academic and research institutions as discussed in Section 5.3.1. Production cost extrapolations will again in part be based on long term global oil price projections produced by organisations such as the US Energy Information Administration and International Energy Agency.

Future bioenergy crop yields will be sourced from the resource models and yield estimates (as discussed in Section A). Crop and by-product price projections will be based in part on medium term global agricultural commodity price forecasts produced by organisations such as the United Nations Food and Agricultural Organisation and the US Food and Agricultural Policy Research Institute. For second generation crops, guidance will be sought from the NNFCC in determining price projections to 2050.

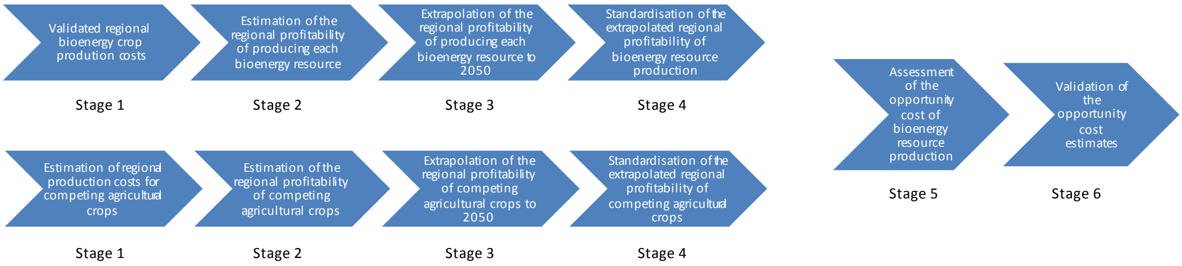
The current value of agricultural subsidies will be sourced from Defra data and assumptions on the value of direct subsidies to 2050 will be agreed in association with the NFU and CLA.

5.4.2 Description of the applied methodology

The availability of land as a production resource is a limiting factor in the production of agricultural and forestry crops for bioenergy, food or other uses. Therefore, land used to produce bioenergy crops has an opportunity cost. A farmer’s decision to produce a crop for bioenergy production will thus not only depend on the cost of producing that crop (including its risk margin premium), but it will also depend on its overall profitability vis-à-vis other crops for bioenergy production as well as for food and other non-food uses.

Farmers will therefore make rational planting decisions by choosing the crop and end-use (given that crops can have competing uses for both food and non-food uses) that maximise profitability.

To produce consistent and comparable regionally explicit opportunity cost estimates for the different bioenergy crops in different regions of the UK over time, a six stage methodology will be employed (Figure 5-5) which builds on the calculated production cost data.



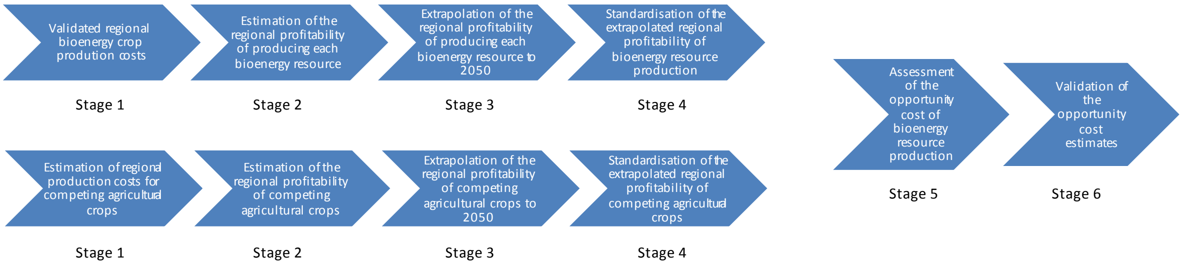


Figure 5-5 Six stage opportunity cost estimation methodology

Regional bioenergy and agricultural crop production costs

Given that a farmer's decision to produce a crop for bioenergy production depends on its overall profitability *vis-à-vis* other crops for bioenergy production as well as for food and other non-food uses, the production costs of competing agricultural crops will first need to be estimated. The same five stage production cost methodology, input data and data sources as that outlined in Sections 5.3.1 and 5.3.2 will be used to estimate these costs. The choice of competing agricultural crops will be those typically produced within each region as part of a farmer's normal crop rotation[7]. This will be undertaken based on typical regional cropping land use data which is collected from the Agricultural Survey, commissioned by the government and administered in June and December each year.

Estimation of the current regional profitability of bioenergy and agricultural crops

Having estimated regional bioenergy and agricultural crop production costs, regional profitability of the range of bioenergy and agricultural crop will be estimated whereby

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[7] Crop rotation is the practice of growing a series of dissimilar types of crops in the same area in sequential seasons for various benefits such as to avoid a decrease in soil fertility (as growing the same crop in the same place for many years in a row disproportionately depletes the soil of certain nutrients) and the build up of pathogens and pests (that often occurs when one species is continuously cropped).

profitably will be determined by:

[crop (and by-product) yield x market prices (values) + subsidies] – production costs

where: production costs include: pre-planting costs, establishment costs and operational costs.

The input data required to calculate production costs and the data sources were discussed in Section 5.3.1. The yield, price and subsidy data and sources were discussed in Section 5.4.1. In all cases, 'typical' (i.e. excluding the large cost swings that we have experienced in recent years) average yield, price and subsidy data for the range of bioenergy and agricultural crops will be computed based on available time series data.

The resulting regional profitability estimates will be validated against regional crop and bioenergy specific gross and net margin data, published by the government, industry and various academic and research institutions, where available for the individual bioenergy resources and regions. While such data is generally more widely available for first generation agricultural and bioenergy crops and their by-products, data is less widely available for second generation biomass and forest based wood resources.

Extrapolation of the regional profitability of bioenergy and agricultural crops to 2050

The estimated regional profitability of producing each competing agricultural and bioenergy crop will be extrapolated forward to estimate the profitability of producing each crop in each decade to 2050. Yield, price and subsidy data will be extrapolated based on historic trends and expectations of their likely future evolution. Specifically, future bioenergy crop yields will be sourced from the resource models and yield estimates (as discussed in Section A); those for the competing agricultural crops will be based on historic trends as well as the first generation yield estimates produced for wheat, oilseed rape and sugar beet. Future crop and by-product price projections will in part be based on medium term international forecasts available from forecasting organisations such as the United Nations Food and Agricultural Organisation and the US Food and Agricultural Policy Research Institute.

Standardisation of the extrapolated regional profitability of bioenergy and agricultural crops

To account for the perennial nature of some second generation biomass and forest based wood resources, the profitability data for each bioenergy and agricultural crop will be annualised using discounted cash flow analysis.

Assessment of the opportunity cost of bioenergy resource production

Any assessment of the opportunity cost of alternative production choices needs to recognise the importance of 'crop rotational' constraints in determining the optimum crop production choice over the (crop rotation) period. Our assessment of the profitability of crop production for bioenergy and the opportunity cost of alternative production choices will therefore also consider the 'per farm/enterprise hectare basis' rather than solely the 'per crop hectare basis', to capture the dynamics of crop rotation. Accordingly, assumptions on the typical cropping land use for farms or enterprises in each region (based on data contained in the regional land use surveys of agricultural and horticultural holdings commissioned by the government) will be used to aggregate the individual production cost data from a 'per crop hectare basis' to 'per farm/enterprise hectare basis'.

In the assessment of the opportunity cost of alternative production choices, we will consider how different business models may affect the opportunity cost of production. This assessment will be made based on discussions with industry stakeholders and an analysis of available datasets, and where identifiable differences over the long-term are deemed to exist the production/opportunity cost analysis will be modified to reflect these.

In addition, the impact on land values of producing perennial second generation biomass and forest based wood resources that have longer production cycles, compared to annual first generation biomass crops, will be considered as part of this assessment of opportunity costs. The opportunity cost of such increases in land values will be calculated based on industry standards (e.g. Nix, 2010).

Validation of the opportunity cost estimates

The opportunity cost data used in this study is based on secondary data sources, from industry surveys carried out for Defra, academic sources or respected industry data (as discussed above). The applicability of the opportunity cost data will be validated through discussion with industry stakeholders. The same iterative four stage validation process as that presented in Figure 5-3 above will be undertaken.

Firstly, industry stakeholders have been identified to whom the methodology and opportunity cost data will be presented, and feedback received will be used to assess whether the industry agree that the opportunity cost estimates are likely to reflect the true opportunity cost of production in general for the industry. Any significant deviations will be used to recalibrate our opportunity cost methodology to ensure that the final opportunity cost dataset reflects “real life” costs.

The same three sets of stakeholder groups will be used in the validation of opportunity costs as were previously discussed in the production cost validation process, namely:

1. University/government regional Rural Business Research Units.
2. Industry bodies
3. Farmers.

Figure 5-6 summarises how the validation process operates within the six stage opportunity cost estimation methodology. Stakeholder consultation is already underway as part of the methodological stages I and II. Stakeholders will be consulted as part of methodological stages III and VI as soon as the opportunity cost data and assumptions are ready (and only after the spatially explicit yield data has been generated) using the most appropriate means depending on timing/availability.

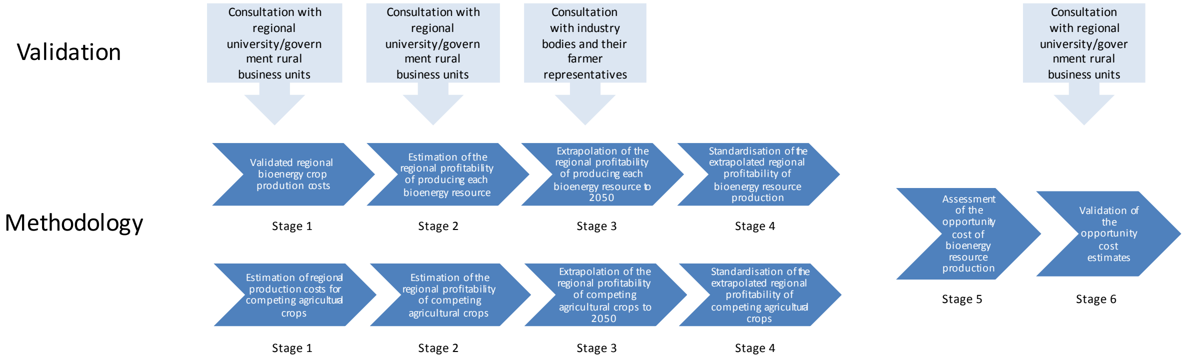

Figure 5-6 Six stage opportunity cost estimation methodology and stages of validation

5.4.3 Functionality

The proposed opportunity cost calculations will feature the added functionality, when compared to existing limited estimates of the opportunity cost of bioenergy resource production, of being spatially explicit.

These cost calculations will be developed in MS Excel. Spatially explicit inputs will be based on secondary data from a combination of published farm survey data of actual revenue and costs, and crop and bioenergy specific profitability data published by the industry and various academic and research institutions (as discussed in Section 5.4.1 and 5.4.2). Outputs will be Excel datasets, available for further GIS visualisation and manipulation as described in Section 5.4.4.

Although data on soil carbon will only be available post the ecosystem and land-use modelling project, this could be built into a future analysis of the production/opportunity costs.

5.4.4 Model output

The key output of the opportunity cost modelling, which will feed into WP2, will be:

- Total opportunity cost of each biomass resource, in each decade to 2050, in each UK region
- Increase in land value over a baseline land use associated with a switch to each biomass resource, in each decade to 2050, in each UK region

The model outputs will be visualised in GIS as well.

Section C: GHG Emission Model

6 GHG Emissions Model

6.1 Introduction

6.1.1 Objectives of the model

The objective of the greenhouse gases (GHG) emissions model is to estimate the GHG emissions associated with the production of the bioresources included in the project. The GHG model will not include emissions from land use change (LUC), both direct and indirect, as their rigorous assessment is considered outside the scope of this project[8].

6.1.2 Review of existing model and approaches

Even though several studies on spatially explicit supply of bioenergy crops in the UK have been carried out in the past, a spatially explicit modelling of the GHG emissions is often either absent or at a high level only. In E4tech (2009), GHG emissions for first generation biofuels where calculated at NUTS2[9] region level; however, most emissions factors, such as those associated with fertiliser requirements, where still expressed at either NUTS1 or UK wide level. In Hillier et al. (2009), blanket fertiliser application rates and management emissions for the whole England and Wales were considered[10]. No GHG emissions were instead considered in either Aylott et al. (2010) or Dunnett et al. (2008).

In this project, we will build on the existing literature to augment existing GHG modelling framework with spatially explicit features suited to the development of UK wide biomass value chain optimisation modelling.

6.2 Description of the applied methodology

The assessment of the GHG emissions from cultivation in the BVCM model will be carried out in accordance with the methodology used in the current version of the Carbon Calculator (DfT, 2011) developed by E4tech for the Department for Transport for the UK Renewable Transport Fuels Obligation (RTFO). The current version of the calculator is compliant with the methodology and values set out in the European Renewable Energy Directive (RED) (EU, 2009). For avoidance of doubt, in this document when RTFO default values are used, these will be RED-compliant values. When values and/or methodologies different than those in the Carbon Calculator are used, we will highlight so in the following sections, and provide justification for doing so. For example, the RED methodology considers only a small set of second generation biofuels, so for certain emissions components other literature sources will need to be used.

The GHG emissions model will include CO_2, methane (CH_4) and nitrous oxide (N_2O) as GHG gases and emissions will be expressed as carbon dioxide equivalent (CO_2e).

An overview of GHG emission components, as compared to what is included in the RTFO is given in Table 6-1. .

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[8] However, the optimisation framework will be built in such a way that LUC emissions can be considered once available in the future, e.g. from other ETI projects.

[9] Nomenclature of Territorial Units for Statistics (NUTS) regions are European standards for the definition of country subdivisions. In case of the UK, NUTS1 regions corresponds to England, Wales, Scotland and Northern Ireland, while NUTS2 regions are typically counties (at times grouped) and groups of unitary authorities/districts.

[10] Hiller et al. (2009) consider indeed spatially explicit soil carbon emissions, which are outside the scope of this project.

LCA emissions from cultivation	Included in the RTFO	Included in the BVCM	Methodology/values used in the BVCM
N fertilisers	Y	Y	DEFRA's fertilisers manual methodology
P fertilisers	Y	Y	
K fertilisers	Y	Y	
Direct N_2O	Y	Y	IPCC Tier 1 methodology
Indirect N_2O	Y	Y	
Seeding materials	Y	Y	RTFO default values
Pesticides	Y	Y	RTFO default values
Machinery construction and disposal	N	N	n/a
Machinery fuels	Y	Y	RTFO default values for 1G crops, NNFCC solid biomass calculator emissions for 2G
Land use change	Y	N	Land use change (LUC) emissions assessment is beyond the BVCM scope. However, functionality will be built in in the value chain optimisation to include LUC emissions data when available from other ETI projects (see WP2-D1 and D2 deliverables)
Indirect land use change	N	N	n/a

Table 6-1 Summary of GHG emissions included in the BVCM as compared to those in the RTFO.

6.2.1 Fertilisers requirement assessment methodology

The RTFO default values for GHG emissions from fertiliser production are not dependent on factor such as soil, yield, etc, so are not spatially explicit. For the BVCM project we propose a methodology to generate spatially explicit values, which we believe is an improvement when compared to the RTFO methodology. This will be done by linking the fertiliser requirements to the soil type, the rainfall regime, and the cultivation regime as proposed in DEFRA's fertiliser manual (DEFRA, 2010). This spatially explicit methodology will apply to winter wheat, oilseed rape and sugar beet. Due to the small number of studies on nutrient requirements for Miscanthus and SRC willow, UK wide values will be considered instead. No nutrient requirement will be assumed here for forestry.

The general methodology for fertiliser requirement assessment as in DEFRA's manual is outlined below, with assumptions and simplifications specific to each bioresource discussed later on.

The methodology for the assessment of the fertiliser requirement covers Nitrogen (N), Phosphate (P_2O_5) and Potash (K_2O).

Nitrogen

DEFRA's manual recommends the amount of nitrogen that should be applied to give the on-farm economic optimum yield. The manual identifies five steps to assess such N requirements[11]. The assessment is based on the Soil Nitrogen Supply (SNS) Index, which represents the amount of nitrogen (kg N/ha) in the soil[12]. The higher the index, the lower is the requirements on nitrogen fertiliser. The five steps are the following:

- Step 1. Identify the soil type of the field.
- Step 2. Identify the previous crop.
- Step 3. Select the rainfall range of the field.
- Step 4. Identify the provisional Soil Nitrogen Supply index using the appropriate table from the Manual.
- Step 5. Make any necessary adjustments to the Soil Nitrogen Supply index.

A description of each step and the proposed simplifications are detailed hereafter.

Step 1. Identify the soil type of the field

Seven soil categories are defined in the Manual: Peaty soil, Organic soil, Shallow soil, Light sand soil, Deep silty soil, Medium soils and Deep clayey soil. Here we will use the HWSD soil database (IIASA, 2011) to classify the UK soils into these seven categories, as explained in Section 6.8.1.

Step 2. Identify the previous crop

A factor influencing the Soil Nitrogen Supply index is the Nitrogen residue left in the soil from fertilisers applied to a previous crop.

In this project, we will assume that Winter wheat (WW), Sugar beet (SBt) and Oilseed rape (OSR) are grown in a standard crop rotation of WW/WW/OSR and WW/WW/SBt. Such rotations are assumed to be fixed, i.e. not changing for future scenarios. If needed and time allows, different crops rotations (e.g. over four years and including high residual nitrogen vegetable crops) may be also investigated.

Step 3. Select the rainfall range for the field

The amount of N-fertiliser will depend on the nitrate that will be lost through leaching, which is a function of excess winter rainfall (since the latter is closely related to drainage). For the purpose of this project, and in line with the Manual, the typical annual rainfall can be used instead as a proxy of excess winter rainfall. Three categories of annual rainfall are identified:

- Low - typical annual rainfall is less than 600 mm
- Medium - between 600-700 mm
- High - over 700 mm

The annual rainfall data from the UKCP09 projections will be used here, as explained later in Section 6.8.

Step 4. Identify the provisional Soil Nitrogen Supply index using the appropriate table

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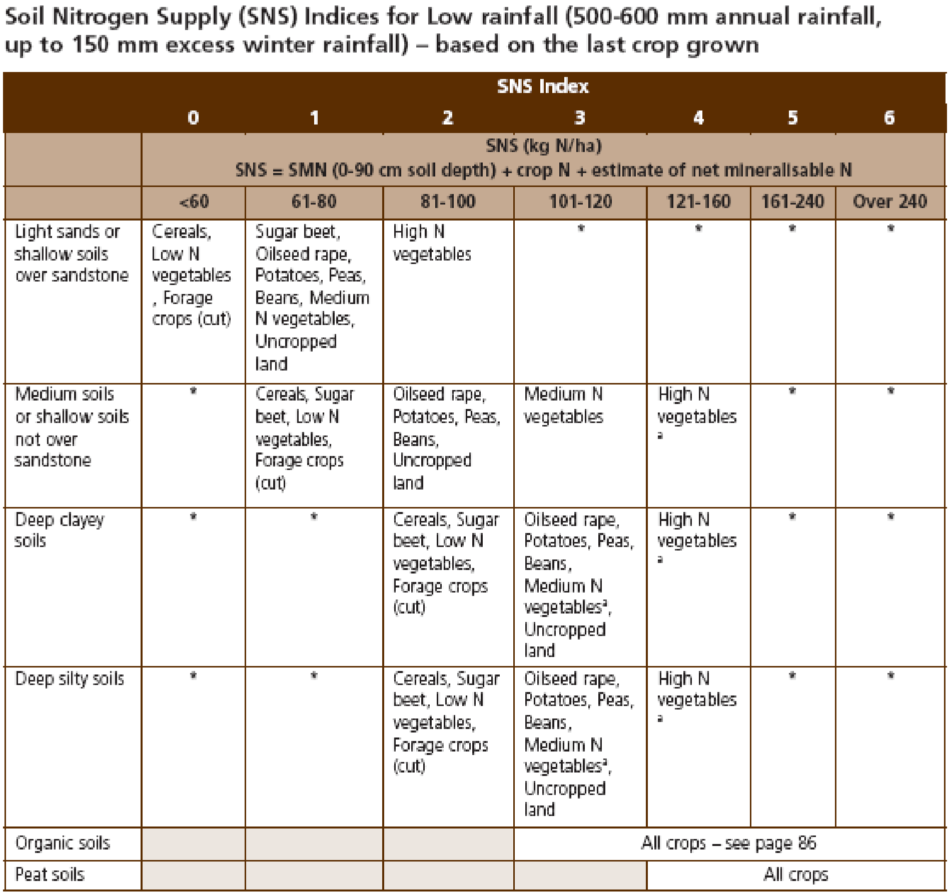
[11] The Manual proposes two methods: the Field Assessment Method and the Measurement Method. As the Measurement Method applies only to fields where it is possible to sample the soil for Nitrogen content analysis, we will consider the Field Assessment Method only.

[12] Apart from that applied for the crop in manufactured fertilisers and manures and that is available for uptake by the crop throughout its entire life, taking account of nitrogen losses.

Based on the soil type, the previous crop and the rainfall range, it is possible to find a Soil Nitrogen Supply_index from lookup tables in the Manual[13]. A table per each rainfall regime exists in the manual and an example of the table for the Low rainfall regime is given in Figure 6-1. In the Figure it can be seen how by fixing the previous crop, it is possible to univocally link the soil type to the Soil Nitrogen Supply_index. For crops in a rotation, a weighted average over 10 years (i.e. the decadal time step used in the optimisation model) of the previous crops in a WW/WW/SBt and WW/WW/OSR rotation will be considered, in order to take into account the impact of a rotation on the nitrogen requirement.



Soil Nitrogen Supply (SNS) Indices for Low rainfall (500-600 mm annual rainfall, up to 150 mm excess winter rainfall) – based on the last crop grown

	SNS Index						
	0	1	2	3	4	5	6
	SNS (kg N/ha) SNS = SMN (0-90 cm soil depth) + crop N + estimate of net mineralisable N						
	<60	61-80	81-100	101-120	121-160	161-240	Over 240
Light sands or shallow soils over sandstone	Cereals, Low N vegetables, Forage crops (cut)	Sugar beet, Oilseed rape, Potatoes, Peas, Beans, Medium N vegetables, Uncropped land	High N vegetables	*	*	*	*
Medium soils or shallow soils not over sandstone	*	Cereals, Sugar beet, Low N vegetables, Forage crops (cut)	Oilseed rape, Potatoes, Peas, Beans, Uncropped land	Medium N vegetables	High N vegetables[a]	*	*
Deep clayey soils	*	*	Cereals, Sugar beet, Low N vegetables, Forage crops (cut)	Oilseed rape, Potatoes, Peas, Beans, Medium N vegetables[a], Uncropped land	High N vegetables[a]	*	*
Deep silty soils	*	*	Cereals, Sugar beet, Low N vegetables, Forage crops (cut)	Oilseed rape, Potatoes, Peas, Beans, Medium N vegetables[a], Uncropped land	High N vegetables[a]	*	*
Organic soils				All crops – see page 86			
Peat soils					All crops		

Figure 6-1 Soil Nitrogen Supply index table for low rainfall regime.

Step 5. Make any necessary adjustments to the SNS Index

Some adjustments to the Soil Nitrogen Supply index may be required in case of regular application of organic manure to previous crops in the field. In this project, for the sake of the Soil Nitrogen Supply index assessment, we will assume that no adjustment is needed to the Soil Nitrogen Supply index found in Step 4 above.

Phosphate and Potash

The supply of Phosphate and Potash is based on maintaining a so called target soil index for P and K amounts, i.e. maintaining an appropriate amount of P and K in the soil. For our model, we will assume that the amount of Phosphate and Potash needed is exclusively

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[13] Note that the SNS lookup tables are not specific to the crop to be planted, rather depend only on the soil type, the previous crop and the rainfall range.

based on the amount of each nutrient removed from the field through the harvested crops. For certain crops, this will also depend on whether part of the harvest (e.g. straw) is returned to the field or not. This approach is in line with what proposed in the DEFRA’s manual, which indicates for each crop the amount of P and K fertiliser needed to maintain the target soil index.

6.3 GHG emissions associated with fertiliser production

The GHG emissions associated with fertilisers production depend on the amount of fertilisers applied and the emissions factor (EF) of fertiliser production. For a generic fertiliser, this is illustrated in Figure 6-2.

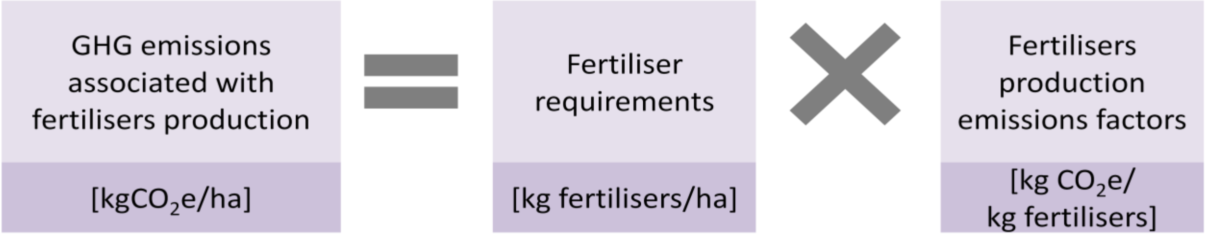


Figure 6-2 GHG emissions associated with fertilisers production

The values assumed for the fertilisers requirements and the fertilisers production emissions factor will be illustrated below.

6.3.1 Fertiliser requirements

Winter wheat

The N requirements for winter wheat as a function of the soil type and the Soil Nitrogen Supply index are shown in Table 6-2. N application is not explicitly dependent on yield. However, yield will depend on the Soil Nitrogen Supply index and the type of soil, so ultimately a link between N application and yield exists. The same applies to oilseed rape and sugar beet. When a range of nutrient requirements (e.g. 0-40 kg N/ha) is proposed, the average value is considered in the model.

	SNS Index						
	0	1	2	3	4	5	6
	kg N/ha						
Light sand soils	160	130	100	70	40	0-40	0-40
Shallow soils	280	240	210	180	140	80	0-40
Medium soils	250	220	190	160	120	60	0-40
Deep Clay soils	250	220	190	160	120	60	0-40
Deep Silty soils	220	190	160	130	100	40	0-40
Organic soils				120	80	40-80	0-40
Peat						0-60	

Table 6-2 N requirements for winter wheat

The amount of Phosphate and Potash requirements for winter wheat, expressed as a function of the crop (grain only or grain and straw) is shown in Table 6-3.

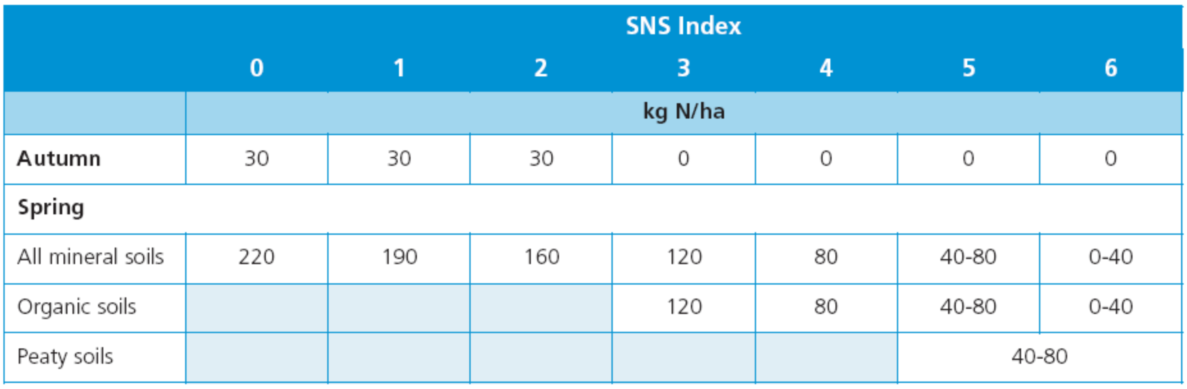
Crop	Phosphate	Potash
	kg nutrient/t of fresh material	
Grain only	7.8	5.6
Grain and straw	8.4	10.4

Table 6-3 Phosphate and Potash requirements for winter wheat

It is important to note that, as the amount of Phosphate and Potash requirements is a function of the amount of fresh material, the requirements depend on the yield (and the yield estimates) for winter wheat. The same applies to the Phosphate and Potash requirements for oilseed rape and sugar beet later in the text.

Oilseed rape

The N requirements for oilseed rape as a function of the soil type and the Soil Nitrogen Supply index are shown in Table 6-4.



	SNS Index						
	0	1	2	3	4	5	6
	kg N/ha						
Autumn	30	30	30	0	0	0	0
Spring							
All mineral soils	220	190	160	120	80	40-80	0-40
Organic soils				120	80	40-80	0-40
Peaty soils						40-80	

Table 6-4 N requirements for oilseed rape[14]

The amount of Phosphate and Potash requirements for oilseed rape, expressed as a function of the crop (seed only or seed and straw) is shown in Table 6-5.

Crop	Phosphate	Potash
	kg nutrient/t of fresh material	
Seed only	14.0	11.0
Seed and straw	15.1	17.5

Table 6-5 Phosphate and Potash requirements for oilseed rape

Sugar beet

The Nitrogen requirements for sugar beet as a function of the soil type and the Soil Nitrogen Supply index are shown in Table 6-6.

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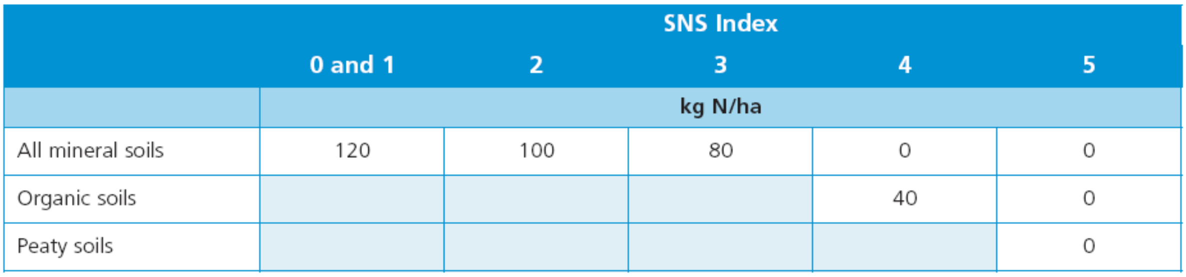
[14] The model does not need to take into account the recommended seasonal application of fertiliser (“Autumn” and “Spring” in the table), so the Nitrogen application to be modelled is the sum of the autumn and the spring applications.



	SNS Index				
	0 and 1	2	3	4	5
	kg N/ha				
All mineral soils	120	100	80	0	0
Organic soils				40	0
Peaty soils					0

Table 6-6 N requirements for sugar beet

The amount of Phosphate and Potash requirements for sugar beet, expressed as a function of the crop (roots only or roots and straw) is shown in Table 6-7.

Crop	**Phosphate**	**Potash**
	kg nutrient/t of fresh material	
Roots only	0.8	1.7
Roots and tops	1.9	7.5

Table 6-7 Phosphate and Potash requirements for sugar beet

Miscanthus

The fertiliser requirements for Miscanthus are based on typical offtake of nutrients in harvested biomass as in the DEFRA's fertiliser manual[15] and reported in Table 6-8.

Nutrients	**Amount [kg per odt biomass]**
Nitrogen	6
Phosphate	1
Potash	8.5

Table 6-8 Nutrient requirements for Miscanthus

SRC Willow

Similarly to Miscanthus, the fertiliser requirements for SRC Willow are based on typical offtake of nutrients in harvested biomass as in the DEFRA's fertiliser manual and reported in Table 6-9.

Nutrients	**Amount [kg per odt biomass]**
Nitrogen	3

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[15] Variability of requirements depending on weather and time of harvest, as well as nutrient requirements during the first two years after planting (when yields are much lower) are not considered.

Phosphate	1.8
Potash	2.4

Table 6-9 Nutrient requirements for SRC Willow

Forestry

No fertiliser application is assumed for forestry.

6.3.2 Fertilisers production emissions factors

The RTFO default values for N-fertilisers production emissions factors consider the production of ammonium nitrate (AN) fertiliser only. Differently than some other N-fertilisers such as urea, the manufacture of AN generates N_2O. It follows that GHG emissions from the manufacture of urea are much less than from the manufacture of AN.

In the UK, around 20% of N-fertilizer applied to combinable crops is in the form of urea (E4tech, 2010), so we propose that the use of urea, even though is not in the RTFO default values, should be taken into account. Also, evidence gathered in (E4tech, 2010) suggests that N fertiliser manufacturing plants operating in the UK and in the countries from which the greatest amounts of N fertiliser are imported to the UK are already fitted with N_2O abatement technology[16]. In (E4tech, 2010), the project reviewed available information collected under the LINK research project 'MIN-NO'[17] on the adoption of N_2O abatement technology by N fertiliser manufacturers in the UK. In addition two UK companies (GrowHow UK Ltd and the Yara plants located in the UK) were consulted directly. The topic was also discussed informally with a representative of Fertilisers Europe. The information gathered indicated that N fertilizer manufacturing plants operating in the UK and in the countries from which the greatest amounts of N fertiliser are imported to the UK were as 2010 already fitted with N_2O abatement technology. In conclusion, for the GHG model here developed, it is assumed that 20% of the N requirements will be provided by urea, and the rest by AN, produced by plants fitted with N_2O abatement technologies. This will apply for the entire time horizon covered by the BVCM model (i.e. till 2050).

Data for phosphate (as rock phosphate) and potash are taken from the RTFO default values.

Emissions factors for Nitrogen, Phosphate and Potash fertiliser production are summarised in Table 6-10.

Fertiliser	**Emissions factor [kg CO_2e/kg nutrient]**	**Reference**
AN (unabated)[18]	5.9	RTFO (as in BioGrace Standard Value v2.3)
AN (abated)	1.36	Ahlgren et al., 2009

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[16] In recent years N_2O abatement technology has been developed to reduce N_2O emissions from AN production. For example, catalysts may be used to break down N_2O under high temperature into nitrogen gas (N_2) and oxygen (O_2), achieving a reduction in N_2O emissions of up to 70-85%. Using these catalysts reduces the total carbon footprint of AN production to less than 3 tonnes CO_2e per tonne AN-N. Brentrup and Palliere, 2009 forecast that virtually all operating plants in Europe will have abatement systems by the mid 2010s.

[17] http://www.adas.co.uk/Home/Projects/MINNO/tabid/283/Default.aspx

[18] This is for reference only, since it will not be used in the model

Urea[19]	1.3	RTFO
Phosphate	0.1	RTFO
Potash	0.6	RFTO (as in BioGrace Standard Value v2.3)

Table 6-10 Emissions factors for fertiliser production

6.4 Nitrous oxide (N_2O) emissions from soil

Different methodologies exist for assessing the N2O emissions from soil, The Inter-Governmental Panel on Climate Change (IPCC) Guidelines provide three Tiers, or levels of increasing complexity, for the methodologies which may be used for estimating the emissions from agriculture (IPCC, 2006). Tier 1 is the basic method, designed to use readily-available national statistics in combination with default emissions factors and additional parameters that are provided by the IPCC. Tier 2 represents an intermediate level of complexity, where e.g. country-specific data are used instead of default parameters. Tier 3 represents the greatest complexity. e.g. by using mechanistic or process-based models to derive emissions factors. For example, the DeNitrification-DeComposition (DNDC) biochemistry model developed by the University of New Hampshire (US) would correspond to an IPCC Tier 3 level.

Each method has its own advantages and disadvantages, particularly in the context of the modelling to be carried out in the BVCM project. While the DNDC model is currently believed to provide better emission estimates for certain crops in certain world regions, much remains to be done in finalising and validating the approach with actual field measurements in the UK. Also, more importantly for the BVCM, the complexity and the dynamic nature of the DNDC model does not allow for its seamless and transparent integration within the value chain model optimisation framework (i.e. the DNDC model will need to be run off-line anytime new assumptions on e.g. yield, climate, fertilisers, etc are explored by the optimisation runs), This is assuming that the DNDC model is actually available within the BVCM consortium, which is not the case.

In turn, the IPCC Tier 1 methodology does not allow to fully consider the regional differences in soil and climate. However, it is a standardised, internationally accepted methodology that can be readily applied within the optimisation model, as it can be readily coupled with the spatially explicit mapping of fertilisers requirements as proposed here. In addition, in 2010 regional (NUTS2 level) emissions for biofuels from crops grown in the UK were calculated by using the IPCC Tier 1 methodology (E4tech, 2010), and the European Commission approved those emissions and the methodology used to calculate them. In conclusion, for the reasons above, we believe that the IPCC Tier 1 methodology offers the best option for the BVCM and therefore we recommend its use to estimate soil N_2O emissions. If validated, spatially explicit values, which can be directly linked to the fertiliser input, will be available in the future for the UK from models such as DNDC or others, the BVCM model can be readily updated with such values. Pros and cons of the IPCC Tier 1 methodology and the DNDC model are summarised in **Error! Reference source not found.**.

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[19] Original value is 2.9 kg CO_2e/kg N. A content of 0.47 kg N per kg urea is assumed.

	IPCC Tier 1	DNDC model
Pros	It allows for ready integration in the optimisation model, by providing a direct link between soil types, fertilisers amounts and emissions It is standardised, internationally accepted methodology It has been approved by the EU for the calculation of UK NUTS2 regional emissions calculation for biofuels	Detailed, process-oriented simulation model of C and N biogeochemistry in agricultural ecosystems It allows the effect of soils, crops, climates and farming practices to be reflected in the emission estimate
Cons	Does not take into local biogeochemistry in agricultural ecosystems. It is a simplistic approach in which, for example, N input has no effect on crop N uptake or yield It under/overestimate emissions for certain crops	Calibration and validation for the UK still on going Model is not owned/developed by the BVCM consortium, therefore it cannot be run by the consortium. This means that any results from the model we may be able to obtain may not be fully transparent as regards e.g. assumptions It cannot be readily integrated in the optimisation model. A separate off-line model run would be needed for each scenario e.g. on climate

Table 6-11 Summary of pros and cons of IPCC Tier 1 methodology and DNDC model

N_2O emissions from soil are classified into direct and indirect. Direct emissions include those where N_2O is emitted directly (e.g. via volatilisation) to the atmosphere from cultivated soils. Indirect emissions result from transport of N from agricultural systems into ground and surface waters through drainage and surface runoff, or emission as ammonia or nitrogen oxides and deposition elsewhere, causing N_2O production.

6.4.1 Direct N_2O soil emissions

According to the IPCC Tier 1 methodology, direct N_2O soil emissions are calculated as a linear function of the Nitrogen fertiliser application, where 1% of the N in the fertilisers turns into N_2O. Given that we already use a spatially explicit methodology to calculate the N-fertilisers need for some of the crops, we believe that the IPCC Tier 1 would suffice for the scope of this project.

6.4.2 Indirect N_2O soil emissions

Indirect N_2O emissions arising from the following processes will be included in the model:

- denitrification of fertilizer-N lost from the soil by leaching to ground and surface waters as nitrate (NO_3)
- nitrification and denitrification following deposition to land of fertilizer-N emitted as

NH_3 after application

Indirect losses arising from NO_3 leaching will be calculated using the IPCC default emissions factors for the fraction of N-fertilizer lost by leaching (0.30) and for the fraction of leached N subsequently denitrified to N_2O-N (0.0075).

As in (E4tech, 2010), the emission factors for the proportion of N-fertilizer lost as NH_3 will be taken as the weighted average emission factors for tillage land for AN and urea as reported in the UK Ammonia Emissions Inventory (Misselbrook et al., 2009). These were 1.5% of N applied as AN, and 17.0% of N applied as urea. Emissions following deposition of NH_3 to land are calculated as 1.0% of the N deposited, according to IPCC Tier 1 methodology.

6.5 Machinery inputs

In line with the RTFO, emissions from machinery inputs include only fuel emissions, thus excluding emissions from manufacture and disposal of machineries. Values for on-farm fuel use (as diesel) for machineries are taken from the RTFO for first generation crops Farm fuel use emissions in the RED do not include all the 2G crops considered here. For this reason values for 2G crops are taken from BEAT2 v2.1 (AEA Technology et al, 2011). This is in line with what done in solid biomass carbon calculator currently under development by E4tech for the NNFCC.

Diesel consumptions include all consumption incurred during cultivation, harvest, and any other on-the-field operation to take the resource to the roadside. So, for example, in the case of Miscanthus, machinery inputs include baling.

Emissions factor for diesel, which includes both upstream and downstream emissions, is equal to 0.088 $kgCO_2e/MJ$ diesel (RTFO default value).

Resource	**Diesel fuel consumption (MJ/ha/year)**	**Comment**	**Reference**
Winter wheat	3716.5		RTFO
Oilseed rape	2963.0		
Sugar beet	6331.0		
Miscanthus	4011.9	1049.4 MJ/ha/year for cultivation and 2962.5 MJ/ha/year for harvesting and baling. A 10% loss in weight from harvested to bailed Miscanthus is considered	NNFCC solid biomass calculator (based on BEAT2 v2.1)
SRC Willow	1220.0	440.0 MJ/ha/year for cultivation and 780 MJ/ha/year for harvesting and chipping. Stick harvesting would be equal to 278 MJ/ha/year.	
Short rotation forestry	925.0	231.3 MJ/ha/year for cultivation and 693.7 MJ/ha/year for harvesting	

Forest stemwood and branchwood	332.0	For extraction and roadside drying and baling (if applicable)	

Table 6-12 Machinery emissions

6.6 Other emissions

Two emissions types will be considered under this category:

- Seeding material
- Pesticides

6.6.1 Seeding material

Default values for the rates of application of seeding materials and the GHG emissions due to their production exists in the RFTO calculator for all first generation crops included in this project (winter wheat, oilseed rape and sugar beet). However, these have a very small contribution to the total emissions from feedstock cultivation (typically around 1%) and their omission from the calculations for all other resources in this study is not likely to significantly affect the results.

Resource	Seed application rate (kg/ha/year)	Emissions factor seed production (kg CO_2e/kg seed)
Winter wheat	120.0	0.277
Sugar beet	6.0	3.558
Oilseed rape	6.0	0.733

Table 6-13 Seed application rate and emissions factor for seed production for winter wheat, oilseed rape and sugar beet

6.6.2 Pesticides

Default values for the rate of application of pesticides and the GHG emissions due to their production exists in the RFTO calculator for all first generation crops included in this project (winter wheat, oilseed rape and sugar beet). The default value for the emissions factor of all pesticides productions is 11 kg CO_2e/kg pesticide.

Resource	Pesticide application rate (kg/ha/year)
Winter wheat	2.30
Oilseed rape	1.23
Sugar beet	1.30

Table 6-14 Pesticides application rate for first generation crops

6.7 Functionality

As already explained, the proposed GHG emissions model will feature the added functionality, when compared to existing models, of being spatially explicit as regards the fertiliser requirements, and hence the fertiliser emissions, for first generation resources. Emissions for Miscanthus and SRC Willow will also be spatially explicit, as emissions factors for fertiliser application are assumed as depending on the yield.

The overall generic architecture of the GHG model, with input, output and parameters is illustrated in Figure 6-3. For some bioresources, e.g. forestry, for which no spatially explicit modelling is envisaged, the GHG model will be as matter of fact a simpler version of the one illustrated.

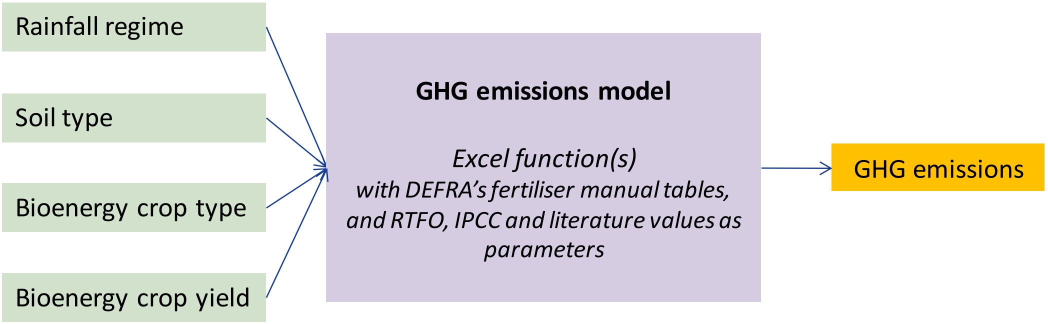

Figure 6-3 GHG meta-model structure

The model will be developed in MS Excel. Spatially explicit inputs will be extracted from GIS databases into Excel datasets (see Section 6.8) and outputs will be Excel datasets, available for further GIS visualisation and manipulation.

Also, the sub-model for the assessment of the fertiliser requirements could be used by the resource cost model to calculate the cost of fertilisers for first and second generation resources. In order to do so, the fertiliser requirement databases will need to be aggregated at the resolution used by the cost model.

6.8 Input data requirements

In addition to the data reported in the previous sections, data on soil type, rainfall, and yield will be needed to estimate the fertiliser requirements.

6.8.1 Soil types

As said before, the DEFRA's fertiliser manual considers seven soil categories:

- Peaty soil
- Organic soil
- Shallow soil
- Light sand soil
- Deep silty soil
- Medium soils
- Deep clayey soil

For the GHG model we propose to use the Harmonised World Soil Database (HSWD) at 1x1 km resolution in order to classify the UK soil into the seven soil categories above. In order to do so, the soil properties from the HWSD in Table 6-15 will be considered:

HWSD soil categories	**Definition**
T_OC	Organic carbon in topsoil (%)
T_SAND and S_SAND	Topsoil and Subsoil Sand Fraction (%)
T_SILT and S_SILT	Topsoil and Subsoil Silt Fraction (%)
T_CLAY and S_CLAY	Topsoil and Subsoil Clay Fraction (%)
ROOTS	Obstacle to roots (1 to 6 depending on depth of obstacle)

Table 6-15 HWSD soil categories used for the soil classification according to the DEFRA's fertiliser manual.

The soil classification according to the DEFRA's fertiliser manual and using the soil properties in the HWSD can be then expressed by the flow diagram in Figure 6-4[20].

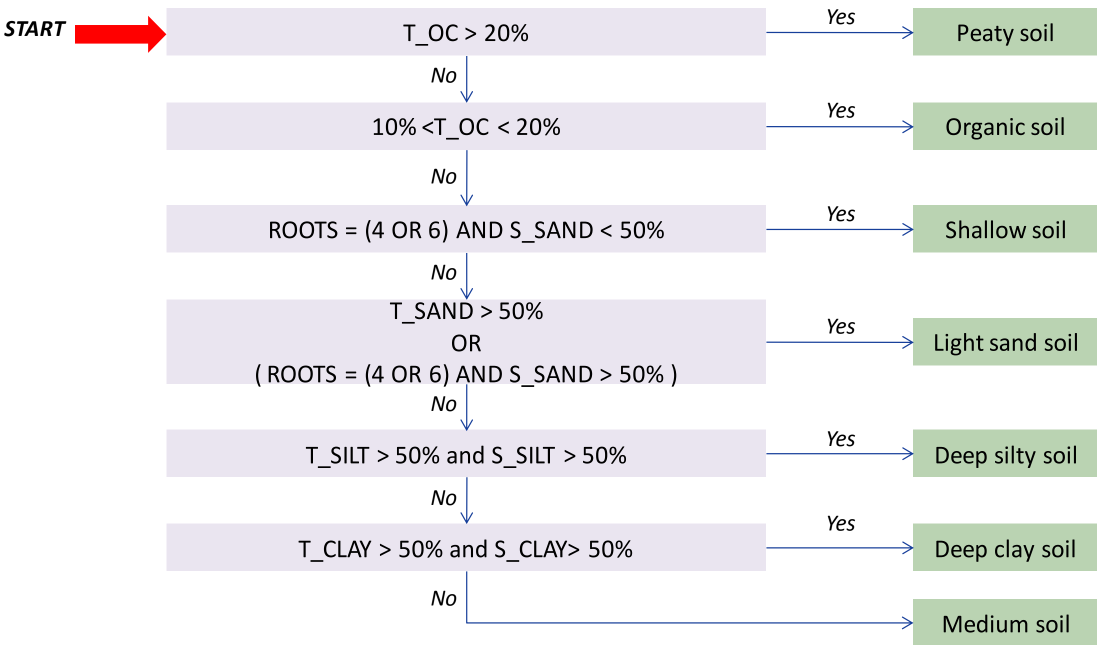

Figure 6-4 Proposed soil classification flow diagram based on HWSD soil properties

For non shallow, mineral soil (i.e. not peaty, organic soil or shallow soil) the flow diagram for the soil classification corresponds to the classification in the soil triangle as shown in Figure 6-5.

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[20] In the Manual, soil is classified as organic when it features from 10% to 20% organic matter, and peaty if it has more than 20% organic matter.

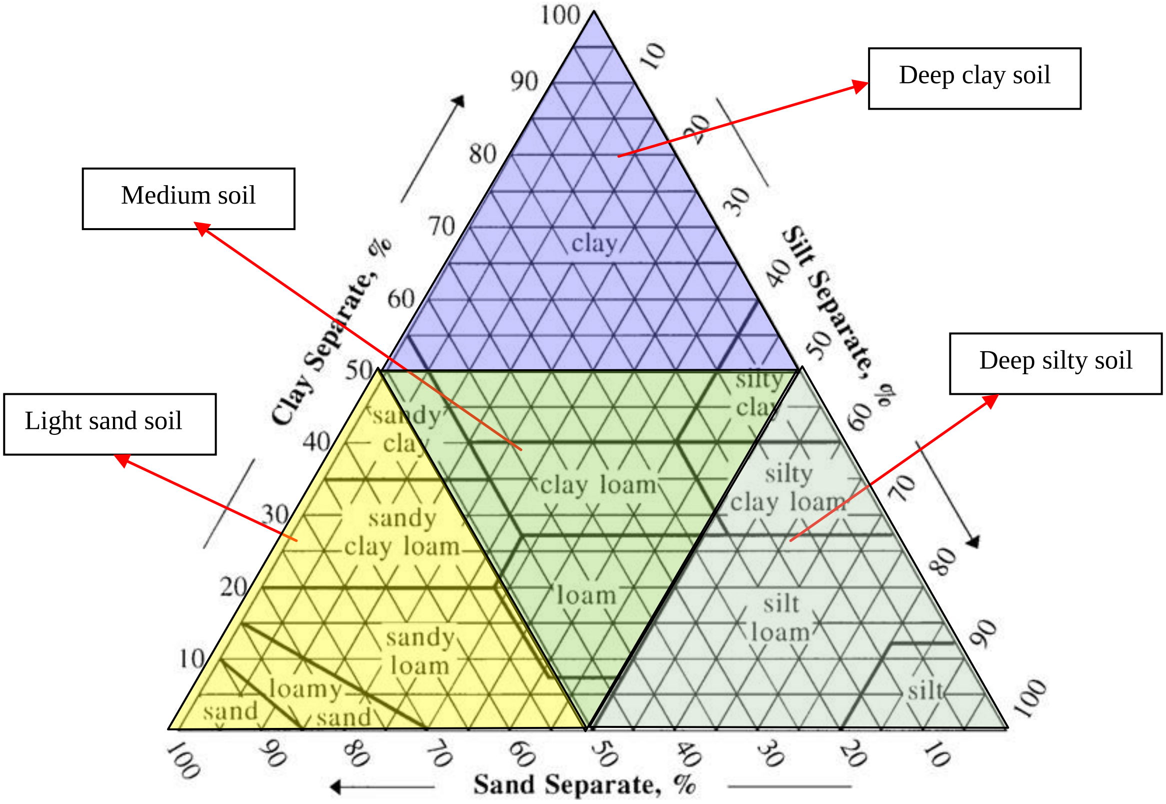

Figure 6-5 Soil classification in the soil triangle

6.8.2 Rainfall regimes

According to the proposed methodology, rainfall regimes classified into three categories are needed for the GHG emissions model:

- Low - typical annual rainfall is less than 600 mm
- Medium - between 600-700 mm
- High - over 700 mm

A preliminary analysis of the Soil Nitrogen Supply index lookup tables in the DEFRA's manual and of the UKCP09 climate scenarios has found that:

- when it is assumed that the previous crop for the sake of calculating the Soil Nitrogen Supply index is cereals, the Soil Nitrogen Supply index lookup tables for Medium and High rainfall regimes are identical
- when assessing how the rainfall will change in the UK from 2020 to 2050 under different emissions scenarios, only a very small share (less that 1%) of the UK will switch from/to a Low to/from High rainfall regime as defined above.

From the findings above it follows that:

- for the modelling sake, rainfall regimes need to be classified into two categories only: Low (< 600 mm) and High (> 600 mm)
- any rainfall dataset can be used for deriving the Low/High rainfall regimes without introducing any significant error. Here it is then proposed to use the UKCP09 2020s Low emission scenario for the annual rainfall dataset.

6.8.3 Yield estimates

The Phosphate and Potash requirements for all crops depend on the yield estimates. Therefore relevant yield maps (current and future estimates) will be needed as input to the GHG emissions model. If different, future yield estimates are generated under different scenarios (e.g. climate), we will choose only one of these yield estimates as baseline for the GHG emissions calculation.

Yield maps will need to be aggregated to appropriate resolution (likely to be the 1x1 km resolution which will be used to calculate the Nitrogen requirements).

Also, as per the BVCM model specification report (WP2- Deliverable 1), the BVCM will need GHG emissions expressed as tCO_2e per odt of a given resource. Therefore, yield datasets will be needed also to normalise the GHG emissions on a odt basis.

6.9 Model output

The GHG emissions model output will be a dataset of GHG emissions (expressed as tCO_2e/odt) for each bioresource, for each decade from 2010 to 2050, and, if applicable, depending on whether part of the crop (e.g. wheat straw, oilseed rape straw, and sugarbeet tops) is returned to the field or not.

Section D: Data Requirement

7 Environment Data

7.1 Introduction

This section outlines the environmental data required to model the yield and costs of some first generation, second generation biomass and forest based wood resources as well as GHG emission of those resources (explained in Section A, B and C). Moreover, additional data e.g. land use, administrative boundary etc. are required for the WP2 model. Therefore, different geophysical and climate data such as soil, climate scenario, digital elevation model, land cover, road network as well as regional administrative boundary data are required to collect from different sources. Then they will be integrated into the GIS (in a Geodatabase with individual layer) for further modelling and visualisation.

This chapter also explains the characteristics (formats, resolution, variables, license, etc.) of the above datasets and illustrates the methods and platforms of data harmonisation.

7.2 Description of required data

Three types of soil data - Harmonised World Soil Database (HWSD), European Soil Database (ESDB) and LandIS (NATMAP); two types of climate data - UKCIP02 and UPCP09 as well as Shuttle Radar Tomography Mission (SRTM) 90m Digital Elevation Data, Corine Land Cover Data, UK Road Data and Regional Boundary Data have been investigated. A general overview of the data set is given in Table 8-3.

A detail description is followed in these sub-sections.

7.2.1 Soil data

HWSD, ESDB and NATMAP were identified as potential sources of soil data. Different variables of these datasets can be fed into the resources and GHG emissions models.

Harmonized World Soil Database (HWSD)

The HWSD contributes sound scientific knowledge for planning sustainable expansion of agricultural production and for guiding policies to address emerging land competition issues concerning food production, bio-energy demand and threats to biodiversity (FAO et al., 2009). The most recent updates of the HWSD Version 1.1 is from 26 March, 2009 and can be found at the HWSD Website[21].

Detail description of the datasets and variables are given in Appendix 2 and in Appendix 3.

European Soil Database (ESDB)

The Soil Geographical Data Base of Europe at Scale 1:1,000,000, which is part of the European Soil Data Base, is the resulting product of a collaborative project involving all the European Union and neighbouring countries during the last 20 years. It is a simplified representation of the diversity and spatial variability of the soil coverage (JRC, 2008).

The most recent updates of the ESDB V2 can be found at the EUSOIL Website[22].**LandIS (NATMAP).**

The National Soil Resources Institute (NSRI) offers digital data products (NATMAP) that

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[21] http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/index.html?sb=1

[22] http://eusoils.jrc.ec.europa.eu/esdb_archive/ESDB/Index.htm

characterise the soil resources that cover England and Wales (NSRI, 2011).

Data sets are held in the LandIS relational database, which is available under licence. Detailed information on datasets is available on LandIS Website23.

For this project, HWSD and ESDB soil data will be used since they cover complete coverage of the UK (including Scotland and Northern Ireland) - a feature absent from NATMAP (providing only for England and Wales). Moreover all the required model variables are available in these datasets. A comparative overview of these datasets is given in Table 8-3.

7.2.2 Climate data

UKCIP02

The UKCIP02 climate change scenarios were derived from a series of climate modelling experiments commissioned and funded by Defra, undertaken by the Hadley Centre and analysed by the Tyndall Centre in 2002. The UKCIP02 scenarios are based on four different IPCC SRES emissions scenarios and three future time-slices Hulme et al., 2002. Detailed database structure and filenames of UKCIP02 are outlined in Appendix 5.

Not all of the changes described by UKCIP02 are given with the same confidence. Based on both expert judgement and comparison with other global climate models, some changes in future UK climate have been assigned a higher confidence than others. When using the UKCIP02 climate change scenarios, regardless of the level of detail, it is important to understand the confidence associated with the specific changes described and to ensure that the use of the information is consistent with and fully reflects the associated uncertainties UKCIP, 2002.

UKCIP02 were produced at a spatial resolution of 50 km and 5 km grid in ESRI shape format and in ESRI ASCII format.

UKCP09

In June 2009, Defra and the UK Climate Impacts Programme (UKCIP) published a new set of projections of the UK's climate to 2100 known as UKCP09. It is the fifth generation of climate information for the UK and is the most comprehensive package yet UKCIP (2010). For the first time it provides probabilistic projections of climate change based on quantification of the known sources of uncertainty.

Four different (land) data sources come under the title of UKCP09.

- Probabilistic projections
- Spatially Coherent Projections
- Weather Generator
- 11-member RCM

UKCP09 Spatially Coherent Projections (UKCP09-SCP) are most suitable to this project, because SCPs are spatially coherent across grid squares, a large number of climate variables are available and a wider UKCP09 probabilistic range is considered here[24].

SCPs provide projections of climate change and absolute future climate. The climate projections in UKCP09 should be seen as superseding the scenarios from UKCIP02.

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[23] http://www.landis.org.uk/index.cfm

[24] http://ukclimateprojections.defra.gov.uk/content/view/1194/500/

Although many of the projected changes are of a broadly similar nature, UKCP09 incorporates scientific advances that may have significant implications for the specifics of the projected climate change. It is strongly recommended by the UKCIP that users no longer employ UKCIP02 in new projects.

In UKCP09, the projections are presented for three different future scenarios representing High, Medium and Low greenhouse gas emissions. The types of climate information provided are:

- Observed climate data (20th and 21st century historical information about temperature, precipitation, storminess, sea surface temperatures and sea level)
- Climate change projections (e.g. temperature, precipitation, air pressure, cloud and humidity)

Detailed database structure of UKCP09 and filenames are outlined in Appendix 6.

UKCP09 is available in CSV files; a particular form of text file where each row contains a set of fields separated by commas.

UKCIP02 Vs UKCP09

Main differences between UKCIP02 and UKCP09 are:

- Unlike UKCP09, the UKCIP02 projections were not probabilistic.
- UKCIP02 were produced at a spatial resolution of 50 km and 5 km grid rather than the 25 km resolution of the UKCP09 projections.
- The climate projections in UKCP09 supersede the scenarios from UKCIP02.

Appendix 7 outlines the main differences between the new climate change scenarios UKCP09 and those issued in 2002.

The both datasets UKCIP02 and UKCP09 is focussed on the UK, and is free of charge, but to obtain access to the either UKCP02 or UKCP09 data one must register.

For BVCM, mainly UKCP09-SCP datasets and in some cases UKCIP02 datasets will be used depending on the type of biomass resource (see Section A, B) and input variables. For example, for modelling Miscanthus, baseline values (from 1961 to 1990) of total downward surface shortwave flux (DSWF) is required and this data is available only in UKCIP02. ,

7.2.3 Digital elevation model

SRTM 90m Digital Elevation Data

A digital elevation model is highly desirable to improve the predictive power of the ecological site classification (ESC) component of the forest biomass modelling aspect of the BVCM tool. The Shuttle Radar Tomography Mission (SRTM4) model as corrected by the Consortium for Spatial Information (CGIAR-CSI), is available free for download from http://srtm.csi.cgiar.org/.This dataset is available at three arc second (90 m) resolution for the whole of the UK and is considered one of the highest quality freely-available data sets. This resolution is exceeds the requirement for providing elevation information to the ESC model for the BVCM tool.

7.2.4 Land cover data

CORINE Land Cover

The objectives of the CORINE (Coordination of Information on the Environment) Land Cover (CLC) project are: (i) to provide those responsible for and interested in the European policy on the environment with quantitative data on land cover, which is consistent and comparable across Europe; (ii) to prepare one comprehensive land cover database for the 25 EC member states and other European countries, at an original scale of 1: 100,000, using the same nomenclature.

CLC is based on interpretation of satellite images with land cover types in 44 standard classes Bossard et al., 2000. The scale 1:100,000, minimum mapping unit (MMU) (25 hectares) and minimum width of linear elements (100 metres) for CLC mapping represents a trade-off between production costs and level of detail of land cover information (Heymann et al., 1994). These two basic parameters are the same for CLC1990, CLC2000 and the subsequent CLC2006. The UK contribution to the CLC1990 and CLC2000 products were based on the generalisation of Land Cover Map of Great Britain and the Land Cover Map 2000 (CEH, 2000).

The standard CLC nomenclature includes 44 land cover classes. These are grouped in a three-level hierarchy. The five main (level-one) categories are: (i) artificial surfaces, (ii) agricultural areas, (iii) forests and semi-natural areas, (iv) wetlands, and (iv) water bodies (Heymann et al., 1994). Detailed description of 44 classes of the CLC 2000 database is outlined in Appendix 8.

CLC data is required for the WP2 model and can be downloaded free of charge from the EEA Website[25].

The grid data is in the ETRS89 Lambert Azimuthal Equal Area (ETRS_LAEA) projection system.

7.2.5 Road data

OpenStreetMap

The OpenStreetMap (OSM) data is available in vector files representing road and railway network, forests, water areas, and some points of interest Geofabrik 2010. The maps are created using data from portable GPS devices, aerial photography, other free sources or simply from local knowledge. Both rendered images and the vector graphics are available for download under a Creative Commons Attribution-Share Alike 2.0 licence.

The data is required for the WP2 model and can be downloaded free of charge from the Geofabrik Website[26].

7.2.6 Regional boundary data

UK NUTS2

NUTS (Nomenclature of Territorial Units for Statistics) was created by the European Office for Statistics (Eurostat) as a single hierarchical classification of spatial units used for statistical production across the European Union. In UK, NUTS1 regions corresponds to England, Wales, Scotland and Northern Ireland, while NUTS2 regions are typically counties (at times grouped) and groups of unitary authorities/districts. The NUTS2 regional boundary data for the UK is available at vector format and can be downloaded from the Ordinance

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[25] http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-clc2000-seamless-vector-database
[26] http://www.geofabrik.de/data/download.html

Survey UK[27].

7.3 Description of the software platform

The data harmonisation process and mapping of yield potential, GHG and costs of biomass sources are carried out using the ESRI's ArcGIS 10[28] software products. Some ArcGIS extensions e.g. spatial analyst, 3D analyst as well as additional tools and models will also be exploited for this purpose.

7.4 Description of the harmonisation method of data

The above-mentioned environmental data needed for estimating yield potentials, costs of energy crops and GHG emission are very different in nature. An example of non-uniform characteristic of data is given in Figure 7-1. Therefore, it is important to harmonise them before feeding into the models in WP1 and WP2.

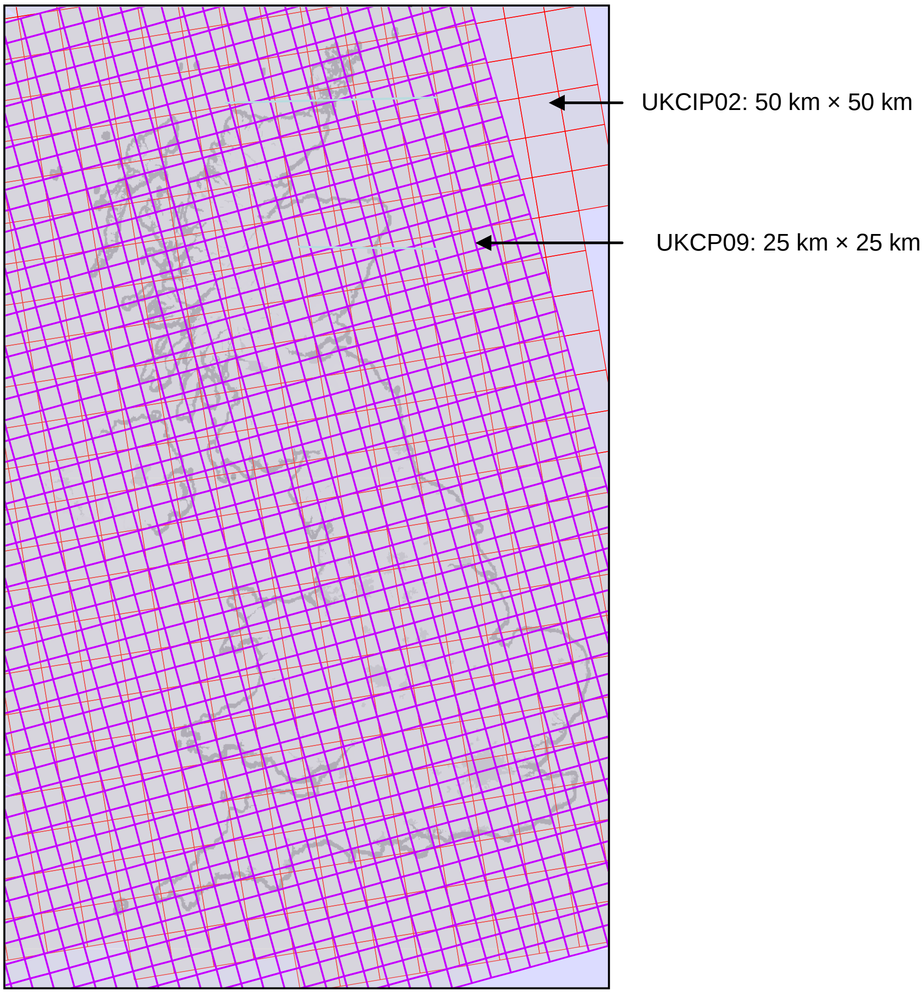

Figure 7-1 Example of two non-harmonised datasets (UKCIP02 and UKCP09)

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[27] (https://www.ordnancesurvey.co.uk/opendatadownload/products.html)

[28] It was confirmed that ETI will upgrade to ArcGIS 10. Otherwise, data/tool will be made compatible to ArcGIS 9.3

The harmonisation process consists of several operations, for example:

1. Transformation of all spatial data into uniform coordinate systems (British National Grid)
2. Conversion of data for instance from vector to raster, BIL to raster, raster to ASCII and vice versa
3. Translation of data by shifting all the coordinates equally and / or rotation by rotating all the coordinates by some angle
4. Setting uniform cell size (disaggregation or aggregation of raster data)

This process as well as the functionalities is explained in Figure 7-2.

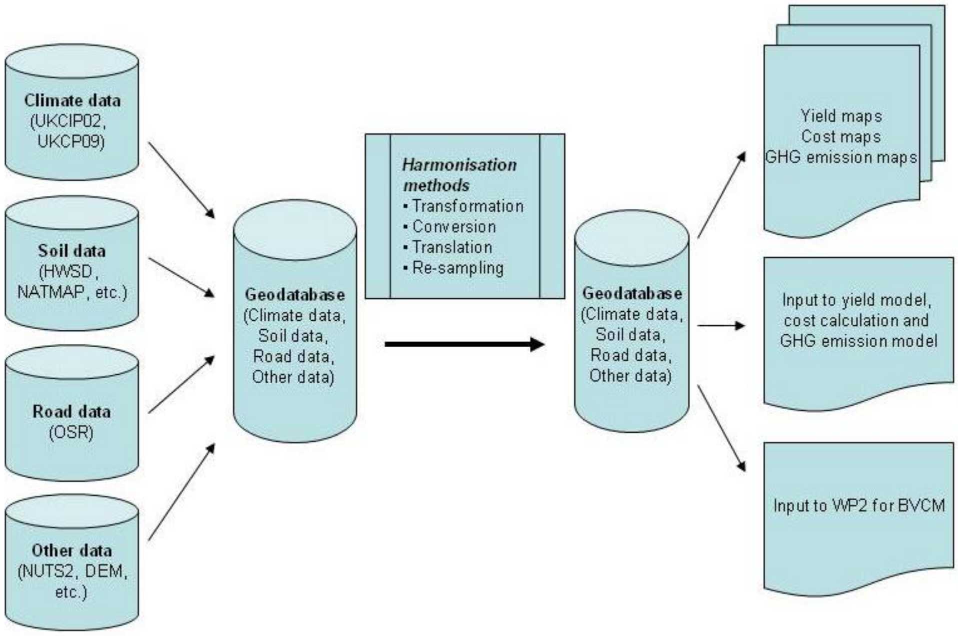

Figure 7-2 Overview of methods and functionality of data harmonisation

The standard re-sampling tools in ArcGIS 10 is used when cells in different but registered[29] rasters often do not line up, either because their cells are different sizes or because their cell boundaries are shifted relative to one another (Figure 7-1).

The re-sampling tool will be used in order to convert the output data (e.g. yield of biomass) into a grid of 10km x 10km, which will be input data for WP2. It is worth to mention that the re-sampling operation may cause data/information loss, especially when re-sampling from small cells to large ones but this does not affect the ultimate goal of the project.

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[29] With common coordinate system

8 Conclusion

8.1 Summary

8.1.1 Yield

At this moment we have highly sophisticated and successfully evaluated process-models for first generation energy crops (winter wheat, sugar beet and oilseed rape) which were used in various climate impact studies and which allow to estimate obtainable yields (water, and temperature effects). These yield estimates using a "perfect model" are being used to derive simple, but physically- based empirical models ("imperfect models") using a regression analysis for a wide range of environments for of the baseline scenario executed for a wide range of environmental situations. These regression models can then be implemented into a GIS environment using spatially specified soil and agro-climatic variables, defined for each of these crops (Table 8-1). For Miscanthus we had developed a similar model in a past project.

All of the empirical models can be linked to new climatic data and respective empirical correction factors accounting for yield gap, technological progress and CFE. While for arable crops yield gaps and technological advancement are well-known, these are largely speculation for second generation crops but hopes for greater improvements are justified likely from experience with first generation crops experience.

For SRC willow, we have a parameterised and validated a process-based model, evaluated using a minimum of six UK field trials (across diverse soil and climate ranges) with data supplied by Forest Research. This SRC process-based model will now be linked to spatial input data sets for soils and climate, including future climate scenarios using the UKCP09 datasets. The output data for yield at a 1 km resolution should be available from end of July 2011. Over the course of the next two months, ten discrete scenarios will be run (consisting of two emission scenarios, medium and high, and five decades 2000-2050) and model output for yield supplied to WP3.

Biomass estimates for forest products (short-rotation forest, high forest stemwood, and high-forest branchwood) derived from agro-climatic variables are produced by the CARBINE model where species, management type and yield class are also specified as parameters. At present, information for existing forest areas is available from the Forestry Commission sub-compartment database and the National Inventory of Woodland and Trees. Prediction of future yield-class for the required time steps and climatic scenarios may be achieved using a framework based on the ESC model with additional information from more specific, localised, empirical measurements.

Yield	Type of model	Input variable	Output	Format of delivery	Functionality
Winter wheat	Empirical physically based model	Soil available water capacity (AWC) using European soil database, aggregated weather variables of mean monthly air temperature, total monthly precipitation and global radiation	Grain yield, biomass	Equations, spatially referenced spreadsheets or maps at UK $1km^2$ grid or any other scale (if needed)	Implemented in a GIS, the meta-model is spatially explicit, predicts decadal future yields as function of climate, CO_2 and technological progress
Sugar beet	Empirical, physically based model	Soil available water capacity (AWC) using European soil database , aggregated weather variables of mean monthly air temperature, total monthly precipitation and global radiation	Sugar yield, biomass		
Oil seed rape	Empirical, physically based model	Soil available water capacity (AWC) using European soil database , aggregated weather variables of mean monthly air temperature, total monthly precipitation and global radiation	Grain yield		
Miscanthus	Empirical, physically based model	Soil available water capacity (AWC) derived from petro-transfer function (PTF), using European soil database, aggregated weather variables of mean monthly air temperature, total monthly precipitation	Biomass yield		
SRC-willow	Process-based biophysical model	Soil var's, Climate var's, [CO2] mean value derived for each decade and emission scenario, Management details and SRC willow parameter values.	Above ground biomass yield (dry mass)	UK-based at 1 Km^2 resolution, provided as maps and text format (e.g. csv)	Yield outputs are spatially explicit and predict mean future yields (odt ha-1 yr-1) derived from harvesting every three years and as a function of climate, CO2 and management
High forest and SRF	Analytical growth and yield model	Soil type, accumulated temperature, soil moisture deficit, elevation, possibly windiness and continentality	Biomass yield stemwood, roots, branches or primary products	Either equations or spatially-referenced lookup values	Dependent on user requirements for temporal resolution

Table 8-1 Description of the yield meta-model

8.1.2 Cost

The production and opportunity cost costing methodology will provide annualised regional production cost estimates for a range of bioenergy resources as well as the opportunity cost of producing bioenergy resources vis-à-vis traditional agricultural crops. These cost calculations will be based on data from a combination of farm surveys of actual revenue and costs, and crop and bioenergy specific profitability data published by the industry and various academic and research institutions. The cost estimates feature the added functionality, when compared to existing limited estimates of production and opportunity costs of bioenergy resource production, of being spatially explicit.

8.1.3 GHG emissions

A methodology has been proposed to estimate the GHG emissions associated with the production of the bioresources included in the project. This methodology is broadly based on well-established GHG emissions accounting approaches and modelling, such as the Carbon Calculator developed for the UK Renewable Transport Fuel Obligation and the IPCC Tier 1 method. Compared to other existing GHG models developed to assess the supply of bioenergy in the UK, the proposed GHG emissions model features the added functionality of being spatially explicit as regards the fertiliser requirements, and hence the fertiliser emissions (which are typically the largest source of direct emissions) for first generation resources.

GHG	Type of model	Input variable	Output	Format of delivery	Functionality
Wheat	Excel functions and look up tables	Rainfall regime, soil type, yield	GHG emissions map	Excel spreadsheet	Spatially explicit emissions depending on rainfall, yield, and crop residue use
Sugar beet					
Oil seed rape					
Miscanthus		Yield			Spatially explicit emissions depending on yield
SRC-willow					
SRF and Forestry systems		None	GHG emissions (blanket) value		Constant value (not spatially explicit) if resource is harvested
Straw	See wheat				

Table 8-2 Description of the GHG meta-model

8.1.4 Datasets

Different data sets are required for modelling of yield, cost and GHG emissions. They have been identified, e.g. both HWSD and ESDB soil data, both UKCP09-SCP and UKCIP02 climate scenario data will be used, this is mainly due to different nature of resources and types of models. It is also evident that the characteristics of datasets are different, and that they need to be harmonised. Therefore, a rigorous harmonisation method has been proposed. On the other hand, mapping of the data variables with model variables are investigated as well. For example, modelling of resources requires climate variable of same or different nature as input into the models and these variables are identified within the climate datasets from where they are retrieved afterwards.

Table 8-3 explains the characteristics of different input datasets that are required for modelling.

Data	Coverage	Format	Scale	Availability	Owner
Harmonised World Soil Database	UK	BIT	30 arc-second (or 1km × 1km)	Publicly available	IIASA
European Soil Database	UK	Grid	1km × 1km, 10km×10km	Publicly available	JRC
LandIS (NATMAP)	England, Wales	Vector	1:250,000	Academic license at RR and Soton	National Soil Resources Institute
UKCIP02	UK	Vector, ASCII	50km × 50km	Publicly available	UK Climate Impacts Programme
UKCP09	UK	CVS, ASCII	25km × 25km	Publicly available	UK Climate Impacts Programme
SRTM 90m Digital Elevation Data	UK	ASCII, tiff	3 arc second (or 90m × 90m	Publicly available	NASA/USGS
Corine Land Cover Data	UK	Vector	1: 100 ,000	Publicly available	European Environment Agency (EEA)
UK Road Data	UK	Vector	N/A	Publicly available	Geofabrik GmbH
NUTS 2 Region boundary	UK	Vector	N/A	Publicly available	Ordinance Survey UK

Table 8-3 An overview of the geophysical and climate data required for modelling in WP1 and WP2

8.2 Next steps

First generation arable bioenergy crops (winter wheat, oilseed rape, sugar beet)

Based on the strong and highly significant relationships between yields estimated by a process-based (“perfect”) model and empirical regression (“imperfect”) model, which are determined by the same climatic and soil variables we conclude that the empirical model is sufficient for the study at this scale. Furthermore, the advantage of these simple functions is that they can be easily implemented within a GIS framework and that they can be re-run with inputs from new or other climate scenarios.

We recommend however, (a) to cross-validate estimates for the future based on this empirical approach, which is founded on the baseline scenario, with an independent data set for the future, and (b) to compare the simulated yields against real observations, e.g. yields from variety trials around the country. With regard to second generation biomass crops we recommend (a) to use the respective process-models to explore technological advancement and (b) to cross-validate process and empirical model as done for first generation energy crops.

Second generation, perennial bioenergy crops (Miscanthus and SRC willow)

With regard to second generation biomass crops we recommend that the best available options for spatial modelled yield outputs will be applied. For Miscanthus, an empirical approach will be taken and for SRC willow, process-based model runs will be utilised.

Once climate and soils data are available in a spatially referenced dataset, we can begin the SRC willow model runs as defined in this document, providing ten yield maps covering two climate change scenarios and five decades. We hope to complete the first phase of this task by end of July 2011 and to supply these data to WP3. A second set of model scenarios will be run over the summer with data available during September 2011.

Forestry resources (High forest, SRF)

Initial work will focus on developing the necessary linkages between spatial climate, site and soil datasets, to enable the forestry models to be run for regions of the UK under relevant scenarios. A critical first step will involve clarifying with the project partners the exact requirements for temporal resolution in biomass estimates for forest resources, as this will determine how models are applied and the most appropriate approach to delivery of outputs. The projected delivery date for a ‘first cut’ set of outputs by Forest Research to other project partners is end August 2011; a final set will be elaborated and made available by early October 2011.

Cost Calculation

For the resource cost modelling, having identified the base production cost structure for each bioenergy resource and competing agricultural crop, the next steps involve the preparation of the input datasets, notably the estimation of production costs.

The completion of the production and opportunity cost data is predicated on the generation of the spatial yield data by the project partners. We hope to complete the initial production cost data phase by the beginning of September and the initial opportunity cost data phase by the middle of September. Following receipt of the second set of spatial yield data, a final set of both production and opportunity cost data will be made available by mid October 2011.

Initial contact with industry stakeholders has been made. Selected industry bodies will be contacted during August and given the opportunity to comment on the methodology and the initial assumptions being put forward. In September, the initial production and opportunity cost data will be presented for comment, with the final production and opportunity cost data presented for validation in October.

GHG Emission Model

The next steps for the GHG model consist in preparing the relevant input datasets for running the model, developing the mode itself, and test it against other published model (e.g. E4tech, 2010)

Environmental Data

Data retrieval activities will continue until end of August 2011. It is noted that the biomass crop cultivation area is naturally constrained by physical factors such as rivers, lakes, urban areas, steep slopes as well as areas of natural and cultural designation (e.g. key habitats, nature reserves and heritage sites (Lovett et al. 2009). Therefore, the selection of factors that can preclude the energy crop planting will be elaborated, the datasets and their sources will be adequately described and investigated in the next step. In this regard it will be investigated whether the consortium can use the outcome of the UKERC funded project-biocrop constraints mapping led by Prof Andrew Lovett at the University of East Anglia. Moreover, data harmonisation method will be applied and a Geodatabase with definition of individual layers will be built. It would act as the base for further yield calculation, cost estimation, GHG emission assessment and BVCM. Different maps will be produced as well as data layers will be delivered to the WP2 for further modelling. This task will continue until the end of 2011.

References

First Generation Biofuel Crops

Amthor, J. S. 2001 Effects of atmospheric CO2 concentration on wheat yield: review of results from experiments using various approaches to control CO2 concentration. Field Crops Res. 73, 1–34. (doi:10.1016/S0378-4290(01)

Armour, T, Jamieson, PD and Zyskowski, RF 2002. Testing the Sirius Wheat Calculator. Agronomy New Zealand 32, 1-6.

Berry PM and Spink JH, 2006. A physiological analysis of oilseed rape yields: Past and future. Journal of Agricultural Science, Cambridge 144, 381-392.

Berry PM and Spink JH, 2009. 'Canopy management' and late nitrogen applications to improve yield of oilseed rape. Report 447 to Home-Grown Cereals Authority.

Butterworth MH, Semenov MA, Barnes A, Moran D, West JS, Fitt BDL, 2010. North–South divide: contrasting impacts of climate change on crop yields in Scotland and England. J. R. Soc. Interface doi:10.1098/rsif.2009.0111

Clarke J, Twining S, Harris D, Wynn S and Peers D 2009 Future of UK winter oilseed rape production. ADAS UK Ltd.

Ewert F, Rounsevell M D A, Reginster I, Metzger M J and Leemans R 2005 Future scenarios of European agricultural land use I. Estimating changes in crop productivity. Agriculture Ecosystems & Environment 107, 101-116.

Ferrara R.M., Rana G., Trevisiol P., Acutis M., Richter G.M., Baggaley N. (2010), Topographic impacts on wheat yields under climate change - a case study in Europe, Theoretical Applied Climatology, 99: 53-65.

Gabrielle B, Denoroy P, Gosse G, Justes E and Andersen M N 1998 Development and evaluation of a CERES-type model for winter oilseed rape. Field Crops Research 57, 95-111.

Hillier J. Whittaker C., Dailey G., Aylott M., Casella E., Richter G., Riche G., Murphy R., Taylor G., Smith P., Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analysis, GCB Bioenergy (2009) 1, 267-281.

Jaggard, K.W., Werker, A.R. 1999. An evaluation of the potential benefits and cost of autumn-sown sugar beet in NW Europe. Journal of Agricultural Science, Cambridge 132, 91-102.

Jaggard K W, Qi A and Armstrong M J 2009 A meta-analysis of sugarbeet yield responses to nitrogen fertilizer measured in England since 1980. Journal of Agricultural Science 147, 287-301.

Jaggard K W, Qi A and Semenov M A 2007 The impact of climate change on sugarbeet yield in the UK: 1976-2004. Journal of Agricultural Science 145, 367-375.

Jaggard K W, Qi A M and Ober E S 2010 Possible changes to arable crop yields by 2050. Philos T R Soc B 365, 2835-2851.

Jamieson P D, Semenov M A, Brooking I R and Francis G S 1998 Sirius: a mechanistic model of wheat response to environmental variation. European Journal of Agronomy 8, 161-179.

Lancashire, P.D., Bleiholder, H., van den Boom, T., Langeluddeke, P., Stauss, R., Weber, E., Witzenberger, A., 1991. A uniform decimal code for growth stages of crops and weeds. Ann Appl Biol 119, 561 - 601.

Lawless C, Semenov M A and Jamieson P D 2005 A wheat canopy model linking leaf area and phenology. European Journal of Agronomy 22, 19-32.

Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop Yield Gaps: Their Importance, Magnitudes, and Causes. Annual Review of Environment and Resources 34, 179-204.

Lobell D B and Burke M B 2010 On the use of statistical models to predict crop yield responses to climate change. Agricultural and Forest Meteorology 150, 1443-1452.

Long, S. P.; Ainsworth, E. A.; Leakey, A. D. B. & Morgan, P. B. 2005 Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. Phil. Trans. R. Soc. B 360, 2011-2020. (doi:10.1098/rstb.2005.1749.)Lunn G D, Spink J, Stokes D T, Wade A, Clare R W and Scott R K 2001 Canopy Management in winter oilseed rape. In Project Report OS49. Ed. HGCA. p. 86. Home-Grown Cereals Authority.

Qi A, Kenter C, Hoffmann C and Jaggard K W 2005 The Broom's Barn sugar beet growth model and its adaptation to soils with varied available water content. European Journal of Agronomy 23, 108-122.

Richter G M, Acutis M, Trevisiol P, Latiri K and Confalonieri R 2010 Sensitivity analysis for a complex crop model applied to Durum wheat in the Mediterranean. European Journal of Agronomy 32, 141-150.

Richter G M, Jaggard K W and Mitchell R A C 2001 Modelling radiation interception and radiation use efficiency for sugar beet under variable climatic stress. Agricultural and Forest Meteorology 109, 13-25.

Richter G M, Jaggard K, Mitchell R and Semenov M A 2002 Assessing drought risks for UK crops under climate change. DEFRA Project CC0336, Final Report. 22pp.

Richter GM, Glendining M, Coleman K, Qi A, Jaggard KW, Semenov MA, 2004. Re-assessing drought risks for UK crops using UKCIP02 climate change scenarios. Report to DEFRA, Commission CC0368.

Richter G M, Qi A, Semenov M A and Jaggard K W 2006 Modelling the variability of UK sugar beet yields under climate change and husbandry adaptations. Soil Use and Management 22, 39-47.

Richter G M, Rana G, Ferrara R M, Ventrella D, Acutis M, Trevisiol P, Mayr T, Baggaley N, Morris J, Holmes A, Trawick P, Dailey A G, Robbins P, Simota C, Whitmore A P and Powlson D S 2006 Stability and Mitigation of Arable Systems in Hilly Landscapes. In Final Report. p. 280. European Commission, Brussels.

Richter G M and Semenov M A 2005 Modelling impacts of climate change on wheat yields in England and Wales: assessing drought risks. Agr Syst 84, 77-97.

Richter GM, Riche AB, Dailey AG, Gezan SA, Powlson DS (2008) Is UK biofuel supply from Miscanthus water-limited? Soil Use and Management 24: 235-245.

Ritchie J T and Otter S 1985 Description and performance of CERES-Wheat: a user-oriented wheat yield model. In ARS Wheat Yield Project. Ed. W O Willis. pp 159–175. USDA-ARS.

Semenov M A 2007 Development of high-resolution UKCIP02-based climate change scenarios in the UK. Agricultural and Forest Meteorology 144, 127-138.

Spink, J., Street, P., Sylvester-Bradley, R., Berry, P., 2009. The potential to increase productivity of wheat and oilseed rape in the UK. In: BIS, G. (Ed.). Department of Business, Innovation and Services. http://www.bis.gov.uk/go-science/science-in-government/global-issues/food/~/media/5C4E476342334B608B748767805B1115.ashx

van Ittersum, M.K., Leffelaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J., 2003. On approaches and applications of theWageningen cropmodels. Eur. J. Agron. 18, 201–234.

Werker A R and Jaggard K W 1998 Dependence of sugar beet yield on light interception and evapotranspiration. Agricultural and Forest Meteorology 89, 229-240.

Second Generation Biomass/Biofuel (Miscanthus)

Aylott, M.J., Casella, E., Tubby, I., Street, N.R., Smith, P. and Taylor, G. 2008. Yield and spatial supply of bioenergy poplar and willow short rotation coppice in the UK. New Phytologist 178, 358-370.

Berry JK (1993) Cartographic modeling: the analytical capabilities of GIS: In Goodchild MF, Parks BO and Steyaert LT (eds) Environmental Modeling with GIS, Oxford University Press, Oxford, 58-74

Boorman, D.B., Hollis, J.M. and Lilly, A., 1995. In Hydrology of soil types: a hydrologically-based classification of the soils of the United Kingdom. Report No. 126, CEH, Wallingford.

Clifton-Brown J C, Stampfl P F and Jones M B 2004 Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. Global Change Biology 10, 509-518.

Finch J W and Riche A B 2010 Interception losses from Miscanthus at a site in south-east England-an application of the Gash model. Hydrological Processes 24, 2594-2600.

Long, S. P., Ainsworth, E. A., Leakey, A. D. B. and Morgan, P. B. 2009 Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. Phil. Trans. R. Soc. B 360, 2011–2020. (doi:10.1098/rstb.2005.1749)

Lovett AA; Sünnenberg GM; Richter GM; Dailey AG; Riche AB and Karp A., 2009. Land use implications of increased biomass production identified by GIS-based suitability and yield mapping for Miscanthus in England. Bioenergy Research 2: 17-28.

Price L, Bullard M, Lyons H, Anthony S, Nixon P (2004) Identifying the yield potential of Miscanthus x giganteus: an assessment of the spatial and temporal variability of M. x giganteus biomass productivity across England and Wales. Biomass Bioenergy 26 (1):3-13

Richter GM, Riche AB, Dailey AG, Gezan SA, Powlson DS (2008) Is UK biofuel supply from Miscanthus water-limited? Soil Use and Management 24: 235-245.

Richter GM, Dailey AG, Riche AB 2008b. A new type of process-based model for biomass yield from grass crops. Book of Abstracts. Soc of Exp Biol, Conference Marseille, 6-9 July 2008.

Richter, G.M., Dailey, G.A., Riche, A.B., 2010. Identifying key process parameters in a sink-source interaction model for energy crops. XI ESA Congress Agro2010, Montpellier, pp. 97-98.

Woesten, J.H.M., Lilly, A., Nemes, A. and Le Bas, C., 1999. Development and use of a database of hydraulic properties of European soils. Geoderma, 90(3-4): 169-185.

Second Generation Biomass/Biofuel (SRC-Willow)

Aylott, M.J., Casella, E., Tubby, I., Street, N.R., Smith, P., Taylor, G. (2008), Yield and spatial supply of bioenergy poplar and willow short rotation coppice in the UK, New Phytologist, 178, 358-370.

Aylott MJ. 2011. Climate change impacts on the availability of short rotation coppice. PhD thesis University of Southampton.

Ball, J.T., Woodrow, I.E. and Berry, J.A. 1987. A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. In: Progress in photosynthesis research, vol.4, ed. J. Biggins. M Nijhoff, Dordrecht, 221–224.

Deckmyn, G., Evans, S. P. and Randle, T. J. 2006. Refined pipe theory for mechanistic modeling of wood development. Tree Physiology, 26, 703-717.

Evans S, Randle T, Henshall P, Arcangeli C, Pellenq J, Lafont S, and Vials C. 2003. Recent advances in the mechanistic modelling of forest stands and catchments. Forest Research Annual Report and Accounts 2003–2004.

FAO/IIASA/ISRIC/ISSCAS/JRC, 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria)

Farquhar, G. D., Caemmerer, S. v. and Berry, J. A. 1980. A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species. Planta, 149, 78-90.

Karnosky DF, Tallis MJ, Darbah J and Taylor G. 2007. Direct Effects of Elevated CO2 on Forest Tree Productivity. Published in Forestry and Climate Change [P.H. Freer-Smith, M.S.J.Broadmeadow, and M.J. Lynch (eds.)], CABI Publishing pp. 136-142.

Liberloo M, Lukac M, Calfapietra C, Hoosbeek MR, Gielen B, Miglietta F, Scarascia-Mugnozza GE and Ceulemans R. 2009. Coppicing shifts CO2 stimulation of poplar productivity to above-ground pools: a synthesis of leaf to stand level results from the POP/EUROFACE experiment. New Phytologist 182: 331–346

Long, S.P. 1991. Modification of the response of photosynthetic productivity to rising temperature by atmospheric CO_2 concentrations: has its importance been underestimated? Plant, Cell and Environment 14: 729–739.

Long SP, Ainsworth EA, Rogers, A and Ort DR. (2004) Rising atmospheric carbon dioxide: Plants FACE the future. Annual Review of Plant Biology, 55, 591-628.

McMurtrie, R.E. and Wang, Y. 1993. Mathematical models of the photosynthetic response of tree stands to rising CO2 concentrations and temperatures. Plant, Cell and Environment 16: 1–13.

Nelson ND and Isebrands JD. (1983) Late-season photosynthesis and photosynthate distribution in an intensively-cultured Populus-nigra x laurifolia clone. Photosynthetica, 17, 537-549

Oliver, RJ. Finch, JW. and Taylor G. 2009. Second generation bioenergy crops and climate change: a review of the effects of elevated atmospheric CO_2 and drought on water use and the implications for yield. GCB Bioenergy, 1: 97–114

Somerville, C., Youngs, H., Taylor, C., Davis, S.C., Long, S.P., 2010. Feedstocks for Lignocellulosic Biofuels. Science 329, 790-792.

Tallis MJ, Henshall P, Aylott MJ, Casella E, Randle T, Morison JIL and Taylor G. 2011. Development and evaluation of a process model for SRC bioenergy yield potential. GCB Bioenergy in prep.

Tricker PJ, Trewin H, Kull O, Clarkson GJJ, Eensalu E, Tallis MJ, Colella A, Doncaster CP, Sabatti M and Taylor G (2005) Stomatal conductance and not stomatal density determines the long-term reduction in leaf transpiration of poplar in elevated CO_2. Oecologia, 143, 652-660

Tricker, PJ. Pecchiari M, Bunn, SM. Vaccaric, FP. Peressotti, A. Miglietta, F. and Taylor , G. 2009. Water use of a bioenergy plantation increases in a future high CO_2 world. Biomass and Bioenergy 33: 200-208.

von Caemmerer, S. and Farquhar, G. D. 1981. Some relationships between the biochemistry of photosynthesis and the gas exchange of leaves. Planta, 153, 376-387.

Forest Based Wood Resources

Allison, S.M., Proe, M.F. and Matthews, K.B. (1994) The prediction and distribution of general yield classes of Sitka spruce in Scotland by empirical analysis of site factors using a geographic information system. Canadian Journal of Forest Research, 24, 2166-2171.

Anderson, M.L. (1950). The selection of tree species. Oliver & Boyd, Edinburgh.

Cajander, A.K. (1926). The theory of forest types. Acta Forestalia Fennica 29: 1-108.

Cleland, D. T., J. B. Hart, et al. (1993). Ecological Classification and Inventory System of the Huron-Mainistee National Forests. Forest Service, United States Department of Agriculture.

Beets, P.N., Robertson, K., Ford-Robertson, J.B., Gordon, J. and Maclaren, J.P. (1999) Description and validation of C-change: a model for simulating carbon content in managed pinus radiate stands. New Zealand Journal of Forestry Science, 29, 409-427.

Broadmeadow, M. S. J., Ray, D. and Samuel, C. J. A. (2005). Climate change and the future for broadleaved tree species in Britain. Forestry 78.

Dewar, R.C. (1990). A model of carbon storage in forests and forest products. Tree Physiology 6: 417-428.

Dewar, R.C. (1991). Analytical model of carbon storage in trees, soils, and wood products of managed forests. Tree Physiology 8: 239–258.

Dewar, R.C. and Cannell, M.G.R. (1992). Carbon sequestration in the trees, products and soils of forest plantations: an analysis using UK examples. Tree Physiology 11: 49–71.

Edwards, P.N. and Christie, J.M. (1981) Yield models for forest management. Forestry Commission Booklet 48. Forestry Commission: Edinburgh.

Klinka, K., Krajina, V.J., Ceska, A., & Scagel, A.M. (1989). Indicator plants of coastal British Colombia. UBC Press, Vancouver.

Krajina, V.J. (1969). Ecology of forest trees in British Colombia. In Ecology of western North America, Vol. 2, ed. V.J. Krajina. University of British Colombia Department of Botany, Vancouver.

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J, Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J. and Apps, M.J. (2009). CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecological Modelling, 220, 480-504.

Kuusipalo, J. (1985). An ecological study of upland forest site classification in Southern Finland. Acta Forestalia Fennica 192, 1–78.

Lavers, G.M. (1983). The strength properties of timber. Building research Establishment Report CI/SfB1976. HMSO, London.

Macmillan, D.C. and Towers, W. (1991) Estimating the yield class of Sitka spruce from the Land Capability for Forestry classification. Scottish Forestry, 45, 298-301

Macmillan, D.C.; Towers, W. and Crabtree, J. R. (1990) Yield class and windthrow hazard characteristics of forestry in Grampian region. Report to Scotish Forestry Trust. The Macaulay Land Use Research Institute: Aberdeen.

Marland G. and Schlamadinger, B. (1995) Biomass fuels and forest management strategies: How do we calculate the greenhouse-gas emissions benefits? Energy, 20, 1131-1140.

Marland, G., and Schlamadinger, B. (1999) The Kyoto Protocol could make a difference for the optimal forest-based CO2 mitigation strategy: some results from GORCAM. Environmental Science and Policy, 2, 111–124.

Matthews, G.A.R. (1993). The carbon content of trees. Technical Paper 4. Forestry Commission, Edinburgh.

Matthews, R.W. (1991) Biomass production and carbon storage by British forests. In: Aldhous, J.R. (ed.) Wood for energy: the implications for harvesting, utilisation and marketing. Proceedings of a discussion meeting, Heriot-Watt University, Edinburgh, 5-7 April 1991. Institute of Chartered Foresters: Edinburgh, 162-177.

Matthews, R.W., Matthews, G.A.R., Anderson, R.A. and Sencee, S.S. (1991) Construction of yield tables for woody biomass production and carbon storage by British plantation tree species. Proceedings 10th World Forestry Congress, 2, 87-97.

Matthews, R.W. (1994) Towards a methodology for the evaluation of the carbon budget of forests. In: Kanninen, M. (ed.) Carbon balance of the world's forested ecosystems: towards a global assessment. Proceedings of a workshop held by the Intergovernmental Panel on Climate Change AFOS, Joensuu, Finland, 11-15 May 1992. Painatuskeskus: Helsinki, 105-114.

Matthews, R.W. (1996) The influence of carbon budget methodology on assessments of the impacts of forest management on the carbon balance. In Apps, M.J. and Price, D.T. (eds.) Forest ecosystems, forest management and the global carbon cycle. NATO ASI Series I 40. Springer-Verlag: Berlin, 233-243.

Matthews, R.W. and Methley, J.M. (1996) Site classification and yield prediction for lowland sites in England and Wales. MAFF contract report CSA 2119 supplement. Forest Research: Farnham.

Matthews, R.W., Methley, J.M., Alexander, M., Jokiel, P. and Salisbury, I. (1996) Site classification and yield prediction for lowland sites in England and Wales. MAFF contract report CSA 2119. Forest Research: Farnham.Matthews, R.W., Randle, T.J., Mackie, E.D. and Tubby, I. (2008) Estimating potential biomass production from existing forests in Great Britain. Internal Forest Research Report (unpublished).

Matthews, R. W. and Duckworth, R. R. (2005) BSORT: a Model of Tree and Stand Biomass Development and Production in Great Britain. In: Imbabi, M.S. and Mitchell, C.P. (eds.) Proceedings of World Renewable Energy Congress (WREC 2005), 22-27 May 2005, Aberdeen, UK. Elsevier: Oxford, 404-409.

Matthews, R.W. and Mackie, E.D. (2006) Forest Mensuration: a handbook for practitioners. Forestry Commission: Edinburgh.

Matthews, R.W., Randle, T.J., Mackie, E.D. and Tubby, I. (2008) Estimating potential biomass production from existing forests in Great Britain. Forest Research internal report. (unpublished).

Matthews, R.W. and Broadmeadow, M.S.J. (2009) The potential of UK forestry to contribute to Government's emissions reduction commitments. In: Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds.) Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office: Edinburgh, 139-161.

Mohren, G.M.J. and Klein Goldewijk, C.G.M. (1990). CO2FIX: a dynamic model of the CO2-fixation in forest stands. "De Dorschkamp", Research Institute for Forestry and Urban Ecology Report 624: Wageningen.

Mohren, G.M.J., Garza Caligaris, J.F., Masera, O., Kanninen, M., Karjalainen, T. and Nabuurs, G.-J. (1999). CO2FIX for Windows: a dynamic model of the CO2 fixation in forest stands. Institute for Forestry and Nature Research (The Netherlands), Instituto de Ecologia (UNAM, Mexico), Centro Agronomico Tropical de Investigacion y Ensenanza (Costa Rica) and European Forest Institute (Finland).

Nabuurs, G.-J. (1996) Significance of wood products in forest sector carbon balances. In: Apps, M.J. and Price, D.T., Forest ecosystems, forest management and the global carbon cycle (eds M.J. Apps and D.T. Price). NATO ASI Series I 40. Springer-Verlag: Berlin, 245-256.

Pyatt, D. G. and Ray, D. et al. (2001) An Ecological Site Classification for Forestry in Great Britain. Forestry Commission Bulletin 124, Forestry Commission: Edinburgh.

Ray, D. (2001) Ecological Site Classification: A PC-based Decision support system for British Forests V1.7 User Guide. Forestry Commission: Edinburgh.

Ray, D., Reynolds, K., Slade, J., & Hodge, S. (1998). A spatial solution to Ecological Site Classification for British Forestry using Ecosystem Management Decision Support. 3rd International Conference on GeoComputation, University of Bristol, United Kingdom, 17–19 September 1998.

Ray, D., Suarez, J. and Pyatt, D.G. (1996). Development of an Ecological Site Classification System Decision Support System for British Forestry. Proceedings: 1st International Conference on GeoComputation, Leeds University, September 1996.

Robertson, K., Ford-Robertson, J., Matthews, R.W. and Milne, R. (2003). Evaluation of the C-Flow and CARBINE carbon accounting models. In: UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry Activities (ed. R. Milne). Report to DEFRA (contract EPG1/1/160). Centre for Ecology & Hydrology: Edinburgh.

Schlamadinger B. and Marland, G. (1996) Carbon implications of forest management strategies. In: Apps, M.J. and Price, D.T., Forest ecosystems, forest management and the global carbon cycle. NATO ASI Series I 40. Springer-Verlag: Berlin, 217-232.

Smith, S. and Gilbert, J. (2003) Forestry Commission: National Inventory of Woodland and Trees. Country report for Great Britain. Forestry Commission: Edinburgh.

Thompson, D.A. and Matthews, R.W. (1989) The storage of carbon in trees and timber. Forestry Commission Research Information Note 160. Forestry Commission: Edinburgh, UK.

Tyler, A.L., Macmillan, D.C. and Dutch, J. (1996) Models to predict the General Yield Class of Douglas fir, Japanese larch and Scots pine on better quality land in Scotland. Forestry, 69, 13-24.

Tyler, A.L., MacMillan, D.C. and Dutch, J. (1995) Predicting the yield of Douglas-Fir from site factors on better quality sites in Scotland. Annales des Sciences Forestieres, 52, 619-634.

Waring, R.H. (2000) A process model analysis of environmental limitations on the growth of Sitka spruce plantations in Great Britain. Forestry, 73, 65-79.

White, E.J. (1982) Relationship between height growth of Scots pine (Pinus sylvestris L.) and site factors in Great Britain. Forest Ecology and Management, 4, 225-245.

Worrell, R. and Malcom, D.C. (1990a) Productivity of Sitka Spruce in Northern Britain 1. The Effects of Elevation and Climate. Forestry, 63, 105-118.

Worrell, R. and Malcom, D.C. (1990b). Productivity of Sitka Spruce in Northern Britain 2. Prediction from Site Factors. Forestry, 63, 119-128.

Zadeh, L. A. (1992). Knowledge representation in fuzzy logic. An introduction to fuzzy logic applications in intelligent systems pp.1–25. Eds. R. R. Yager and L. A. Zadeh, Kluwer Academic, Boston.

Cost calculation

Aylott, M.J., Casella, E., Tubby, I., Street, N.R., Smith, P., Taylor, G. (2008), Yield and spatial supply of bioenergy poplar and willow short rotation coppice in the UK, New Phytologist, 178, 358-370.

Bell J., Booth E., Ballinghall M. (2007), Commercial viability of alternative non food crops and biomass on Scottish farms, a special study supported under SEERAD Advisory Activity 211.

DEFRA (2010), Fertiliser Manual (RB209), 8th Edition, June 2010

Rosenqvist H., Nilsson L. (2006), Energy crop production costs in the EU, RENEW renewable fuels for advanced power trains project, available on: http://www.renew-fuel.com/download.php?dl=del_sp5_wp3_5-3-4_07-01-30_lu.pdf&kat=18

Ericsson K., Rosenqvist H., Nilsson L. (2007), Future energy crop production costs in the EU, Paper presented at the 15th European Biomass Conference and Exhibition, 7-11 May 2007, Berlin, Germany.

Ericsson K., Rosenqvist H., Nilsson L. (2009), Energy crop production costs in the EU, Biomass and Bioenergy, 33(11), 1577-1586.

Ferrara R.M., Rana G., Trevisiol P., Acutis M., Richter G.M., Baggaley N. (2010), Topographic impacts on wheat yields under climate change - a case study in Europe, Theoretical Applied Climatology, 99: 53-65.

Nikolaou A., Remrova M., Jeliazkov I. (2003), Biomass availability in Europe. Report for the European Commission, Lot 5: Bioenergy's role in the EU Energy Market.

Nix J. (2010), Farm management Pocket Pocketbook, 41st Edition, September 2010

Richter G. M., Semenov M.A., (2005), Modelling impacts of climate change on wheat yields in England and Wales - assessing drought risks, Agricultural Systems 84(1), 77-97.

Richter G. M., Semenov M.A., Jaggard K.W., (2006), Modelling the variability of UK sugar beet yields under climate change and husbandry adaptations. Soil Use Management 22, 39-47.

Richter G. M., Riche A. B., Dailey A.G., Gezan S.A., Powlson D.S., (2008), Is UK biofuel supply from Miscanthus water-limited? Soil Use and Management, 24, 235-245.

VIEWLS, (2005), Shift gear to biofuels, Results and recommendations from the VIEWLS project. Final report.

GHG emission model

Ahlgren S, Hansson P-A, Kimming M, Aronsson P, Lundkvist H, (2009). Greenhouse gas emissions from cultivation of agricultural crops for biofuels and production of biogas from manure - Implementation of the Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Revised according to instructions for interpretation of the Directive from the European Commission 2009-07-30. SLU Report Dnr SLU ua 12-4067/08, Uppsala, 08-09-09, 52 pp.

AEA Technology and North Energy Associates (2011), The Biomass Environmental Assessment Tool (BEAT) v2.1, available on: http://www.biomassenergycentre.org.uk/portal/page?_pageid=74,153193&_dad=portal&_schema=PORTAL

Aylott M., Casella E., Rarral K., Taylor G., (2010), Estimating the supply of biomass from short-rotation coppice in England, given social, economic and environmental constraints to land availability, Biofuel (2010) 1(5), 719-727.

Brentrup F., Pallière C. (2008) ,GHG emissions and energy efficiency in European nitrogen fertiliser production and use, Proceedings of the International Fertiliser Society (ISSN 1466-1314 ; no. 639).

BioGrace (2011), Harmonised Calculation of Biofuel Greenhouse Gas Emissions in Europe, GHG calculation tool, available on: http://www.biograce.net/content/ghgcalculationtools/overview

DEFRA (2010), Fertiliser Manual (RB209), 8th Edition, June 2010

DfT (2010), Carbon Calculator, Department for Transport Date published:17 May 2011, available on: http://www.dft.gov.uk/pgr/sustainable/biofuels/carbon-calculator/

Dunnet A., Adjiman C., Shah N., A spatially explicit whole-system of the lignocellulosic bioethanol supply chain: an assessment of decentralised processing potential, Biotechnology for Biofuels 2008, 1:13.

E4tech, (2010), Regional emissions from biofuel cultivation, revised report: December 2010, for the Department for Transport, 2010

EU (2009), Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

Misselbrook TH, Chadwick DR, Gilhespy SL, Chambers BJ, Smith KA, Williams J, Dragosits U, (2009). Inventory of Ammonia Emissions from UK Agriculture 2008. Defra Contract AC0112, Inventory Submission Report, November 2009, 31 pp.

Hillier J. Whittaker C., Dailey G., Aylott M., Casella E., Richter G., Riche G., Murphy R., Taylor G., Smith P., Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analysis, GCB Bioenergy (2009) 1, 267-281.

IIASA, Harmonized World Soil Database v 1.1, available on:
http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/

IPCC, (2006). Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use.

Environment data

Avery, B. W. (1980). Soil Classification for England and Wales (Higher Categories). Soil Survey Technical Monograph No. 14. Harpenden.

Bossard, M., et al. (2000). CORINE land cover technical guide – Addendum 2000. Copenhagen, European Environment Agency.

CEH (2000). Land Cover Map 2000 of Great Britain , http://www.ceh.ac.uk/sci_programmes/BioGeoChem/LandCoverMap2000.html. Edinburgh, Lancaster, Bangor, Wallingford, The Centre for Ecology & Hydrology (CEH).

Clayden, B. and J. M. Hollis (1984). Criteria for Differentiating Soil Series. Soil Survey Technical Monograph No. 17. Harpenden.

FAO, et al. (2009). Harmonized World Soil Database (version 1.1). Avialable online: http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/HWSD_Data.html?sb=4 [Last access: 20.4.2011]. Rome, Italy, Laxenburg, Austria.

Geofabrik (2010). Geofabrik - OpenStreetMap at a scale 1: 50 000. Online http://download.geofabrik.de/osm/europe/ [Last access: June 21, 2010].

Heymann, Y., et al. (1994). CORINE Land Cover. Technical Guide. Luxembourg, Office for Official Publications of the European Communities.

Hulme, M., et al. (2002). Climate Change Scenarios for the United Kingdom. The UKCIP02 Scientific Report. Norwich, UK, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia.

JRC (2008). European Soil Database ESDB V.2 Available online: http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB_data_1k_raster_intro/ESDB_1k_raster_data_intro.html [Last access: 23.10.2010]. Ispra, Italy, Joint Research Centre (JRC).

Lovett, A. A., et al. (2009). Land Use Implications of Increased Biomass Production Identified by GIS-Based Suitability and Yield Mapping for Miscanthus in England. Bioenergy Research **2**(1-2): 17-28.

NSRI (2011). LandIS—Land information system, http://www.landis.org.uk/gateway/ooi/intro.cfm Cranfield, The National Soil Resources Institute (NSRI)

UKCIP (2002). The UKCIP02 climate change scenarios http://www.ukcip.org.uk/ukcp09/ukcip02/ [Last access: 22.11.2010]. Oxford.

UKCIP (2010). Climate change projections for the UK (UKCP09) http://ukclimateprojections-ui.defra.gov.uk/ui/admin/login.php [Last access: 11.5.2011]. Oxford, UK Climate Impacts Programme

Appendices

Appendix 1 Description of General Yield Class

In forestry, yield class is an index measure of forest productivity based on the maximum mean annual increment (MAI) of cumulative timber volume achieved by a given tree species growing on a given site and managed according to a standard prescription. It is measured in units of cubic metres per hectare per year. In Figure 0-1, there are 10 mean annual increment curves representing yield classes of 6 to 24, which cover the productivity range commonly observed for Sitka spruce in Britain. Figure 0-2 demonstrates the same yield classes in terms of cumulative volume.

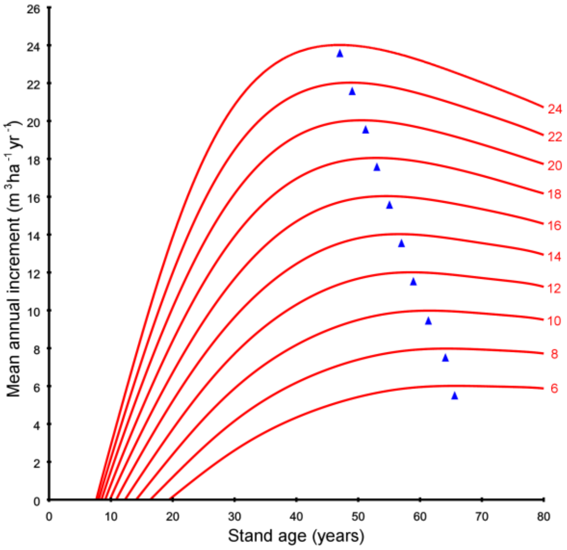

Figure 0-1 Illustration of a set of growth curves for describing development of mean annual increment with respect to stand age, showing 10 distinct productivity classes (yield classes). The curves shown are based on the Forestry Commission Booklet 48 yield models for Sitka spruce.

The yield class of a stand can be assessed by directly monitoring cumulative volume production and comparing with standard growth curves of a yield model. An estimate of yield class derived in this way is known as ‘Local Yield Class’.

Yield models can be used to predict future growth for an actual stand, with certain limitations. On the one hand, making a prediction is a very simple procedure – the curve that best represents (i.e. is closest to) the measured cumulative volume is selected and can be used to estimate the future cumulative volume increment in the stand. On the other hand, a prediction made in this way will only be an approximation of the actual development of cumulative volume in a particular stand because, in general, stands will not grow exactly according to the pattern described by the model curves.

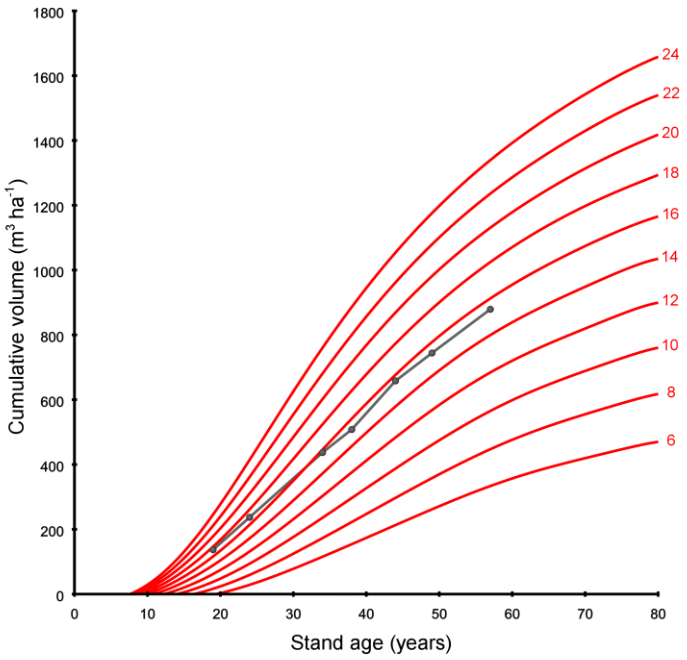

Figure 0-2 Illustration of a set of growth curves for describing development of cumulative volume production with respect to stand age, showing 10 distinct productivity classes (yield classes). The curves shown are based on the Forestry Commission Booklet 48 yield models for Sitka spruce. The black points illustrate cumulative volume as measured in an actual stand which can be compared with the model curves.

A problem with an approach to yield class estimation based on assessment of cumulative volume production is that cumulative volume is difficult and expensive to measure. As a consequence, estimating Local Yield Class from direct measurement of cumulative volume as described above is rarely attempted in practice. Fortunately studies of forest growth have shown that cumulative timber volume production is closely related to top height growth in most tree species when grown as even aged stands. It is striking and very useful that this relationship can be described with reasonable precision by a single curve, which was called a ‘master table’ relationship by the original developers of the yield models (Hummel and Christie, 1957; Christie, 1972). The existence of the master table relationship between cumulative volume and top height makes it possible for yield class to be estimated from an assessment of stand top height and the stand age. This type of estimate is known as ‘General Yield Class’.

General Yield Class is not an exact estimate of Local Yield Class. The application of General Yield Class in forestry practice relies on the assumption that General Yield Class will be an unbiased estimate of Local Yield Class on average over many stands. However, the possibility exists that General Yield Class may systematically overestimate or underestimate Local Yield Class in certain situations, for example due to the particular growth characteristics of stands of a certain species growing in a certain region or managed in a certain way.

Appendix 2 Overview of the Harmonized World Soil Database (HSWD)

The harmonization and data entry in a GIS was assured at the International Institute for Applied System Analysis (IIASA) and verification of the database was undertaken by all partners involved in that project. The HWSD combines existing regional and national updates of soil information worldwide (SOTER, ESD, Soil Map of China, WISE) with the information contained within the 1:5,000,000 scale FAO-UNESCO Soil Map of the World.

The HWSD is a 30 arc-second raster database with over 16,000 different soil mapping units and is composed of a GIS raster image file linked to an attribute database in Microsoft Access format. The HWSD image raster file format, which is provided in “Band interleaved by line[30]” (BIL) format and can be read or imported by most GIS software including ESRI ArcGIS.

The resulting raster database consists of 21,600 rows and 43,200 columns, which are linked to harmonized soil property data. The use of a standardized structure allows for the linkage of the attribute data with the raster map to display or query the composition in terms of soil units and the characterization of selected soil parameters (organic Carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry). Figure 0-3 shows different soil units within the HWSD.

The HSWD raster is in the World Geodetic System - 1984 (WGS84) coordinate system.

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[30] BIL is the standard method of organizing image data and is rather a scheme for storing the actual pixel values of an image in a file.

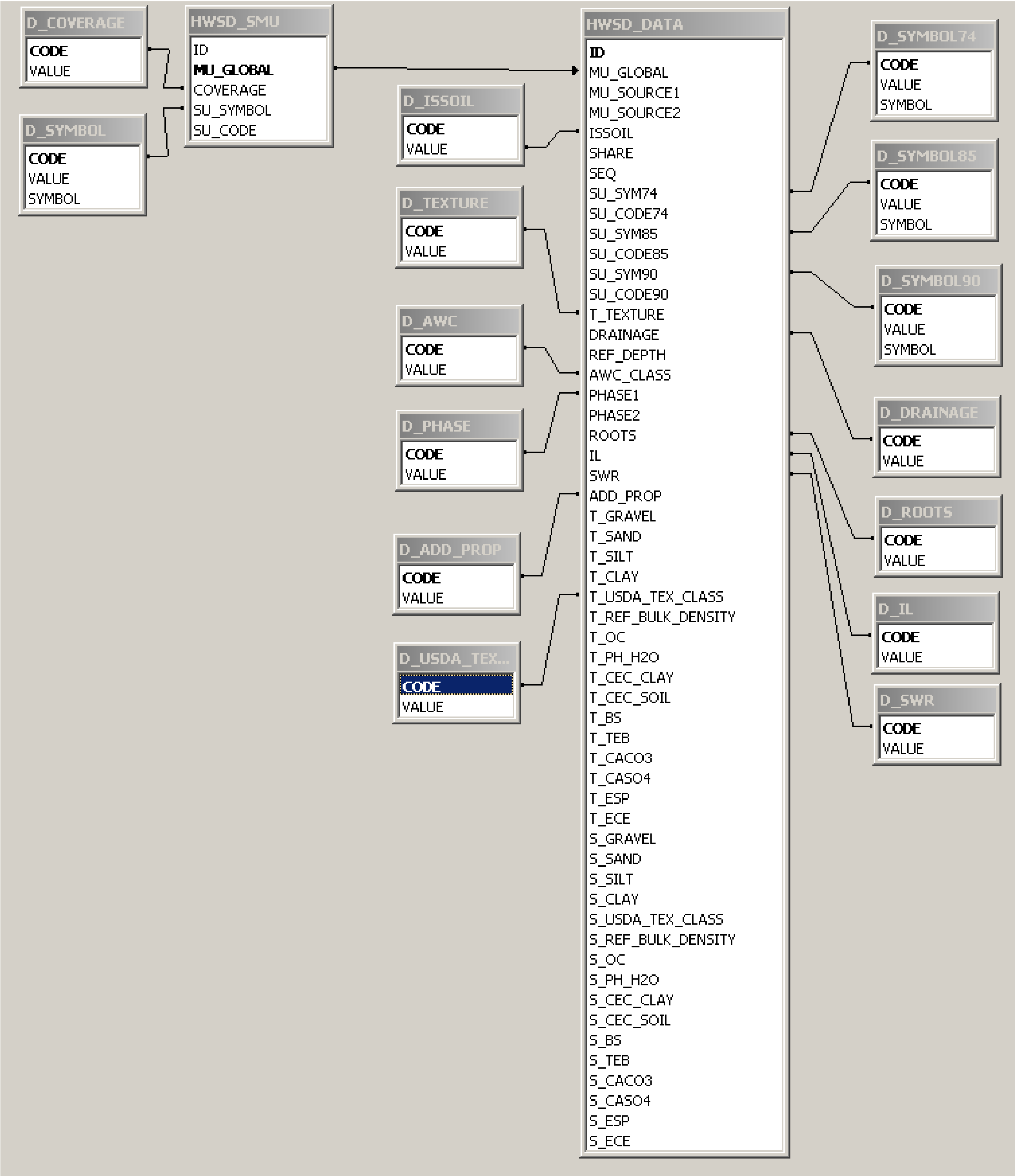

Figure 0-3 Overview of different soil units in Harmonized World Soil Database

Appendix 3 Overview of the meta data of the Harmonized World Soil Database (HWSD)

ID	FIELD	UNIT	DESCRIPTION	DATA TYPE	DOMAIN
0	ID		Database ID	Number	
1	MU_GLOBAL		Soil Mapping Unit	Number	
2	MU_SOURCE1			String	
3	MU_SOURCE2			Number	
4	COVERAGE		Coverage	Number	D_COVERAGE
5	ISSOIL			Number	D_ISSOIL
6	SEQ		Sequence	Number	
7	SHARE	%	Share in Soil Mapping Unit	Number	
8	SU_SYMBOL		Dominant Soil Group Symbol	String	
9	SU_SYM74		Soil Unit Symbol (FAO 74)	String	
10	SU_SYM85		Soil Unit Symbol (FAO 85)	String	
11	SU_SYM90		Soil Unit Symbol (FAO 90)	String	
12	SU_CODE		Dominant Soil Group	Number	D_SYMBOL
13	SU_CODE74		Soil Unit Name (FAO74)	Number	D_SYMBOL74
14	SU_CODE85		Soil Unit Symbol (FAO 85)	Number	D_SYMBOL85
15	SU_CODE90		Soil unit Symbol (FAO 90)	Number	D_SYMBOL90
16	T_TEXTURE		Topsoil Texture	Number	D_TEXTURE
17	REF_DEPTH	cm	Reference Soil Depth	Number	
18	DRAINAGE		Drainage class (0-0.5% slope)	Number	D_DRAINAGE
19	AWC_CLASS	mm	AWC	Number	D_AWC
20	PHASE1		PHASE1	Number	D_PHASE
21	PHASE2		PHASE2	Number	D_PHASE
22	ROOTS	cm	Obstacles to Roots (ESDB)	Number	D_ROOTS
23	IL	cm	Impermeable Layer (ESDB)	Number	D_IL
24	SWR		Soil Water Regime (ESDB)	Number	D_SWR
25	ADD_PROP			Number	D_ADD_PROP
26	T_GRAVEL	%	Topsoil Gravel Content	Number	
27	T_SAND	%	Topsoil Sand Fraction	Number	
28	T_SILT	%	Topsoil Silt Fraction	Number	
29	T_CLAY	%	Topsoil Clay Fraction	Number	
30	T_USDA_TEX_CLASS		Topsoil USDA Texture Classification	Number	D_USDA_TEX_CLASS
31	T_REF_BULK_DENSITY	kg/dm3	Topsoil Reference Bulk Density	Number	
32	T_OC	% weight	Topsoil Organic Carbon	Number	
33	T_PH_H2O		Topsoil pH (H2O)	Number	
34	T_CEC_CLAY	cmol/kg	Topsoil CEC (clay)	Number	
35	T_CEC_SOIL	cmol/kg	Topsoil CEC (soil)	Number	
36	T_BS	%	Topsoil Base Saturation	Number	
37	T_TEB	cmol/kg	Topsoil TEB	Number	
38	T_CACO3	% weight	Topsoil Calcium Carbonate	Number	
39	T_CASO4	% weight	Topsoil Gypsum	Number	
40	T_ESP	%	Topsoil Sodicity (ESP)	Number	
41	T_ECE	dS/m	Topsoil Salinity (ECe)	Number	
42	S_GRAVEL	%	Subsoil Gravel Content	Number	
43	S_SAND	%	Subsoil Sand Fraction	Number	
44	S_SILT	%	Subsoil Silt Fraction	Number	
45	S_CLAY	%	Subsoil Clay Fraction	Number	
46	S_USDA_TEX_CLASS		Subsoil USDA Texture	Number	D_USDA_TEX_CLAS

			Classification		S
47	S_REF_BULK_DENSITY	kg/dm3	Subsoil Reference_Bulk_Density	Number	
48	S_OC	% weight	Subsoil Organic Carbon	Number	
49	S_PH_H2O		Subsoil pH (H2O)	Number	
50	S_CEC_CLAY	cmol/kg	Subsoil CEC (clay)	Number	
51	S_CEC_SOIL	cmol/kg	Subsoil CEC (soil)	Number	
52	S_BS	%	Subsoil Base Saturation	Number	
53	S_TEB	cmol/kg	Subsoil TEB	Number	
54	S_CACO3	% weight	Subsoil Calcium Carbonate	Number	
55	S_CASO4	% weight	Subsoil Gypsum	Number	
56	S_ESP	%	Subsoil Sodicity (ESP)	Number	
57	S_ECE	dS/m	Subsoil Salinity (ECe)	Number	

Appendix 4 Overview of the European Soil Database (ESDB)

The European Soil Database contains four discrete datasets:

1. Soil Geographical Database of Eurasia at scale 1:1,000,000 (SGDBE), a digitized European soil map and related attributes
2. Pedotransfer Rules Database (PTRDB), the results of the application of the pedotransfer rules to the SGDBE are delivered as a table with new attributes related to the European soil map
3. Soil Profile Analytical Database of Europa (SPADBE), delivered as tables
4. Database of Hydraulic Properties of European Soils (HYPRES), delivered as a set of Word documents.

The European Soil Database V.2 Raster Library at 1 km x 1 km contains raster data files (ESRI GRID format) for most attributes (73 in total) of the SGDBE and PTRDB databases of the European Soil Database (distribution version 2). This version of dataset is used to extract soil variables for the models.

The grids are in the ETRS89 Lambert Azimuthal Equal Area (ETRS_LAEA) coordinate system. The grid origin is defined 4.321.000,0 m west of the projection centre point (52N, 10 E), and 3.210.000,0 m south of projection centre point (52N 10 E). The grid extent is such that it covers all EU25 countries.

A description of the different database fields of the soil variables is given below.

Database Field	Description
AGLIM1	Code of the most important limitation to agricultural use of the STU.
AGLIM2	Code of a secondary limitation to agricultural use of the STU.

Soil Classification WRB

Database Field	Description
WRB-FULL	Full soil code of the STU from the World Reference Base (WRB) for Soil Resources.
WRB-ADJ1	First soil adjective code of the STU from the World Reference Base (WRB) for Soil Resources.
WRB-ADJ2	Second soil adjective code of the STU from the World Reference Base (WRB) for Soil Resources.
WRB-LEV1	Soil reference group code of the STU from the World Reference Base (WRB) for Soil Resources.

Texture

Database Field	Description
TEXT-DEP-CHG	Depth class to a textural change of the dominant and/or secondary surface 3 of the STU.
TEXT-SRF-DOM	Dominant surface textural class of the STU.
TEXT-SRF-SEC	Secondary surface textural class of the STU.
TEXT-SUB-DOM	Dominant sub-surface textural class of the STU.

TEXT-SUB-SEC	Secondary sub-surface textural class of the STU.

Parent Material

Database Field	Description
PAR-MAT-DOM	Code for dominant parent material of the STU.
PAR-MAT-DOM1	Major group code for the dominant parent material of the STU.
PAR-MAT-DOM2	Second level code for the dominant parent material of the STU.
PAR-MAT-DOM3	Third level code for the dominant parent material of the STU.
PAR-MAT-SEC	Code for secondary parent material of the STU.
PAR-MAT-SEC1	Major group code for the secondary parent material of the STU.
PAR-MAT-SEC2	Second level code for the secondary parent material of the STU.
PAR-MAT-SEC3	Third level code for the secondary parent material of the STU.

Soil Classification FAO

Database Field	Description
FAO85-FULL	Full soil code of the STU from the 1974 (modified CEC 1985) FAO-UNESCO Soil Legend
FAO85-LEV1	Soil major group code of the STU from the 1974 (modified CEC 1985) FAO-UNESCO Soil Legend.
FAO85-LEV2	Second level soil code of the STU from the 1974 (modified CEC 1985) FAO-UNESCO Soil Legend.
FAO85-LEV3	Third level soil code of the STU from the 1974 (modified CEC 1985) FAO-UNESCO Soil Legend.
FAO90-FULL	Full soil code of the STU from the 1990 FAO-UNESCO Soil Legend.
FAO90-LEV1	Soil major group code of the STU from the 1990 FAO-UNESCO Soil Legend.
FAO90-LEV2	Second level soil code of the STU from the 1990 FAO-UNESCO soil legend

Land Use

Database Field	Description
USE-DOM	Code for dominant land use of the STU.
USE-SEC	Code for secondary land use of the STU.

Obstacle-Impermeable-Soil Water Regime

Database Field	Description
IL	Code for the presence of an impermeable layer within the soil profile of the STU.

ROO	Depth class of an obstacle to roots within the STU.
WR	Dominant annual average soil water regime class of the soil profile of the STU.

Water Management System

Database Field	Description
WM1	Code for normal presence and purpose of an existing water management system in agricultural land on more than 50% of the STU.
WM2	Code for the type of an existing water management system.

Altitude - Slope

Database Field	Description
SLOPE-DOM	Dominant slope class of the STU.
SLOPE-SEC	Secondary slope class of the STU.
ZMAX	Maximum elevation above sea level of the STU (in metres).
ZMIN	Minimum elevation above sea level of the STU (in metres).

Primary Properties

Database Field	Description
ALT	Elevation
OC_TOP	Topsoil organic carbon content.
PEAT	Peat.
TEXT	Dominant surface textural class (completed from dominant STU).

Chemical Properties

Database Field	Description
BS_SUB	Base saturation of the subsoil.
BS_TOP	Base saturation of the topsoil.
CEC_SUB	Subsoil cation exchange capacity.
CEC_TOP	Topsoil cation exchange capacity.
DIFF	Soil profile differentiation.
MIN	Profile mineralogy.
MIN_SUB	Subsoil mineralogy.

MIN_TOP	Topsoil mineralogy.

Mechanical Properties

Database Field	Description
DR	Depth to rock.
PD_SUB	Subsoil packing density.
PD_TOP	Topsoil packing density.
STR_SUB	Subsoil structure.
STR_TOP	Topsoil structure.
TD	Rule infered subsoil 3.
VS	Volume of stones

Hydrological Properties

Database Field	Description
AWC_SUB	Subsoil available water capacity.
AWC_TOP	Topsoil available water capacity.
DGH	Depth to a gleyed horizon.
DIMP	Depth to an impermeable layer.
EAWC_SUB	Subsoil easily available water capacity.
EAWC_TOP	Topsoil easily available water capacity.
HG	Hydrogeological class.
PMH	Parent material hydrogeological type.

Applications

Database Field	Description
AGLIM1NNI	Dominant limitation to agricultural use (without no information).
AGLIM2NNI	Secondary limitation to agricultural use (without no information).
ATC	Accumulated temperature class.
CRUSTING	Soil crusting class.

ERODIBILITY	Soil erodibility class.
PHYS-CHIM	Physi-chemical factor of soil crusting & erodibility.
TEXT-CRUST	Textural factor of soil crusting.
TEXT-EROD	Textural factor of soil erodibility.
USE	Regrouped land use class.

Appendix 5 UKCIP02 climate change scenarios datasets structure and filenames

Folder structure:

Three types of dataset are available:

(1) **50km gridded datasets**

- Contained in 50km_resolution folder and sorted into 17 sub-folders:

DSWF = Total downward surface shortwave flux
IAVP = Inter-annual variability for precipitation
IAVT = Inter-annual variability for temperature
MSLP = Mean sea level pressure
NSLW = Net surface longwave flux
NSSW = Net surface shortwave flux
PREC = Precipitation rate
RHUM = Relative humidity
SLHF = Surface latent heat flux
SMOI = Soil moisture index
SNOW = Snowfall rate
SPHU = Specific humidity
TCLW = Total cloud in longwave radiation
TEMP = Mean temperature
TMAX = Maximum temperature
TMIN = Minimum temperature
WIND = Wind speed

- Each file is available as both a raw text file (*.txt) and as a zip file containing an ESRI GIS shapefile (*.zip)
- There is a folder '50km_grid_template' which contains an empty template version of the 50km resolution grid

(2) **5km gridded data**

- Contained in 5km_resolution folder and sorted into six sub-folders:

Cloud = Cloud cover
PREC = Precipitation
TEMP = Mean temperature
TMAX = Max temperature
TMIN = Min temperature
WIND = Wind speed

- All individual text files are also available as a single archive file per climate variable named [variable]_5km_scenarios.zip

(3) **5km time-series data**

- Contained in 5km_resolution folder within the sub-folder monthly_timeseries_temp
- This folder contains the monthly time series data contained into three time-periods (2020s, 2050s, 2080s)
- Each time period folder contains a single zip file containing the monthly time-series output for each of the scenarios (LO, ML, MH, HI)

Filenames:

For the 5km and 50km gridded datasets (1 and 2 above), the following naming convention is used for the individual text files:

[climate variable] _ [emissions scenario] _ [time-slice] _ [resolution]_[time period] . txt

Climate variable = Climate variable codes are given in UKCIP02_metadata.doc
Emissions scenario = Low (LO); Medium-Low (ML); Medium-High (MH); High (HI)
Time-slice = 6190 (1961 to 1990, i.e. observed climate)
2020s (predictions for 2011 to 2040)
2050s (predictions for 2041 to 2070)
2080s (predictions for 2017 to 2100)
Resolution = 50km; 5km
Time period = monthly (for 50km data); [month] (for 5km data)

For the 5km time-series datasets (3 above), the following naming convention is used for the individual text files:

TEMP _ *[year] _ [month] _ [emissions scenario] . txt*

Year = Future year (2011 to 2100)
Month = Month (January to December)
Emissions scenario = Low (LO); Medium-Low (ML); Medium-High (MH); High (HI)

Appendix 6 Overview of types of information provided by UKCP09

Climate Change Type

The climate change type refers to whether the values are provided as the change relative to the baseline climate or the absolute future climate values.

Short code	Long name
Chg	Future Climate Change Only
Abs	Absolute Future Climate Change

Variable

The name given to quantities for which observed trends are described or future changes are projected in UKCP09. These include climate variables (temperature, precipitation, etc.), marine variables (sea level rise, salinity, etc.) and derived variables (cooling degree days, days of air frost, etc.).

Short code	Long name
Tmean	Mean temperature (degrees C)
Tmax	Mean daily maximum temperature (degrees C)
Tmin	Mean daily minimum temperature (degrees C)
CoolD	Temperature of the coolest day (degrees C)
WarmD	Temperature of the warmest day (degrees C)
ColdN	Temperature of the coldest night (degrees C)
WarmN	Temperature of the warmest night (degrees C)
Pmean	Precipitation (%)
Wet	Precipitation on the wettest day (%)
SLP	Mean sea level pressure (hPa)
Clo	Total cloud (%)
Rhum	Relative humidity (%)
Shum	Specific humidity (%)
NSLWF	Net surface longwave flux (W m-2)
NSSWF	Net surface shortwave flux (W m-2)
TDSSWF	Total downward surface shortwave flux (W m-2)
SkSrgTrd	Long-term trend in skew surge (1951-2099)
ASLR	Absolute Sea Level Rise
RSLR	Relative Sea Level Rise

A period of 30 years over which climate averages are calculated

Short code	Long name
2010-2039	2020
2020-2049	2030
2030-2059	2040
2040-2069	2050
2050-2079	2060
2060-2089	2070
2070-2099	2080

Temporal Average

The time ove which the variables in UKCP09 are averaged (i.e. month, season or annual).

Short code	Long name
Jan	January
Feb	February
Mar	March
Apr	April
May	May
Jun	June

Jul	July
Aug	August
Sep	September
Oct	October
Nov	November
Dec	December
Win	Winter (DJF)
Spr	Spring (MAM)
Sum	Summer (JJA)
Aut	Autumn (SON)
Ann	Annual

Emissions Scenario

A plausible representation of the future development of emissions of substances (e.g. greenhouse gases and aerosols) that can affect the radiative balance of the globe. These representations are based on a coherent and internally consistent set of assumptions about determining factors (such as demographic and socio-economic development, technological change) and their key relationships. The emissions scenarios used in UKCP09 do not include the effects of planned mitigation policies, but do assume different pathways of technological and economic growth which include a switch from fossil fuels to renewable sources of energy.

Short code	**Long name**
Lo	Low
Med	Medium
Hi	High

Appendix 7 Comparison of information in UKCIP02 and UKCP09

	UKCIP02	UKCP09
Variables	17 variables: see Table A.1 of UKCIP02.	Probabilistic projections as for UKCIP02 but minus snow, soil moisture and surface latent heat flux. See Table 1. Projections from 11 variants of the Met Office Hadley Centre regional climate model (RCM) are described in Chapter 5 of the Climate change projections report.
Spatial resolution?	50 km.	25 km for probabilistic projections, 5 km for the Weather Generator, but there is no additional climate change signal over that at 25 km resolution.
Data over larger areas possible?	Yes, by users averaging multiple grid squares.	Yes, data averaged over administrative regions, river basins and marine regions is provided.
Coherence between grid squares?	25 km.	No.
Emissions uncertainty explored?	Yes, by showing projections for 4 emissions scenarios.	Yes, by showing projections for 3 emissions scenarios.
Modelling uncertainty explored?	No, all projections are from Met Office Hadley Centre models.	Yes, within the probabilistic projections.
Natural internal variability explored?	Partly, by having 3 model runs with different initial conditions.	Yes, included in the probabilistic projections.
Pattern-scaling and downscaling uncertainty?	Not included.	Yes, included in the probabilistic projections.
Which 30-yr future time periods?	2020s, 2050s, 2080s.	2020s, 2030s, 2040s, 2050s, 2060s, 2070s, 2080s.
Temporal averaging?	Monthly, seasonal, annual.	Monthly, seasonal, annual.
Daily time series?	Yes, for 2071–2100.	Yes (a) synthetic daily data for 9 variables from the Weather Generator, but there is no climate change signal additional to that at monthly resolution in the probabilistic projections, (b) continuous daily model output 1951–2099 from 11 variants of the Met Office Hadley Centre RCM.
Hourly time series?	No.	Yes, synthetic hourly data from weather generator, but there is no additional climate change signal.
Climate change only or future climate?	Climate change.	Climate change and future climate.
Graphics available in addition to those in Science Report?	Additional maps (including regions) on UKCIP website.	(a) pre-prepared maps and graphs on UKCP09 website, (b) custom graphics from User Interface.
Carbon cycle feedback?	No.	Yes.

Source: http://ukclimateprojections.defra.gov.uk/content/view/1984/500/

Appendix 8 CLC 2000 class description

CLC classes	CLC	Description
Continuous urban fabric	111	Most of the land is covered by structures and the transport network building, roads and artificially surfaced areas cover more than 80 % of the total surface, including: ·= urban centre types and dense ancient suburbs where buildings form a continuous and homogeneous fabric; ·= public services or local governments and commercial/industrial activities with their connected areas inside continuous urban fabric when their surface is less than 25 ha; ·interstices of mineral areas; ·parking lots, concrete or asphalt surfaces; ·transport network; ·small squares, pedestrian zones, yards; ·urban greenery (parks and grass areas) amounting to 20 % of the polygon area; ·unvegetated and vegetated cemeteries less than 25 ha located inside continuous urban fabric
Discontinuous urban fabric	112	Most of the land is covered by structures building, roads and artificially surfaced areas associated with vegetated areas and bare soil, which occupy discontinuous but significant surfaces, including: ·= private housing estates, residential suburbs made of individual houses with private gardens and/or small squares; ·= scattered blocks of residential flats, hamlets, small villages where numerous unmineralised interstitial spaces (gardens, lawns) can be distinguished; ·= large blocks of flats where green spaces, parking areas and adventure playgrounds cover significant surface area; ·= transport network; ·= sport area smaller than 25 ha included within discontinuous urban fabric; ·= buildings with educational, health care and production functions and market places smaller than 25 ha included within this class; ·= unvegetated and vegetated cemeteries smaller than 25 ha included within discontinuous urban fabric; ·= public utilities/communities surfaced areas less than 25 ha; ·= holiday cottage houses are included in 112 if infrastructures like houses, road network are visible in the satellite image; they must also be connected to built-up areas;
Diffused construction (fr Bati duffus)	113*	This class established by CRIGE for the French CLC classification More information on website http://wwwcrige-pacaorg/frontblocks/donnees/select_LOT_DONNEESasp
Industrial or commercial units	121	Artificially surfaced areas (with concrete, asphalt, tarmacadam, or stabilised, eg beaten earth) without vegetation occupy most of the area, which also contains buildings and/or vegetation, including: ·= research and development establishments; ·= security and law and order services (fire stations, penal establishments); ·= company benefit schemes (old people's home, convalescent homes, orphanages, etc); ·= stud farms, agricultural facilities (co-operatives, state farm centres, livestock farms, living and exploitation buildings); ·= exposition sites, fair sites; ·= nuclear power plants, military barracks, testing pistes, test fields, biological waste water treatment plants, water houses, transformers; ·= large shopping and exposition centres; ·= hospitals, spas,; ·= universities, schools; ·= parking lots; ·= abandoned industrial sites and by-products of industrial activities where buildings are still present; ·= water retention dam and hydroelectric dam in total >25 ha; ·= telecommunication networks (relay stations for TV, telescopes, radar stations

Road and rail networks and associated land	122	Motorways, railways, including associated installations (stations, platforms, embankments) of minimum width of 100 m
Port areas	123	Infrastructure of port areas, including quays, dockyards and marinas
Airports	124	Airport installations: runways, buildings and associated land
Mineral extraction sites	131	Areas with open-pit extraction of industrial minerals (sandpits, quarries) or other minerals (opencast mines) Includes flooded gravel pits, except for river-bed extraction
Dump sites	132	Landfill or mine dump sites, industrial or public
Construction sites	133	Spaces under construction development, soil or bedrock excavations, earthworks
Green urban areas	141	Areas with vegetation within urban fabric Includes parks and cemeteries with vegetation
Sport and leisure facilities	142	Camping grounds, sports grounds, leisure parks, golf courses, racecourses, etc Includes formal parks not surrounded by urban zones
Non-irrigated arable land	211	Cultivated areas regularly ploughed and generally under a rotation system Cereals, legumes, fodder crops, root crops and fallow land Includes flower and tree (nurseries) cultivation and vegetables, whether open field, under plastic or glass (includes market gardening) Includes aromatic, medicinal and culinary plants Excludes permanent pastures and meadows (also on disused arable land)
Permanently irrigated land	212	Crops irrigated permanently and periodically, using a permanent infrastructure (irrigation channels, drainage network) Most of these crops could not be cultivated without an artificial water supply Does not include sporadically irrigated land
Rice fields	213	Land developed for rice cultivation, surfaces regularly flooded
Continious area of land parcels	214*	This class established by CRIGE for the French CLC classification More information on website http://wwwcrige-pacaorg/frontblocks/donnees/select_LOT_DONNEESasp
Vineyards	221	Areas planted with vines
Fruit trees and berry plantations	222	Parcels planted with fruit trees or shrubs: single or mixed fruit species, fruit trees associated with permanently grassed surfaces Includes chestnut and walnut groves
Olive groves	223	Areas planted with olive trees, including mixed occurrence of olive trees and vines on the same parcel
Lavendis	224*	This class established by CRIGE for the French CLC classification More information on website http://wwwcrige-pacaorg/frontblocks/donnees/select_LOT_DONNEESasp
Pastures	231	Dense, predominantly graminoid grass cover, of floral composition, not under a rotation system, mainly used for grazing
Annual crops associated with permanent crops	241	Non-permanent crops (arable lands or pasture) associated with permanent crops on the same parcel
Complex cultivation patterns	242	Small parcels of diverse annual crops, pasture and/or permanent crops
Land principally occupied by agriculture. with significant	243	Areas principally occupied by agriculture, interspersed with significant natural areas

areas of natural vegetation		
Agro-forestry areas	244	Annual crops or grazing land under the wooded cover of forestry species
Broad-leaved forest	311	Vegetation formation composed principally of trees, including shrub and bush under stories, where broad-leafed species predominate (Presence of conifers 0– 10%)
Coniferous forest	312	Vegetation formation composed principally of trees, including shrub and bush understories, where coniferous species predominate (Presence of conifers 91– 100%)
Mixed forest	313	Vegetation formation composed principally of trees, including shrub and bush understories, where broad-leafed and coniferous species co-dominate
Natural grasslands	321	Low productivity grassland Often situated in areas of rough uneven ground Frequently includes rocky areas, briars, and heathland
Moors and heathland	322	Vegetation with low and closed cover, dominated by bushes, shrubs and herbaceous plants (heath, briars, broom, gorse, laburnum, etc)
Sclerophyllous vegetation	323	Bushy sclerophyllous vegetation Includes maquis and garrige Maquis: a dense vegetation association composed of numerous shrubs associated with siliceous soils in the Mediterranean environment Garrigue: discontinuous bushy associations of Mediterranean calcareous plateaus Generally composed of kermes oak, arbutus, lavender, thyme, cistus, etc. May include a few isolated trees
Transitional woodland-shrub	324	Bushy or herbaceous vegetation with scattered trees Can represent either woodland degradation or forest regeneration/colonisation
Beaches. Dunes, sands	331	Beaches, dunes and expanses of sand or pebbles in coastal or continental, including beds of stream channels with torrential regime
Bare rocks	332	Scree, cliffs, rocks and outcrops
Sparsely vegetated areas	333	Includes steppes, tundra and badlands Scattered high-attitude vegetation
Burnt areas	334	Areas affected by recent fires, still mainly black
Glaciers and perpetual snow	335	Land covered by glaciers or permanent snowfields
Inland marshes	411	Low-lying land usually flooded in winter, and more or less saturated by water all year round
Peat bogs	412	Peatland consisting mainly of decomposed moss and vegetable matter May or may not be exploited
Salt marshes	421	Vegetated low-lying areas, above the high-tide line, susceptible to flooding by sea water Often in the process of filling in, gradually being colonised by halophilic plants
Salines	422	Salt-pans, active or in process Sections of salt marsh exploited for the production of salt by evaporation They are clearly distinguishable from the rest of the marsh by their segmentation and embankment systems
Intertidal flats	423	Generally unvegetated expanses of mud, sand or rock lying between high and low water-marks On contour on maps
Water courses	511	Natural or artificial water-courses serving as water drainage channels Includes canals Minimum width to include: 100 m
Water bodies	512	Natural or artificial stretches of water

Coastal lagoons	521	Unvegetated stretches of salt or brackish waters separated from the sea by a tongue of land or other similar topography These water bodies can be connected with the sea at limited points, either permanently or for parts of the year only
Estuaries	522	The mouth of a river within which the tide ebbs and flows
Sea and ocean	523	Zone seaward of the lowest tide limit

Appendix 9 The calculated correlation coefficients between total biomass yield (t/ha) and grain yield (t/ha) and respective environmental physical variables

Variables	**Correlation coefficient (r) with**	
	Biomass yield	**Grain yield**
AWC	**0.51**	**0.52**
Ta_Jan	0.09	0.09
Ta_Feb	0.04	0.05
Ta_Mar	0.06	0.10
Ta_Apr	0.07	0.11
Ta_May	-0.11	-0.04
Ta_Jun	-0.20	-0.17
Ta_Jul	**-0.35**	**-0.38**
Ta_Oct	0.00	-0.02
Ta_Nov	-0.01	0.01
Ta_OctNov	-0.01	-0.01
Ta_MarApr	0.09	0.15
Ta_MayJune	-0.21	-0.14
P_Mar	0.04	0.09
P_Apr	0.22	0.25
P_May	0.39	0.38
P_Jun	0.30	0.34
P_Jul	0.11	0.15
P_Oct	0.06	0.09
P_Nov	0.10	0.06
P_OctNov	0.11	0.10
P_MarApr	0.17	0.23
P_AprMayJune	**0.52**	**0.55**
P_MayJune	**0.48**	**0.51**
Rad_Mar	0.04	-0.02
Rad_Apr	-0.03	-0.15
Rad_May	-0.01	-0.22
Rad_Jun	-0.01	-0.17
Rad_Jul	0.04	0.00
Rad_Oct	-0.01	-0.11
Rad_Nov	-0.02	-0.12
Rad_OctNov	-0.02	-0.14
Rad_MarApr	0.00	-0.12
Rad_AprMayJune	-0.02	-0.29
Rad_MayJune	-0.01	-0.27
AWC_Squared	**0.45**	**0.47**
P_AprMayJune_Squared	**0.49**	**0.54**

Appendix 10 The calculated correlation coefficients between total biomass (t/ha) and sugar yield (t/ha) and respective environmental physical variables for sugar beet crop

Variables	Correlation coefficient (r) with	
	Biomass yield	Sugar yield
AWC	**0.51**	**0.51**
Ta_Mar	0.03	0.03
Ta_Apr	**0.25**	**0.25**
Ta_May	0.18	0.18
Ta_Jun	0.08	0.09
Ta_Jul	-0.12	-0.12
Ta_Aug	-0.03	-0.03
Ta_Sep	0.04	0.04
Ta_Oct	0.08	0.09
Ta_MarApr	0.18	0.18
Ta_MayJune	**0.18**	**0.19**
P_Mar	0.10	0.10
P_Apr	0.11	0.11
P_May	0.05	0.05
P_Jun	0.13	0.13
P_Jul	0.34	0.34
P_Aug	0.35	0.35
P_Sep	0.24	0.24
P_Oct	0.12	0.13
P_MarApr	0.14	0.14
P_JuneJulAug	**0.49**	**0.49**
Rad_May	0.14	0.14
Rad_Jun	0.07	0.08
Rad_Jul	0.01	0.01
Rad_Aug	0.12	0.12
Rad_Sep	0.15	0.16
Rad_Oct	0.20	0.20
Rad_JuneJulAug	0.09	0.10
Rad_SepOct	**0.21**	**0.22**
AWC_Squared	**0.48**	**0.48**
P_JuneJulAug_Sqaured	**0.43**	**0.43**

Glossary

Term	Definition
AWC	Available Water Capacity
Baseline	The baseline (or reference) period defines the climatology against which future changes are projected.
CFE	Carbon Fertilisation Effect
Climate	Climate is typically defined as the average weather (or more rigorously a statistical description of the average in terms of the mean and variability) over a period of time, usually 30 years. These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.
DSWF	Total downward surface shortwave flux
ESC	Ecological Site Classification
ESDB	European Soil Database
GYC	General Yield Class
GHG	Greenhouse Gas
HFBW	High Forest Branchwood
HFSW	High Forest Stemwood
HWSD	Harmonized World Soil Database
LandIS	Land Information System
Meta-model	A meta-model is a simple mathematical model whose parameters are fitted by empirical data and/or the outputs of more sophisticated mathematical models (e.g. process models). A meta-model is a continuous function of a certain input parameters or not (i.e. a discontinuous function). In BVCM, a continuous function is likely to be the case for crops like winter wheat and oil seed rape, while a discontinuous function will be the case for forestry and SRC.
ODT	Oven Dried Tonnes. An amount of wood that weighs 2,000 pounds at zero percent moisture content.
PAR	Photosynthetically Active Radiation
PTF	Pedotransfer Function
Process model	A process model in BVCM is a sophisticated model, used to generate large number of yield maps under different sets of assumptions/input variables.
Scenario	A description of a plausible future state which is not associated with an ascribed likelihood.
SCP	Spatially Coherent Projections
SRC	Short Rotation Coppice

SRF	Short Rotation Forest
Uncertainty	Uncertainty refers to a state of having limited knowledge. Uncertainty can result from lack of information or from disagreement over what is known or even knowable
Weather	Weather refers to the state of the atmosphere with regard to temperature, cloudiness, rainfall, wind, and other meteorological conditions