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**YIELD MODELS FOR ENERGY COPPICE
OF POPLAR AND WILLOW**

Volume B - Process-based models



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YIELD MODELS FOR ENERGY COPPICE OF POPLAR AND WILLOW

Volume B – Process-based models

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I. Executive summary

I.i.Introduction

Many willow and poplar varieties are well suited to producing large volumes of biomass when managed as short rotation coppice (SRC). This biomass can displace fossil fuels used to produce heat and power and, as a result, help government meet its legally binding commitments to the reduction of CO₂ emissions.

In order to maximise biomass production it is important that suitable combinations of site type and willow or poplar variety are selected by the grower. This research programme set out to monitor the performance of a selection of willow and poplar varieties at a network of field trials scattered across the UK. Variations in biomass production amongst the site and variety combinations tested were related to site specific variables such as soil type and climatic conditions.

This report summarises the development of process-based model for SRC. Such models may enable predictions of the performance of new varieties of coppice together with any change in growing performance on new sites or under new growing conditions.

I.ii. Projective objectives and work summary

Objectives

As part of Phase 4 of the larger project there were particular objectives relevant to the process-based modelling:

- to make yield assessments and assemble a database of yield information which can be used for modelling
- to collect meteorological data from all experimental sites
- to collect physiological information to characterise clonal differences
- to collect information on the relationship between cutting cycle, spacing and yield from a spacing experiment at Wishanger
- to use the information to construct easy-to-use computer models relating clone, site and climatic factors to expected yields

Work summary

Physiological data were collected from three poplar and three willow clones planted in experiments established at nursery sites near Alice Holt (Hampshire) and Elgin (Morayshire). Fertiliser and irrigation were applied to ensure that growth was not limited by nutrient or water availability.

I.iii.Conclusions and deliverables

- A process-based model for predicting potential growth and impact effects was developed. It produced a comprehensive set of potential yield estimates and goes some way to provide predictions for new varieties and environmental conditions that are outside our current experience; both are issues that cannot be addressed by empirical models.
- The process model is complex and has a high requirement for data input for both in parameterisation of the variety and site description. In the development of the

model, a number of parameters were identified which it is believed represent the most critical and easy to obtain values to distinguish between clonal varieties.

- The network of 49 sites provided only limited coverage of the variation in soil types and climate found in the UK. This restricted the accuracy of the predictive model.
- Only limited validation of the standing biomass estimates and output from the predictive model was been carried out. It would have been advantageous to have taken plot weights at the end of both cutting cycles in order to compare estimated and observed yield.
- A number of assumptions were made, most importantly that the physiology changes little between clones and that the main drivers are the leaf and canopy morphology.
- A particular limitation is that no account is taken of varietal differences in tolerance to harsh environmental conditions, e.g. drought.
- Carbon storage was one of the most critical sets of parameters for the process-based model both as an initial condition and throughout the simulation - stored carbon is used to create growth after cut-back.
- Poplar coppice was simulated well. In contrast the willow simulations were inconsistent, inter-site variability was small, and growth in the second rotation was often less than the first rotation – perhaps a result of incorrect carbon storage. The more realistic simulation of poplar growth was probably a consequence of the more detailed physiological and morphological data provided through this project and the international literature, which concentrates more on poplar than willow.
- The importance of the canopy and foliage morphology became apparent during the experimental work. These parameters are not difficult to obtain and further data would enable a more detailed exploration of the model's range.
- No attempt was made to model the process of pests and diseases outbreaks but defoliation was included as a surrogate to explore their impacts on yield.
- Soil data were sub-optimal for the process-based model, particularly in terms of water availability.
- Provided effective weed control is carried out and browsing animals are excluded from the crop, the software provides growers and stakeholders with a useful guide to potential yields under different scenarios including many aspects of climate change.

Contents

1. Process based models for predicting the yield of short rotation coppice (new varieties, impacts)	5
2. Process based models for predicting the yield of short rotation coppice (new varieties, impacts)	10
2.1. Introduction	10
2.1.1. Overview of the process model	11
2.2. Evapotranspiration	12
2.2.1. Canopy radiative transfer	15
2.2.2. Gas exchange and carbon productivity	16
2.3. Soil moisture	18
2.4. Allocation mechanisms and growth rules	20
2.4.1. Phase 1. Leaf development from carbon stock	20
2.4.2. Phase 2. Height or leaf growth	21
2.4.3. Phase 3. Storage and latewood formation	21
2.4.4. Phase 4. Leaf fall	21
2.4.5. Phase 5. Dormancy	21
2.5. Shoot numbers and Management	21
2.5.1. Number of shoots	21
2.5.3. Scenarios	24
2.6. Data	25
2.6.1. Intensive ecophysiological assessments	25
2.6.2. Populus physiology and morphology	25
2.7. Validation	27
2.7.1. Sensitivity	27
2.7.2. Key parameters	29
2.7.3. Uncertainty in predictions	30
2.8. Software realisation of models	30
3. Simulations	35
3.1. Poplar	35
3.2. Willow	35
3.3. Yield maps of willow and poplar varieties	36
4. Pests and diseases	42
5. Critical review of the process-based model	44
6. Conclusions and deliverables	46
7. References	47

1. Process based models for predicting the yield of short rotation coppice (new varieties, impacts)

This volume covers contract objective 2.1: to develop models relating yield from energy coppice of poplar and willow to site factors and clonal characteristics. Such models may enable predictions of the performance of new varieties of coppice and performance on new sites or under new growing conditions; the novel combinations of CO₂, temperature and rainfall anticipated as a result of rising greenhouse gas concentrations are particularly relevant. More comprehensive details of the project are found in Volume A (Empirical models, Evans et al., 2007a) and Volume C (Appendices, Evans et al., 2007b)

The approach was to:

- Develop a process-based model, operating at the plot scale, to integrate relevant existing and new process knowledge on the growth dynamics of poplar and willow.
- Simulate results of biomass yields over 2 rotations from the 50 experimental sites where clones of poplar and willow were grown (see Figure 1.1, Tables 1.1 and 1.2; a full description is available in Volume C, Evans et al 2007b)
- Develop a user-friendly model front end, allowing the model to be run at the plot scale and in GB conditions.

In addition to the deliverables specified in the contract, the model allows for the effects of defoliation resulting from pest/pathogen activity.

As specified in the contract, the model:

- a. Simulates relevant physiological, biophysical and physical processes at the site/field scale determining annual yield. Through parameterisation, it allows for variations between sites and clones determining yield variation;
- b. Operates at the daily time-step, summarising yield performance at the annual timestep and across a number of rotations and rotation lengths. Model development has concentrated on rotation lengths of three years (2 rotations).
- c. Through parameterisation, the model is suitable for predicting yield at new sites, new clones and relevant site-clone combinations, enabling predictions beyond the range of the empirical model developed under this project.

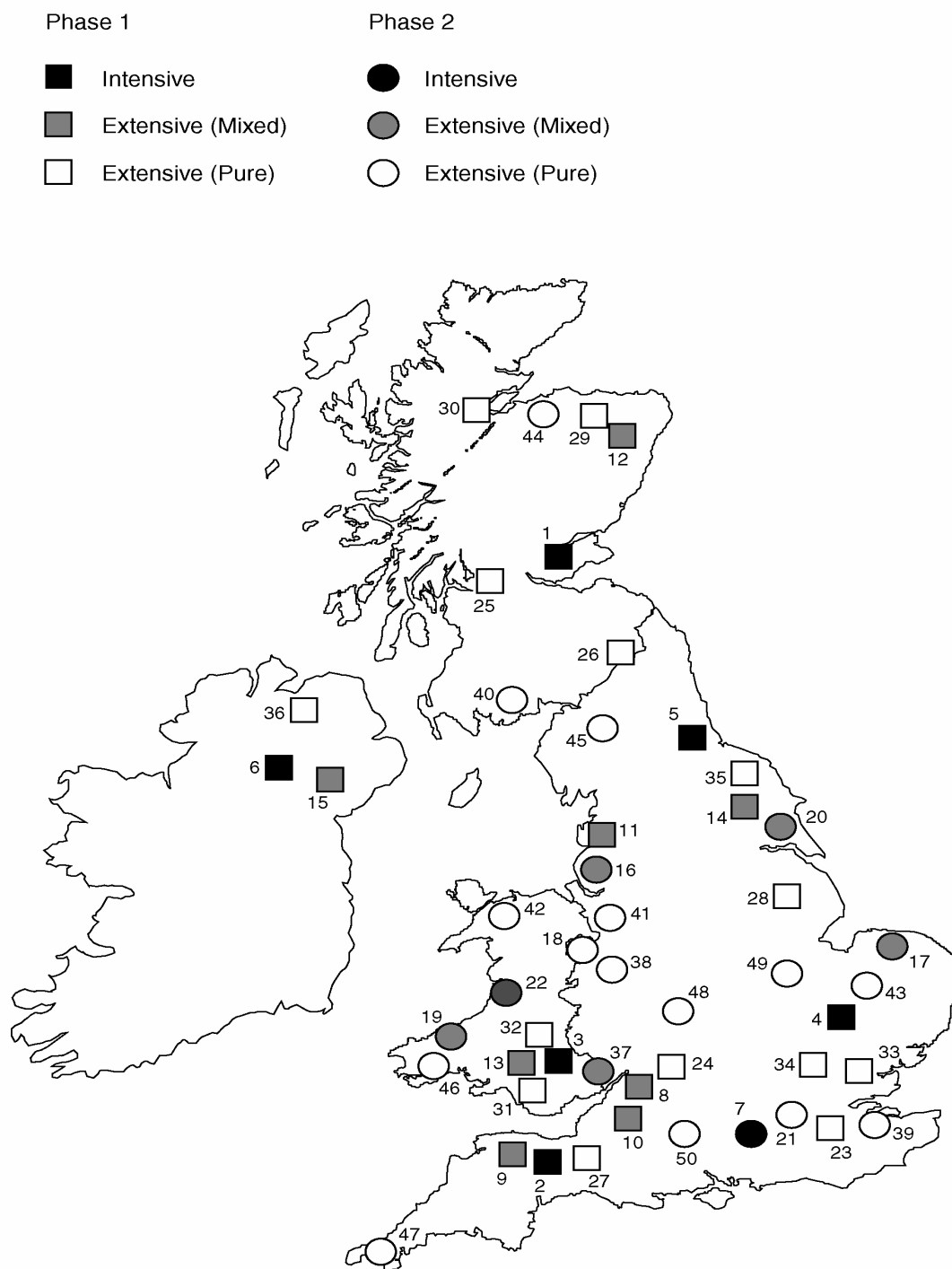
Figure 1.1 Location of Phase 1 and 2 sites (see Table 1.1 for site details)

Table 1.1 Details of field trials established in project 'Phase 1' and 'Phase 2'.**Phase 1 Sites****Planted: Spring 1995****Cutback: Winter 1995/96****First shoot form assessment: Winter 1996/97****First harvest: Winter 1998/99****Second harvest: Winter 2001/02**

Outstation	Site name	Site id (as shown in Figure 1.1)	Notes
Intensive			
Bush	Balbirnie	1	Originally phase1. Delayed by poor growth, treat as Phase 2. Plots 27,43 poplar missing
Exeter	Loyton	2	Poplars phase 1, willows phase 2
Talybont	Trefeinon	3	
Fineshade	Trumpington	4	
Wykeham	Thorpe Thewles (NYM 100)	5	Plots 27, 43 poplar missing
Northern Ireland	Loughall	6	
Mixture			
Alice Holt	Friars Court	8	
Exeter	Bigbrook	9	
Exeter	Long Ashton	10	Replanted, treat as phase 2
Wykeham	Myerscough	11	
Newton	Sunnybrae, Craibstone	12	Replanted, treat as phase 2
Talybont	Talybont	13	
Wykeham	Gilder Beck (NYM 101)	14	
Northern Ireland	Castlearchdale	15	
Pure			
Alice Holt	Bore Place	23	
Alice Holt	Roves Farm	24	
Bush	Craigend	25	
Bush	Tweed horizons	26	
Exeter	Aller Court	27	
Wykeham	Demontfort	28	
Newton	Oyne	29	Plot 02 willow (Germany) not diameter assessed 1998/99
Newton	Teanahuig	30	
Talybont	Tair Onen	31	Replanted, treat as phase 2
Talybont	Llangoed (Newtown11)	32	Replanted, treat as phase 2
Fineshade	Writtle	33	
Fineshade	Dell Piece (Rothamsted)	34	
Wykeham	Hayburn Wyke (NYM 102)	35	
Northern Ireland	Londonderry	36	

Table 1.1 *continued*.**Phase 2 Sites****Planted: Spring 1996****Cutback: Winter 1996/97****First shoot form assessment: Winter 1997/98****First harvest: Winter 1999/2000****Second harvest: Winter 2002/03**

Outstation	Site name	Site id (as shown in Figure 1.1)	Notes
Intensive			
Alice Holt	AH450 (Alice Holt Lodge)	7	Larch v. close to some plots
Mixture			
Wykeham	Mawdesley	16	
Fineshade	Wesum10	17	
Shobden	Charity Farm	18	
Talybont	Llandovery16 (Lawrenny)	19	
Wykeham	Dunnington (NYM 107)	20	
Alice Holt	Loseley	21	
Talybont	Ceredigion	22	
Wykeham	Delamere	41	Larch v. close to plots
Pure			
Talybont	Gwent 16 (Great Pool Hall)	37	
Shobden	Harper Adams	38	
Alice Holt	Charlwood	39	
Mabie	Carruchan	40	
Talybont	Llanwrst8 (Henfaes, Bangor)	42	2 Germany plots killed winter 98/99, possibly by aphids
Fineshade	Soham	43	
Newton	Moray 58	44	
Talybont	Llandovery18 (Slebech)	46	
Exeter	Bonython	47	Very poor growth, water logged soil
Shobden	Dunstall Court	48	Beaupré plots contain many rogue Trichobel
Fineshade	Moscow Farm	49	
Alice Holt	Woodford	50	Poor site, many plots not diameter assessed in 1998/99 and 1999/2000

	ETSU owned met station not present
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Site 45 abandoned following soil survey.

Table 1.2 Willow and poplar varieties used at experiment sites

Willow Name	Variety	Parentage	Poplar Variety Name	Parentage
Jorunn*		<i>Salix viminalis</i> x <i>Salix viminalis</i>	Beaupré*	<i>Populus trichocarpa</i> x <i>Populus deltoides</i>
Germany*		<i>Salix burjatica</i>	Boelare	<i>Populus trichocarpa</i> x <i>Populus deltoides</i>
Q83*		<i>Salix triandra</i> x <i>Salix viminalis</i>	Raspalje	<i>Populus trichocarpa</i> x <i>Populus deltoides</i>
Spaethii		<i>Salix spaethii</i>	Unal	<i>Populus trichocarpa</i> x <i>Populus deltoides</i>
Dasyclados		<i>Salix caprea</i> x <i>Salix cinerea</i> x <i>Salix viminalis</i>	Hoogvorst (690386)	<i>Populus trichocarpa</i> x <i>Populus deltoides</i>
ST/2481/55		<i>Salix triandra</i> x <i>Salix cinerea</i> x <i>Salix viminalis</i>	Hazendans (690394)	<i>Populus trichocarpa</i> x <i>Populus deltoides</i>
Delamere		<i>Salix aurita</i> x <i>Salix cinerea</i> x <i>Salix viminalis</i>	v71015/1	<i>Populus trichocarpa</i> x <i>Populus deltoides</i>
Bebbiana		<i>Salix sitchensis</i>	v71009/1	<i>Populus trichocarpa</i> x <i>Populus deltoides</i>
V789		<i>Salix viminalis</i> x <i>Salix caprea</i>	v71009/2	<i>Populus trichocarpa</i> x <i>Populus deltoides</i>
Stott 10		<i>Salix burjatica</i> x <i>Salix viminalis</i>	Gaver	<i>Populus deltoides</i> x <i>Populus nigra</i>
Stott 11		<i>Salix burjatica</i> x <i>Salix viminalis</i>	Ghoy*	<i>Populus deltoides</i> x <i>Populus nigra</i>
Jorr		<i>Salix viminalis</i> x <i>Salix viminalis</i>	Gibecq	<i>Populus deltoides</i> x <i>Populus nigra</i>
Bjorn		<i>Salix viminalis</i> x <i>Salix schwerinnii</i>	Balsam Spire (TT32)	<i>Populus trichocarpa</i> x <i>Populus balsamifera</i>
Tora		<i>Salix viminalis</i> x <i>Salix schwerinnii</i>	Columbia River	<i>Populus trichocarpa</i>
Orm		<i>Salix viminalis</i> x <i>Salix viminalis</i>	Fritzi Pauley	<i>Populus trichocarpa</i>
Ulv		<i>Salix viminalis</i> x <i>Salix viminalis</i>	Trichobel*	<i>Populus trichocarpa</i>
Bowles Hybrid**		<i>Salix viminalis</i>		

* Planted at all sites (referred to as the 'extensive' varieties), other varieties were planted at the seven 'Intensive' sites only unless stated otherwise

**Only present at Wishanger spacing experiment

2. Process based models for predicting the yield of short rotation coppice (new varieties, impacts)

2.1. Introduction

The absence of model sensitivity to growth variability resulting from the interactions between the genetic make-up of a plant, its environment and the age of the individual is a recognised limitation of the current generation of models. Yet such knowledge underpins national policies aimed at the introduction of bio-energy crops as a renewable energy resource.

Our approach, outlined in detail at sections 2.2-2.5, aims to resolve the known, but little explored, differences in the ecophysiology of clones (De Pury and Farquhar, 1997; Liesebach et al., 1999) that, in order to achieve predictive accuracy, require explicit resolution through a modelling framework. Complementary approaches, such as radiation use and water use efficiency, have been widely tested to simulate the productivity of perennial and agroforestry crops. To date no approach has explicitly accounted for and forecasted the variability in growth and yield observed between clones on the basis of mechanistic understanding. Current stool and field-level process-based models that forecast response to climate, climate change and site management conditions do not account for the variation in growth responses resulting from genotypic and phenotypic selection processes. Given the explicit requirement to develop a model that will be suitable for predicting yield at new sites or relevant site-clone interactions, the modular design proposed below is considered to be the option most appropriate to meet the specifications defined by this project.

The process model has been developed using a modular approach (Brandmeyer and Karimi, 2000). Each module encompasses a set of equations describing processes relevant to a particular component associated with the growth and yield of poplar and willow. Each module has been developed as a stand-alone model, which was then integrated with other modules, tested and calibrated using observational datasets collected for this purpose. The final step was to test [and calibrate!!??] against yields simulated by the empirical model.

This modular design offers the following key characteristics that meet the specified contract requirements:

1. Explicit mechanistic description of the relevant physical (climate) and biophysical (light and water interception, and soil water content) processes that determine site and species interactions.
2. Explicit mechanistic description of the relevant biological processes (assimilation and its interactions with N, allocation, and canopy structure) that characterise the site and species interactions determining growth and yield.
3. Versatility in (a) describing the range of physical conditions observed at UK sites, and (b) through appropriate parameterisation and integration with the clonal libraries allowing for future predictions of growth and yield to be generated across the UK and at clonal level.
4. Adaptability, through appropriate parameterisation of the biological modules, to predict yield for relevant site-clone interactions.

The modular approach was adopted to minimise the risk of failure associated with development of a single and unified modelling system, as it allows full assessment of the predictive capabilities of each module, independently of interactions with other model components. It also allows other approaches, identified through the analysis of modelling techniques developed for perennial and agroforestry crops, to be adopted where, in future, any of the individual modules proposed below are proven to be unsuitable to the task. Future developments are facilitated by the modular approach, e.g. integration into a GIS holding the necessary geo-referenced spatial datasets (soils and climate) that provide the state and dynamic variables required to run the model.

The user-friendly interface, which allows user-determined parameterisation, has been developed to allow for cross-referencing to clonal libraries holding the relevant physiological, morphological and phenological characteristics (e.g. Host et al., 1990), and allowing for appropriate parameterisation of the growth component.

Parallel development of the empirical and process-based models has enabled empirical relationships to support the process model at various phases of completion as follows:

- a. Allometric relationships and size class distributions formulated and calibrated as part of empirical model development have been integrated into the process-based model. These relationships provide sub-models for approximating shoot and stand architecture, and defining their starting conditions.
- b. The shoot number sub-models developed for the empirical model have been incorporated without modification into the process-based model.
- c. The empirical model has provided the harmonised, tested and quality-assured annual estimates of stand productivity for the range of site and cultural conditions represented by trial sites. These are the benchmark against which process-based model calibration and testing has been undertaken. The uncertainties associated with empirical predictions are discussed in Section 2.2 of Volume A (Evans et al 2007a) and in section 2.7 of this report.

In summary, the process-based model may be used with confidence to provide mechanistic predictions of stand allometry, structure and productivity for a range of combinations of site and cultural conditions and clonal varieties covered directly by observations from trial sites. The structure of the model allows it to be used, following appropriate parameterisation, to predict stand allometry, structure and productivity for a range of combinations of site and cultural conditions and clonal varieties not covered by the observations from trial sites. In turn, these predictions may be used in the development and calibration of empirical models representing conditions significantly beyond the range represented in the experimental datasets from field trials. This statement rests on the assumption that the model encompasses an explicit definition of biological and biophysical parameters currently understood as determining the growth differences between clones and species. While the model allows user-determined impacts on growth performance by pests and/or diseases, no such extension can be held valid for predicting the susceptibility of new clones.

2.1.1. Overview of the process model

The model simulates the growth of a number of stools, each with a number of shoots. It captures the bio-physical functions and relationships of various processes and their interaction between each other and the physical environment. There are four major components (see sections 2.2 to 2.5 for further details):

- Evapotranspiration (including light interception, photosynthesis, and assimilation)
- Soil water balance
- Allocation and growth (including functional balance, heights, diameters, dry masses, and carbon storage)
- Shoot numbers and management (including spacing, and rotation length)

Key inputs are (see Volume C; Appendix Q for further details):

- Daily metrology
 - Precipitation
 - Temperature
 - Wind speed
 - Radiation is desirable, but an element of weather generation is included for this within the model as it is often not easily available.
- Physiological parameters of the species
- Soil details, layer depths, constituent parts
- Initial conditions (initial state of the plants)

Key outputs are:

- Biomass
- Shoot height
- Shoot diameter

2.2. Evapotranspiration

The Evapotranspiration (ETp) module is a fully coupled, point scale and daily time step soil-vegetation-atmosphere transfer (SVAT) model that predicts vertical and lateral water movement through the soil-plant-atmosphere continuum and gross primary productivity (GPP). Relevant terrestrial hydrology processes (interception, vertical and lateral soil water movement, runoff, soil and canopy evaporation, and N-sensitive photosynthesis-coupled transpiration) are simulated for a stand of known structure, growing in locally determined soil and climate (Figure 2.1). As an alternative to observational meteorological daily data, the module can be coupled with a weather generator that generates daily time series from monthly summary data. Although the module does not account for snowmelt, a feature of the high latitudes, SRC is unlikely to be commercially grown in these environments. The ETp structure is illustrated in Figure 2.1.

Figure 2.1. Schematic representation of water (solid lines) and carbon cycle (broken lines) processes simulated by ETp (after Evans et al., 2004).

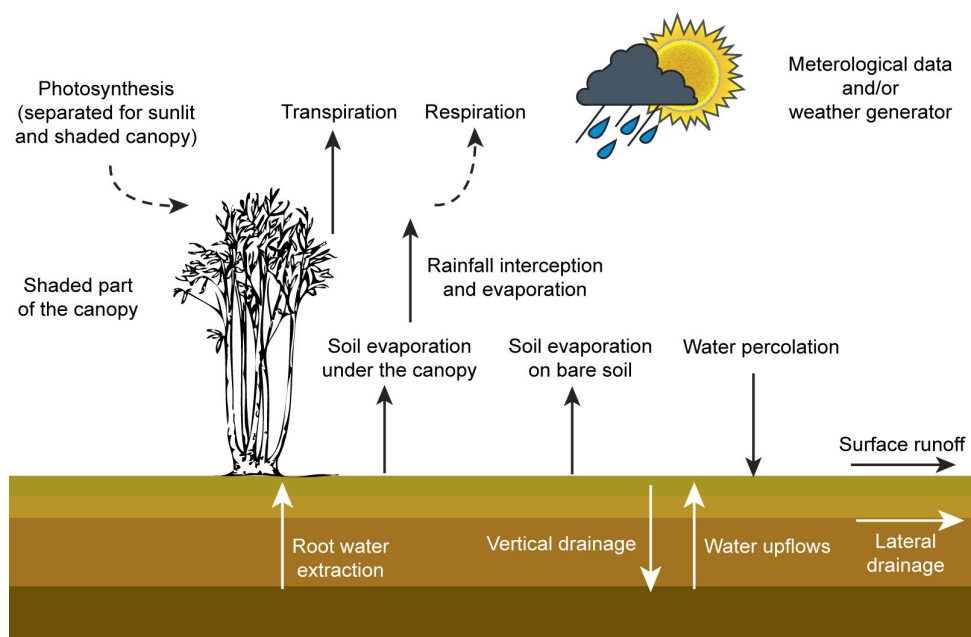


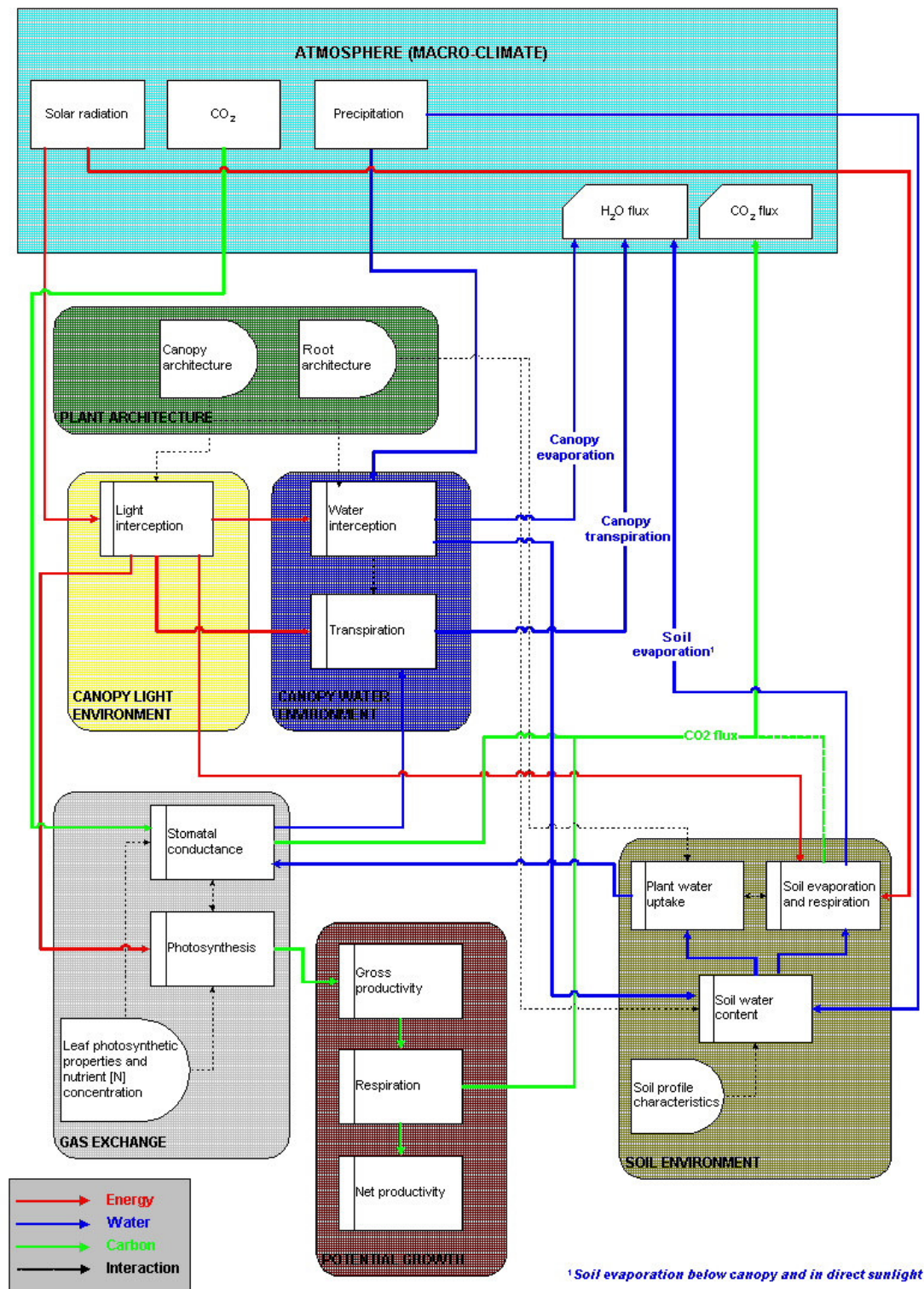
Figure 2.2. ETp structure.

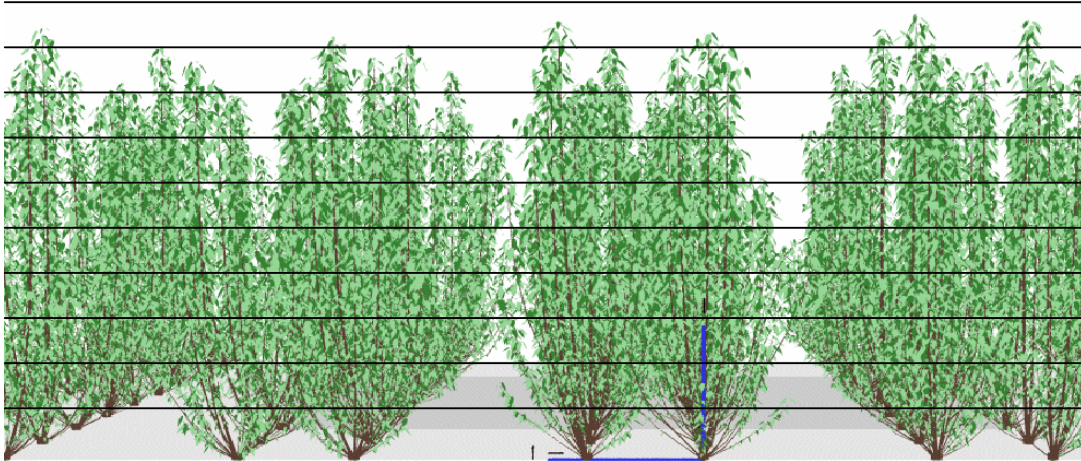
Table 2.1. General features of the ETp model (Evans et al. 2004).

Process	Strategy	Key references
<i>Weather generator</i>	<i>Stochastic-deterministic, site scale model downscaling widely available monthly time step input data to the daily scales</i>	<i>Richardson (1981); Ross (1983); Hutchinson (1991); Evans (1997)</i>
<i>Radiative transfer</i>	<i>Direct and diffuse radiation are accounted for though a canopy in which 2 classes of leaves (sunlight and shaded) within a multi-layered canopy.</i>	<i>Norman (1980); De Pury et al. (1997)</i>
<i>Photosynthesis</i>	<i>Biochemical model where photosynthetic rate is limited either by RuBP regeneration or by Rubisco kinetics</i>	<i>Farquhar et al. (1980); von Caemmerer and Farquhar (1981)</i>
<i>Stomatal conductance</i>	<i>Ball and Berry stomatal conductance model</i>	<i>Ball et al. (1987)</i>
<i>Rainfall interception</i>	<i>Tree canopy partitions gross rainfall into three downward water fluxes (free throughfall precipitation, canopy drip and stemflow) and an upward gaseous flux, resulting from evaporation of the intercepted rainfall</i>	<i>Rutter et al. (1975); Gash (1995); Valente et. al (1997)</i>
<i>Evapotranspiration</i>	<i>Evapotranspiration is computed using the Penman-Monteith equation separately for the tree transpiration, bare soil evaporation, shaded soil evaporation and rainfall intercepted water</i>	<i>Thompson et al. (1981); Burman and Pochop (1994); Ritchie (1972)</i>
<i>Hydrology</i>	<i>Multi-horizon capacity model of soil-water balance simulating the formation of transient perched water tables and the generation of surface runoff and lateral drainage</i>	<i>Evans et al. (1999)</i>

2.2.1. Canopy radiative transfer

This module considers the heterogeneity of radiation in the canopy, as the necessary precursor to approximating the non-linear response of photosynthesis to irradiance (Evans et al., 2004). It employs a radiative transfer scheme that approximates the transmittance, reflectance and absorption of long wave, near infrared, and direct and diffuse photosynthetically active radiation (PAR) by canopy layers. The canopy is divided into equal horizontal layers (Figure 2.3).

Figure 2.3: Visualisation of poplar coppice shoots, and horizontal spatial layers. Canopy characteristics on a layer basis are used in photosynthesis processes. (Visualisation after Casella and Sinoquet, 2003)



Each of the horizontal layers (see Figure 2.3) is heterogeneous and consists of a leaf area index of zero, a fraction, or more than one layer of foliage. After Norman (1980) and de Pury and Farquhar (1997) the module separates penetration of direct and diffuse radiation (net of albedo) through a canopy in which two classes of leaves (sunlit and shaded) are distributed in a multi-layer canopy model. This approach allows the explicit description of within-canopy profiles (on a per layer basis) of both environmental (e.g. wind profile, and vapour pressure deficit) and physiological (e.g. leaf temperature) variables in response to radiation attenuation. The module does not allow for foliage clumping.

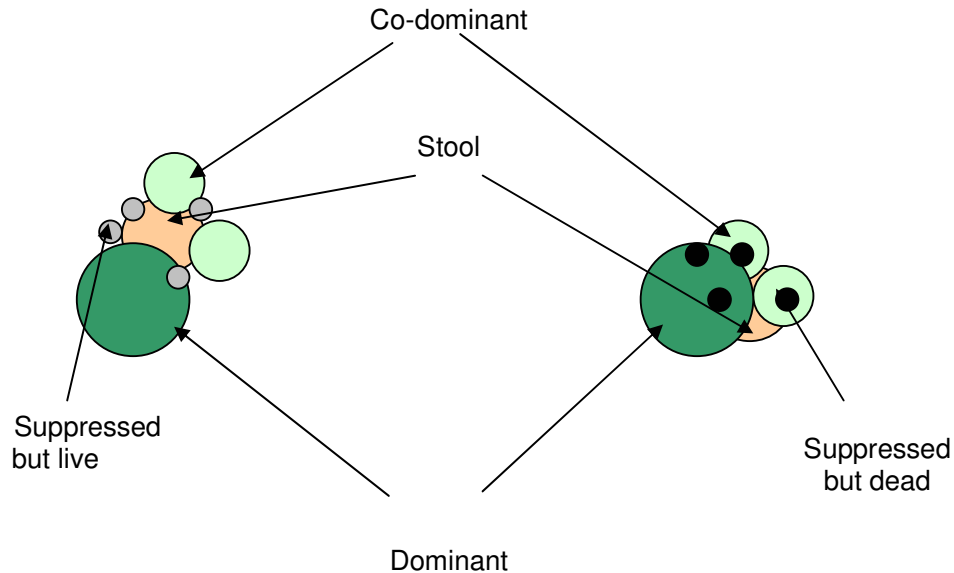
By dynamically calculating the leaf areas of sunlit and shaded leaves along with their mean irradiance, we obtain mean layer assimilation, transpiration and conductance rates, adjusted for the photosynthetic capacity of each leaf class. Through integration, data are up-scaled to approximate total canopy photosynthesis and gas exchange. In each layer, sunlit leaves are assumed to receive both direct and diffuse radiation and shaded leaves receive diffuse light only, assuming no radiative energy transmittance through leaves. The within-canopy profiles of leaf nitrogen follows the predicted distribution of absorbed irradiance through each canopy layer, separately for sunlit and shaded leaves and assuming a uniform leaf angle distribution (spherical). Seasonal variation of nitrogen content in foliage can also be represented with suitable input. Given the separate descriptions of sun and shade leaves and within-canopy variation of photosynthesis, the module allows non-uniform vertical profiles of photosynthetic capacity to be developed.

2.2.2. Gas exchange and carbon productivity

In SRC, a plantation is first established by planting cuttings, these are then grown for one season before being cut-back. New shoots develop from the stool and continue to grow for the rotation (e.g. 3 years), before being cut-back again and the process repeated. Stools at the second cut-back (end of first rotation) will clearly be different to those created at the beginning of the plantation. The model simulates a number of types of stem. Currently three types - suppressed, co-dominant and dominant -

represent the shoots. Competition occurs between shoots, thus it is possible for mortality to occur. Stems of the same type have the same characteristics regardless of stool.

Figure 2.4. Example schematic progressions of shoots on a stool where the suppressed shoots have been killed by competition from the dominant and co-dominant shoots.



Within each canopy layer, and to account for the changing light environment, the gas exchange and carbon productivity module operates at the leaf level (Evans et al., 2004). The well-tested theoretical representation of C_3 photosynthesis developed by Farquhar et al. (1980) and von Caemmerer and Farquhar (1981) has been widely used and tested across a range of species and that describes the regulation of ribulose 1,5-biphosphate carboxylase and electron transport in the leaf. This has been combined with additions from Long (1991), McMurtrie and Wang (1993) and Friend (1995), with further adaptation. In turn the modified C_3 photosynthesis model is tightly coupled with the C_3 version of the Ball et al. (1987) stomatal conductance model that provides a robust phenomenological description of stomatal behaviour. This coupling is required in order to predict leaf response to varying environmental conditions including atmospheric CO_2 concentrations.

The central axiom the Farquhar et al. (1980) C_3 model is that non-limiting photosynthesis is regulated to balance the capacity of limiting processes: at steady state Rubisco will consume RuBP at a rate equal to that of RuBP generation. In theoretical terms, and after Farquhar et al. (1980), the rate of RuBP use (R) equals the carboxylation rate (V_c), plus the rate of oxygenation (V_o), thus $[R = V_c + V_o]$. When limited by Rubisco, R can be described by $[R = W_c + V_o]$ where W_c is the Rubisco-limited rate of carboxylation. Gross rates of photosynthesis (assimilation) are a function of the compensation point in the absence of daylight respiration (I^*), the inter-cellular concentration of CO_2 (C_i) at the site of reaction, limited by both the ribulose biphosphate [RuBP] carboxylase-oxygenase (Rubisco) activity (w_c), and the rate of RuBP regeneration through electron transport (w_j). In this version of the model the effect of potential phosphate limitation (W_p), resulting from the failure of triose phosphate utilisation (production of starches and sugars) to meet triose phosphate production in the Calvin cycle has not been used (Sharkey 1985). Net (potential)

photosynthesis accounts for mitochondrial (dark) respiration. Rubisco activity (w_c) is calculated using the potential maximum velocity of fully activated Rubisco that is inhibitor free (V_{cmax}), the oxygen concentration in the stroma (O_i), and the maximum potential rate of electron transport (J_{max}). RuBP regeneration is calculated using the inter-cellular CO_2 concentration (C_i), compensation point in the absence of daylight respiration (Γ^*), and an actual (PAR adjusted) rate of electron transport (J). The temperature dependencies of the kinetic properties of carboxylation and RuBP regeneration take into account changes in the CO_2 solubility and Rubisco affinity of O_2 ; the kinetic constants of Rubisco are provided by de Pury, and Farquhar, (1997). Temperature optima set at 25°C to reflect those of high latitude temperate vegetation.

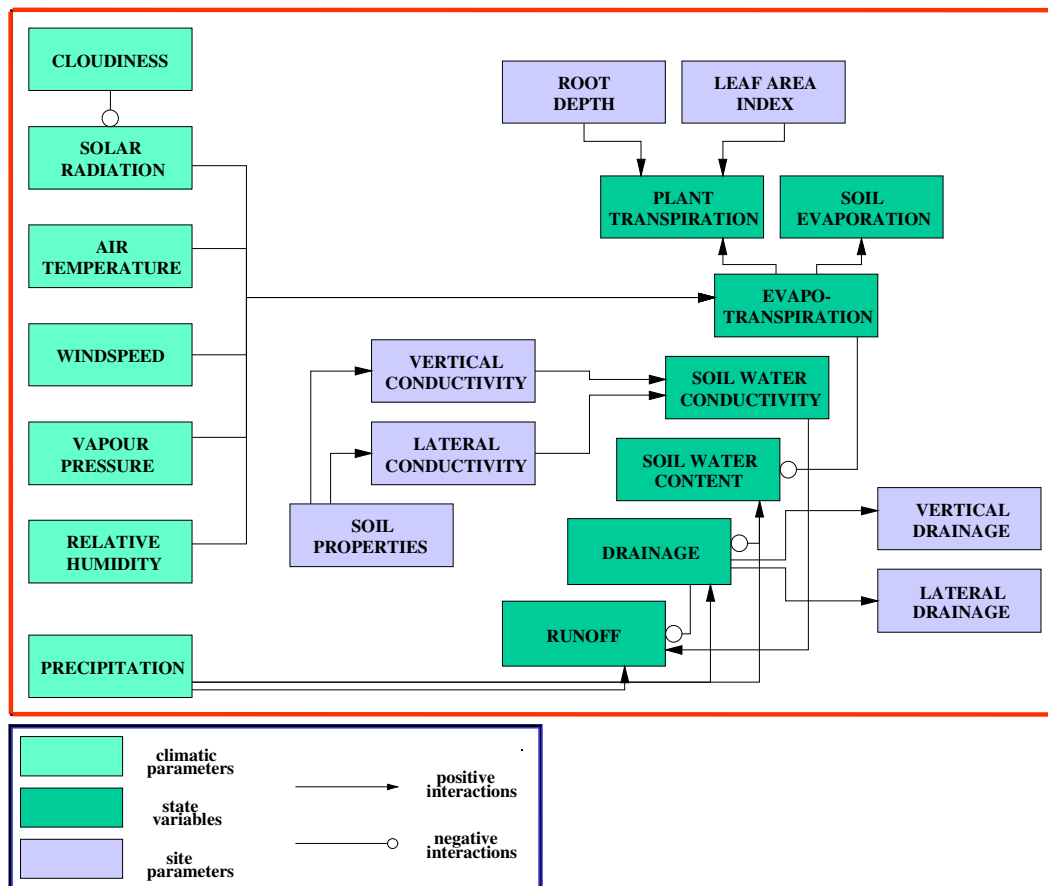
After Farquhar et al. (1980), leaf nitrogen content (linearly) influences two of the rate-limiting photosynthetic processes, namely the potential maximum velocity of fully activated Rubisco that is inhibitor free (V_{cmax}) and the maximum potential rate of electron transport (J_{max}). After Friend (1995), the module explicitly describes the role of nitrogen as a major influence on photosynthesis through influencing the Rubisco concentration in soluble leaf proteins involved in electron transport. Leaf nitrogen content also (linearly) influences mitochondrial (dark) respiration. After Ball and Berry, C_i is determined within the leaf as a function of the interactions between CO_2 assimilation and stomatal conductance to CO_2 , regulated by the leaf boundary layer and mesophyll cell surface resistances to CO_2 transfer. The same processes are assumed to apply for water vapour. As assimilation (demand) and conductance (supply) are inter-dependent, the values of C_i and assimilation are resolved by iteration, and accounting for both leaf water potential and canopy temperature

Foliage respiration is accounted for within the assimilation model. The balance of whole plant respiration during the leafy and non-leafy periods is approximated using a Q_{10} function, based on actual whole system respiration using eddy-covariance measurements of CO_2 fluxes data measured at each site.

Finally, selected outputs from all modules are used to parameterise the Penman-Monteith equation to approximate daily leaf and canopy level evapo-transpiration and soil evaporation.

2.3. Soil moisture

This module outlines a daily-time step, multi-horizon capacity model of soil-water balance which requires climate data, together with soil survey and laboratory-measured physical data as input (see Figure 2.5). Temporal integration is restricted to the daily time step in order to use widely available meteorological data. The module has been designed for application over a wide range of soil lower boundary conditions that commonly occur in most temperate high latitude countries such as the UK, which range from free-draining to impermeable.

Figure 2.5 schematic relationships between climate variables and soil conductivity.

The module simulates the formation of transient perched water tables and the generation of surface runoff. It addresses vertical and lateral water movement at a point in an explicit manner. The predictive ability of the site model has been tested against soil moisture data collected across a range of soil types under permanent grass in the UK (Evans et al., 1999). Root water uptake is calculated from transpiration demand, root distribution and soil water content using the 'sink function' described by Jarvis (1989). This approach assumes the ratio between actual and potential root water uptake varies in proportion with a dimensionless water stress index, or root adaptability factor that adjusts the stress in one part of the root system by increasing uptake from other parts where conditions may be more favourable. After Feddes et al. (1974) root length distribution is assumed logarithmic with depth and root water uptake is distributed within the root depth according to the stress (determined by water availability) in each soil horizon.

Soil surface evaporation, an important component of water loss, is calculated using an evaporation rate assuming a soil boundary layer conductance term. Total incident radiation on the soil surface (net of albedo) provides the net radiation balance, separately for the soil surface beneath the canopy by accounting for the estimated transmission of radiation through the canopy, and for a bare soil surface adjacent to the tree. After Campbell (1985) the model accounts for the increase in effective soil resistance to evaporation that occurs during soil drying by using a matrix model calculating the soil moisture in both the liquid and gaseous phases within soil pores at

various depths. In the current version of the module, soil temperature is assumed to be equal to that of the air.

The response of the evapotranspiration model is tightly coupled with the availability of water in the soil. The amount of water in the initial layer can be depleted by direct evaporation. If this layer is set too deep, then water-limitation problems may arise. At present, the module has its rooting characteristics set, and these do not change with time or water availability.

2.4. Allocation mechanisms and growth rules

Each stool has a number of shoots, and each shoot type is considered separately. To reduce computational time, three types of shoots are categorised for the initial state, and the shooting number module described later.

Requirements for branches are calculated - depending on crown geometry - before the available carbon is allocated to the different tissues (parenchyma, fibres or vessels in stem, branches, leaves, coarse or fine roots. The available carbon for allocation is calculated - depending on the growing phase of the tree - and the changes in biomass of the different tissues are returned. There are five growth phases for SRC (see sections 2.4.1 – 2.4.5).

Before allocating the available carbon, however, the following calculations are made:

- A basic assumption in the allocation module is based on the pipe theory which states that there must be a balance between the leaf area (which results in transpiration) and the pipes/vessels through which the water flows to the leaves (Deckmyn et al., 2006). It follows that leaf area is directly related to the actual number and size of the pipes (or vessels) in the sapwood.
- If the available carbon is negative (i.e. respiration is higher than photosynthesis), this is subtracted from the stored carbon. If stored carbon becomes zero, the shoot dies.
- As some embolism always occurs, there is always a minimal requirement of new pipes (and all other associated tissues) which is calculated before running through the phase (not in phase 5). If there is not enough carbon available to replace the pipes, the associated leaves will fall.

2.4.1 Phase 1. Leaf development from carbon stock

The canopy is initially replenished from the pool of stored carbon; 1/25th can be used daily for 20 days following budburst. If the (previous) canopy is filled before that, the tree will go into phase 2 and no longer use stored carbon.

Over winter, some pipes will have lost functionality; therefore new pipes need to be built. The pipe theory gives the requirement of vessels/pipes (so some increase in stem width) for these leaves, and a minimal requirement of fibres and parenchyma to support the vessels. The size of the pipes/vessels depends on the growth rate and is calculated from the previous day leaf growth rate.

2.4.2 Phase 2. Height or leaf growth

After the stored carbon is used, or if the crown is filled, phase 2 begins. If there is light in the canopy, leaves are added (with their associated pipes, fibres and parenchyma, and roots; the pipe width during phase 2 is equal to the species-specific average value).

Height growth occurs as soon as there is not enough light within the canopy. All carbon of that day will be used to expand the canopy with the same ratio of leaves to wood as in the existing crown thus leaves and branches develop simultaneously.

2.4.3 Phase 3. Storage and latewood formation

The start of phase 3 is determined in the 'budburst' module and depends on soil water potential. If no drought occurs, a species-specific fixed day for cessation of height growth is used.

During phase 3, height growth is no longer possible and all available carbon is used to replace pipes. Some leaves can also possibly grow, though it is unlikely that there will be sufficient light within the canopy. Most carbon is allocated to storage, and stem width will only increase because of pipe replacement and if all available storage space is filled.

2.4.4 Phase 4. Leaf fall

Leaves will fall from the start of phase 4 onwards. This is determined by the 'budburst' module and depends on temperature and day-length. Leaf fall is simulated in the mortality module.

As far as allocation is concerned, there is no difference in growth compared to phase 3 except that there is no possibility to grow leaves, even though there might be light available.

2.4.5 Phase 5. Dormancy

SRC shoots reach phase 5 when there is no leaf area left. Since there will be no carbon assimilation, there is no allocation. However, available carbon will be negative because of respiration and this will be subtracted from the stored carbon.

2.5. Shoot numbers and Management

2.5.1. Number of shoots

The number of shoots on each stool is calculated. The total number of shoots is predicted using the method described below. From the total number of shoots, the shoots are then allocated to one of three shoot types consistent with the observational data.

For the process-based model, the model for predicting the number of shoots is built upon the methodology developed for the empirical model. The number of shoots is

modelled using a Poisson generalised linear model with the log-link. Adjustments were made for over dispersion when testing for the significance of terms.

The empirical model used a number of variables, and included three together with an estimate for D100 such that in the table below, Delta is Log D100. However, since Delta can be represented by a number of coefficients not related to crop size, the model for number of shoots can be written in terms of site, soil and climate characteristics, with some adjustment for clonal sensitivity to each site.

Significant terms only were included in the models. Final models are summarised in the Table 2.2

Table 2.2 Summary of variables included in models used to predict number of shoots. Interaction between terms is indicated by 'x'. Further details are in Volume A; the associated coefficients can be obtained from the model functions listings in Appendix D of Volume C.

Willow	Poplar
Clone type	Clone type
Crop age	Crop age
Clone type x Crop age	Clone type x Crop age
Frost days ¹	Frost days
Frost days x Clone type	
	Frost days x Crop age
Growing degree days per year (GDD ²)	Growing degree days per year (GDD)
GDD x Crop age	GDD x Crop age
	Longitude
	Longitude x Crop age
	pH2 ³
Texture ⁴	Texture
Clone type x Texture	Clone type x Texture
Texture x Crop age	
Delta ⁵	Delta

Note 1: Frost days: Number of frost days between March and May.

Note 2: GDD: Growing degree days in a growing season.

Note 3: Soil pH is labelled 'pH2' because two methods of measuring pH were used. 'pH2' was assessed following methods used by ADAS.

Note 4: Soil texture category - Clay, Loamy, Sandy. This simple three-category soil texture variable was chosen not only for simplicity but also to avoid problems caused by fitting a factor with a large number of categories to data covering a relatively small number of sites.

Note 5: Delta is a complex function based on similar site and climatic variables (Table 2.3)

Table 2.3. A summary of the model terms, including interactions (shown as 'x') used to predict Delta. Further details are in Volume A and the associated coefficients can be obtained from the model functions listings in Appendix E of Volume C

Willow	Poplar
Clone type	Clone type
Crop age	Crop age
Clone type x Crop age	Clone type x Crop age
Annual rain	
Annual rain x Crop age	
Season rainfall ¹	
Season rainfall x Clone	
Season rainfall x Crop age	
	Frost days ²
	Frost days x Crop age
Growing degree days per year (GDD ³)	
GDD x Crop age	
	Latitude ⁴
	Latitude x Clone type
	Latitude x Crop age
pH2 ⁵	pH2
pH2 x Clone type	pH2 x Clone type
pH2 x Crop age	pH2 x Crop age
Texture ⁶	Texture
Texture x Clone type	
	Texture x Crop age

Note 1: Total growing season rainfall (March-October for willow and April-October for poplar)

Note 2: Frost days: Number of frost days between March and May.

Note 3: GDD: Growing degree days in a growing season.

Note 4: Latitude (decimal minutes)

Note 5: Soil pH is labelled 'pH2' because two methods of measuring pH were used. 'pH2' was assessed following methods used by ADAS.

Note 6: Soil texture category - Clay, Loamy, Sandy. This simple three-category soil texture variable was chosen not only for simplicity but also to avoid problems caused by fitting a factor with a large number of categories to data covering a relatively small number of sites.

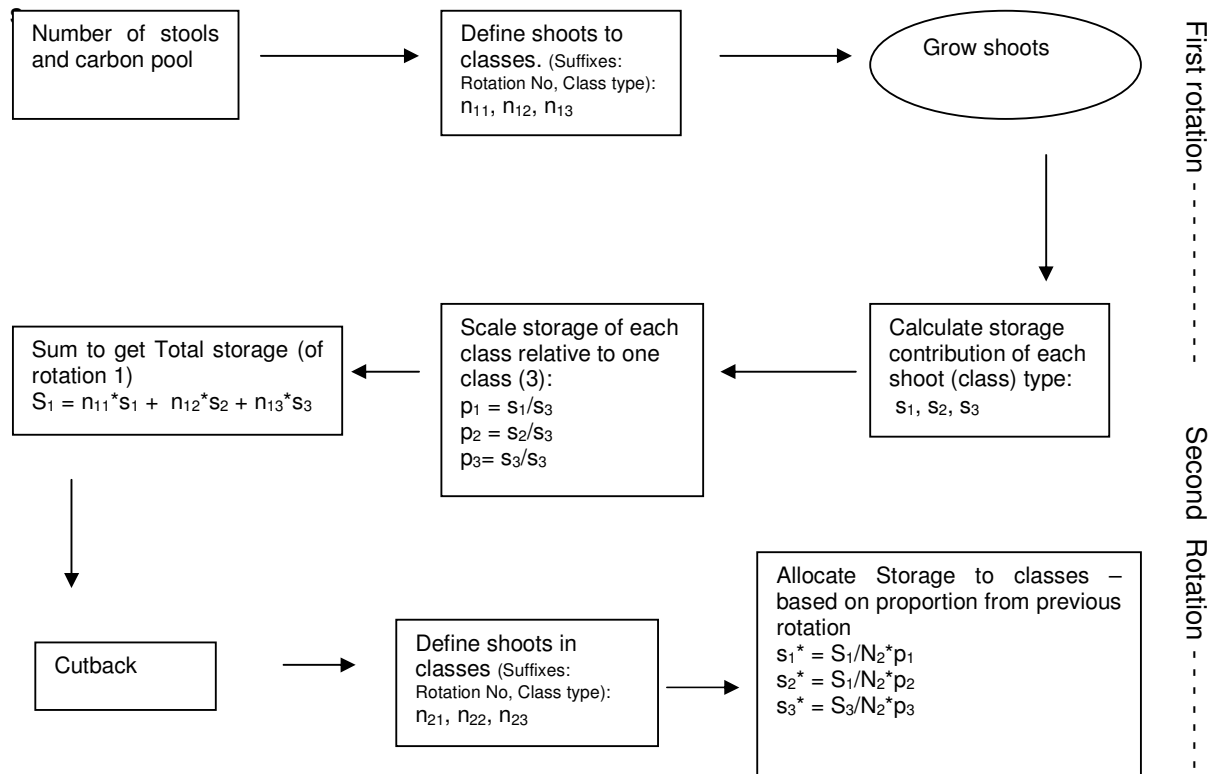
The above method produces the total number of shoots; it does not allocate them to the size 'classes'. The distribution of shoot numbers between the 'classes' of shoot needs to be representative of the coppice. For poplar, coppice tends towards having a single more dominant shoot, a number of slightly shorter shoots, and a number of suppressed shoots. Willow, on the other hand tends to show little difference among shoots. The ratios between the shoot classes are defined in the inputs as the initial number of shoots of each type; these ratios are preserved throughout subsequent rotations even though the total number of shoots may change.

2.5.2 Stored carbon allocation at cut-back

At the point of any cut-back, the initial subsequent growth of shoots is determined by the reserves stored in the rooting system of the stool. The model does not simulate every stool and the shoots emanating from it, but rather the total number of each type of shoots in the plantation. The total carbon stored in all the stools (and roots) is therefore determined as a single pool. Initial growth of the respective shoot types is

proportional to the total stored carbon pool and the allocation characteristics defined in the state variables.

Figure 2.6 Diagram of shoot number development



2.5.3. Scenarios

The effects of metrology are reflected in the process model as these are direct inputs. Although pathogens were observed to influence yield at particular sites in particular years, the current process-based model makes no allowance for pathogen effects. This is contrary to the implicit inclusion of fitting the empirical model to the observed data.

Two mechanisms have been built into the model to allow the user to explore 'what if scenarios'.

1. Changing CO₂ levels. Ambient CO₂ levels are set in the input files of 'local properties' and can be altered, in combination with other metrological inputs such as temperature and rainfall, to explore climate change effects.
2. Defoliation. A range of pests and diseases may attack coppice; leaf rust is a particular problem with many species of poplar and can also be a problem with willow. A defoliation function has been included within the model which allows the user to set a defoliation rate, its time of onset and its duration but we have not modelled defoliation as a process.

2.6. Data

The metrological data were obtained by direct measurement within the project; additional information made available to Forest Research by the British Atmospheric Data Centre (BADC). Measured data is included within the project database but Forest Research is not able to pass on the BADC data to other parties.

Eco-physiological data collection to assist in both the development and parameterisation of the process model was carried out in two parts.

2.6.1. Intensive ecophysiological assessments

Sap flow was assessed on poplar and willow clones at the Headley Nursery site from June to November 2001. This site is separate, and is not one of the main measurement plots - however, its location is close (9km) from site 7. Probes were installed on 3 stems each of Trichobel, Ghoy and Beaupre poplar clones and Germany, Jorunn and Q83 willow clones in June 2001. Each month the gauges were moved to different stems to avoid damage to the trees and prevent build up of resins in the xylem. Sap flow measurement was continued until mid-November 2001, when most of the leaves had senesced. Further methodological details and results are available in Volume C, Appendix L.

Respiration measurements were carried out on a monthly basis at the Headley and Newton nursery sites from November 2002. Like Headley, Newton is a separate nursery site, located close to site 44. Root (extracted with 2.5cm diameter auger) or shoot samples were collected from coppiced poplar (Trichobel, Ghoy and Beaupre) and willow (Germany, Jorunn and Q83). These samples were then used to measure respiration rates of the respective tissues types and clones. Further methodological details and results are available in Volume C, Appendix L.

Seasonal respiration, phenology, sap-flow, and photosynthesis were assessed during 2003. The methodology and results are presented in Volume C, Appendix M; Physiology report 2003.

The current process-based model uses annual, not seasonal, rates of respiration. Due to the modular structure it is possible to incorporate seasonal variations with only small changes to the code.

2.6.2. *Populus* physiology and morphology

Physiology

Extensive biochemical analysis and photosynthetic capacity calculations were measured and evaluated on three-year-old coppice of Trichobel and Ghoy clones during May to September 2005. A full account is given in Volume C, Appendix R with the Abstract below:

Temperature dependencies of the maximal rates of leaf photosynthetic carboxylation (V_{cmax}), light-saturated electron transport (J_{max}) and dark respiration (R_d) were described within three-year-old monoclonal coppice poplar (*Populus spp.*) canopies of clones Trichobel and Ghoy. Response curves of net CO_2 assimilation (A) to intercellular CO_2 concentration (C_i) at saturating leaf irradiance were recorded on mature non-senescent leaves from May to September 2005 and over the temperature range 12 to 37 °C. Values of V_{cmax} and J_{max} were computed by fitting

Farquhar's model on $A-C_i$ curves. For each temperature, positive and linear relationships have been described between A , V_{cmax} , J_{max} or R_d versus leaf nitrogen concentration expressed on an area basis (N_{area}). There were no statistically significant differences between clones and among sampling dates. For N_{area} ranging between 0.5 to 2.5 g N m⁻² (i.e., from bottom to top canopies) A , V_{cmax} , J_{max} and R_d ranged from 6 to 37, 17 to 100, 31 to 212 and 0.5 to 3.1 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at 25 °C, respectively. At this temperature, the averaged J_{max}/V_{cmax} ratio was 2.06. Temperature response functions were computed from results of the linear regression equations and fitted with a thermodynamic model. The activation energy was higher for V_{cmax} (91.4 kJ mol⁻¹) than for J_{max} (61.5) (37.9 for R_d) resulting in a decrease in J_{max}/V_{cmax} ratio with increasing leaf temperature. Because of a limitation in the range of temperatures that could be monitored under field conditions, precise computations of the optimal temperatures for V_{cmax} (> 37 °C) and J_{max} (between 33 and 37 °C) were hopeless. Nevertheless, the results represent an improved ability to model leaf photosynthesis over a wide range of leaf temperature necessary for predicting carbon uptake by fast growing poplar crops.

Morphology

The morphology work of Casella and Cuelemans (2002) has been used in the development of the morphological and light interception description of the process-based model including the central tenet of clonal variation being largely explained by leaf morphology and canopy structure.

Casella and Cuelemans (2002) abstract

Spatial distributions of leaf characteristics relevant to photosynthesis were measured and compared within high-density coppice canopies of *Populus spp.* of contrasting genetic origin. The study was carried out in three clones representative of the range in growth potential, leaf morphology, coppice and canopy structure: Hoogvorst (*Hoo.*) (*Populus trichocarpa* Torr. & Gray $\times$ *Populus deltoides* Bartr. & Marsh), Fritz Pauley (*Fri.*) (*Populus trichocarpa* Torr. & Gray) and Wolterson (*Wol.*) (*Populus nigra* L.). Leaf area index (*LAI*) values ranged from 2.7 (*Fri.* and *Wol.*) to 3.8 m² m⁻² (*Hoo.*). All three clones exhibited large vertical variation in leaf area density (*LAD*) (0.02 - 1.42 m² m⁻³). Leaf dry mass per unit leaf area (*DM_A*) increased with increasing light levels in *Hoo.* and *Fri.*, from ca. 56 g m⁻² at the bottom of the canopy to 162 g m⁻² at the top. In *Wol.*, on the other hand, *DM_A* varied only from 65 - 100 g m⁻², with no consistent relationship with respect to light. Conversely, nitrogen concentration on a mass basis (*N_M*) was nearly constant within the *Hoo.* and *Fri.* canopies, around 1.3 - 2.1%, but increased strongly with light in *Wol.*, from 1.4% at the bottom of the canopy to 4.1% at the top. As a result, nitrogen per unit leaf area (*N_A*) increased with light in all three canopies, from 0.9 g m⁻² at the bottom to 2.9 g m⁻² at the top. Despite the fact that a single linear relationship described the dependence of maximum carboxylation rate (*V_{cmax}*) (17 - 93 $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$) or electron transport capacity (*J_{max}*) (45 - 186 $\mu\text{mol electrons m}^{-2} \text{s}^{-1}$) on *N_A*, for all clones, clone *Wol.* differed from clones *Hoo.* and *Fri.* by exhibiting a higher dark respiration rate (*R_d*) (1.8 as compared to 0.8 $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ for clones *Hoo.* and *Fri.*) at low *N_A*.

The work has continued within this project leading to Casella and Sinoquet (2003).

Casella and Sinoquet 2003 Abstract)

A multi-scale biometric methodology, for the description of the three-dimensional architecture of fast-growing short-rotation woody crops (SRWC), is used to describe 2-year-old poplar clones during the second rotation. To account for expressions of genetic variability observed within this species (i.e., growth potential, leaf morphology, coppice and canopy structure), the method has been applied to two

Clones: Ghoy (Gho) (*Populus deltoides* Torr. & Gray x *Populus nigra* L.) and Trichobel (Tri) (*Populus trichocarpa* Torr. & Gray x *Populus trichocarpa* Torr. & Gray).

The method operates at the stool level and describes the plant as a collection of components (shoots and branches) described as a collection of metameric elements, themselves defined as a collection of elementary units (internode, petiole, leaf blade). Branching and connection between the plant units (i.e., plant topology) and their spatial location, orientation, size and shape (i.e., plant geometry) describe the plant architecture. The methodology has been used to describe the plant architecture of 15 selected stools per clone over a five month-period. On individual stools, shoots have been selected from three classes (small, medium and large) spanning the diameter distribution range. Using a multi-scale approach, empirical allometric relationships have been developed to parameterise and/or explain elementary units of the plant, topological relationships and geometry (e.g., distribution of shoot diameters on stool, shoot attributes from shoot diameter).

The empirical functions form the basis for the 3-Dimensional Coppice Poplar Canopy Architecture model (3-D CPCA), that recreates the 3-D architecture and canopy structure of fast-growing coppice crops at the plot scale. The model provides fisheye images using the ray tracing software POV-Ray™ that are used to assess model outputs through visual and quantitative comparisons between actual photographs of the coppice canopy and simulated images. Overall, results indicate a good predictive ability of the 3-D CPCA model.

2.7. Validation

Validation of the process model has proved difficult. Components of the model have been tested and validated in a range of woody species (Evans et al., 2005; Deckmyn et al., 2006). However direct comparison against the observed data has proved unsatisfactory since the observational data are in many cases influenced by biotic and abiotic factors that were not considered within this model. In particular the rust *Melampsora* spp. significantly affects a number of *Populus* species, especially in the south and south-west of the UK. Our experimental clones in South-west England had significant defoliation and a lower yield. Willow is also susceptible to *Melampsora* spp and occasional outbreaks of willow beetle (*Phratora* spp). During the trial, some varieties of willow also became infested with stem aphids (e.g. *Tuberolachnus salignus*). In turn these will have had impacts on the growth of the coppice. Unfortunately it is impossible to establish how well the clones would have grown in the absence of such pests and diseases. A further difficulty is caused by the variability of such factors from year to year.

Since the process-based model establishes the potential rather than the actual growth, direct comparisons against the observational data have not been made.

2.7.1. Sensitivity

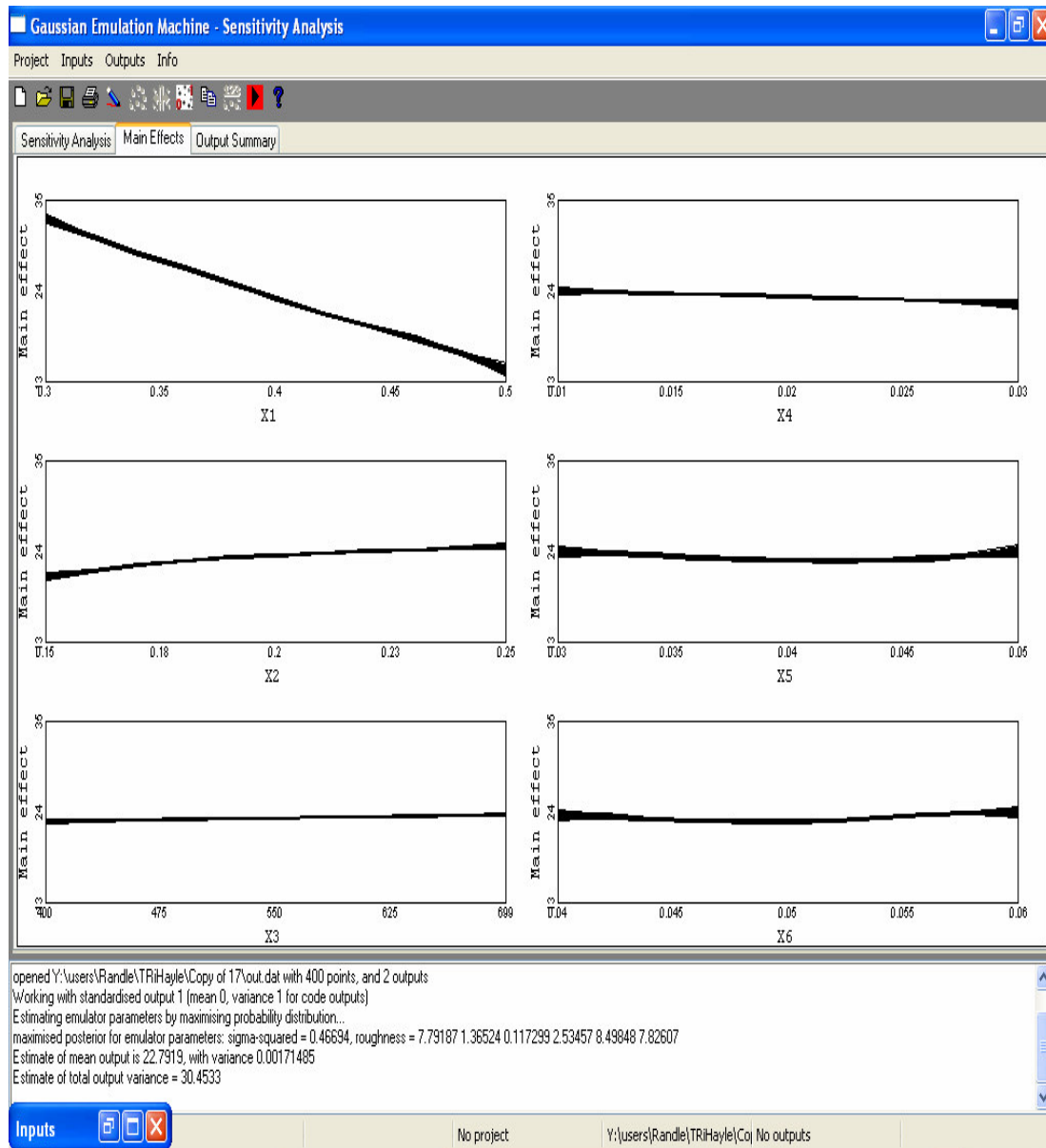
The model has many parameters. In normal usage, many of these parameters are 'stable', i.e. the model is not sensitive to a small change in value. It is worth pointing out that if conditions change, the model may become more sensitive to previously stable parameters.

In view of the variation in observational data and the published literature, we thoroughly investigated the sensitivity of various parameters using GEM-SA which was developed by the University of Sheffield. An example is shown in Figure 2.7, where six parameters were tested for their sensitivity in terms of impact on yield at age 3:

- The ratio of above-ground:below-ground allocation of carbon (Figure 2.7, X1): This is a widely used parameter after McMurtrie and Wolf 1983, which relates the carbon requirement of below-ground root development as a proportion of above-ground development.
- The storage in coarse roots (Figure 2.7, X2): Some assimilated carbon is stored below-ground; this provides a pool of available carbon from which new foliage can be grown in the spring, and also a resource to enable growth following cut-back.
- The height:diameter ratio (Figure 2.7, X3): This is a *form-factor* parameter which changes the shoots from being 'tall and thin', or 'short and stocky'.
- The initial storage in each class of fine roots (Figure 2.7, X4, X5, X6): These parameters help to govern how the different classes of shoot will develop; a shoot with more storage is likely to develop more and faster, than a shoot with little storage.

Clearly the most dominant parameter is the above-below ground allocation ratio.

Figure 2.7: Example of sensitivity analysis; X-axis is the parameter value where X1 is the ratio of above-ground:below-ground carbon allocation, X2 is the carbon stored in coarse roots, X3 is the height:diameter ratio, and X4, 5 and 6 is the initial storage in each class of fine roots; the Y-axis is the effect on yield (above ground total shoot biomass) at age 3.



2.7.2. Key parameters

The number of the parameters required for full parameterisation of the model is significant. However, one of the underlying principles of this model is that differences between clonal varieties of SRC can largely be explained by differences leaf morphology and associated canopy architecture. This approach has been demonstrated previously (Casella and Ceulemans, 2002) and in the development of 3-D CPCA, a coppice canopy architecture model (Casella and Sinoquet 2003, Volume C, Appendix R). Thus a smaller number of parameters are used to explain the differences

between clones, and these parameters are relatively easily obtainable or measurable without substantial expertise and equipment, aiding the usage of the model. The key parameters (explaining clonal differences) are limited to

- The leaf size
- The number of leaves in a layer

The 'basic' interface allows the user to change these parameters easily (further details are given in the process model user guide; see Volume C, Appendix Q). Nevertheless the software is designed to allow the more advanced user to access all parameters, so this approach does not preclude changes of physiology between clones.

2.7.3. Uncertainty in predictions

The biomass predicted by the model has a level of uncertainty due to uncertainty from four sources:

1. Inaccuracies in the model
2. Inadequacies in the model
3. Uncertainty in the estimated parameters of the model
4. Inherent variability in the process being modelled

While the model has been run for selected sites across Britain, there is inevitably a degree of uncertainty about the form of the model. In particular,

1. The range of sites is limited and does not cover in detail the whole of the UK and Northern Ireland.
2. The data are available for a limited number of growing seasons; data is not always complete and continuous.
3. Only one planting density was used in the experiments, extrapolation to other spacing may lead to errors. Insufficient data were available to validate the spacing model used and to estimate the uncertainty associated with it.
4. The simplification of the shoot status to a number of classes may lead to problems especially in the case of Mortality since there is no gradual loss of shoots and shoots of a particular class either live or die.
5. Parameterisation of the initial stored carbon is difficult – it is not directly measurable, but it has a large impact on the growth following a cut-back.

2.8. Software realisation of models

Because the model is complex and complete parameterisation is difficult, we developed software to allow the model to be used at either a basic or advanced user level. In the basic option the user selects the input and output files and can change the most important parameter whereas the advanced option allows the user to have more control over the parameters. Further details are given in the process model user guide, see Volume C, Appendix Q.

In addition to physiological parameterisation, the model requires significant meteorological data. These data are not always readily available, though a good source is via the British Atmospheric Database Centre (BADC). <http://badc.nerc.ac.uk/home/> **Users should however be advised that data may be incomplete or contain erroneous values.**

The model has been developed with a graphical front end. A screen shot of the initial page of the user interface is shown in Figure 2.8. Access to files is given though the

selection of the basic or advanced user option (Figure 2.9), obtained by clicking on the 'cog' icon

:

Figure 2.8: Screenshot of the process-based model interface

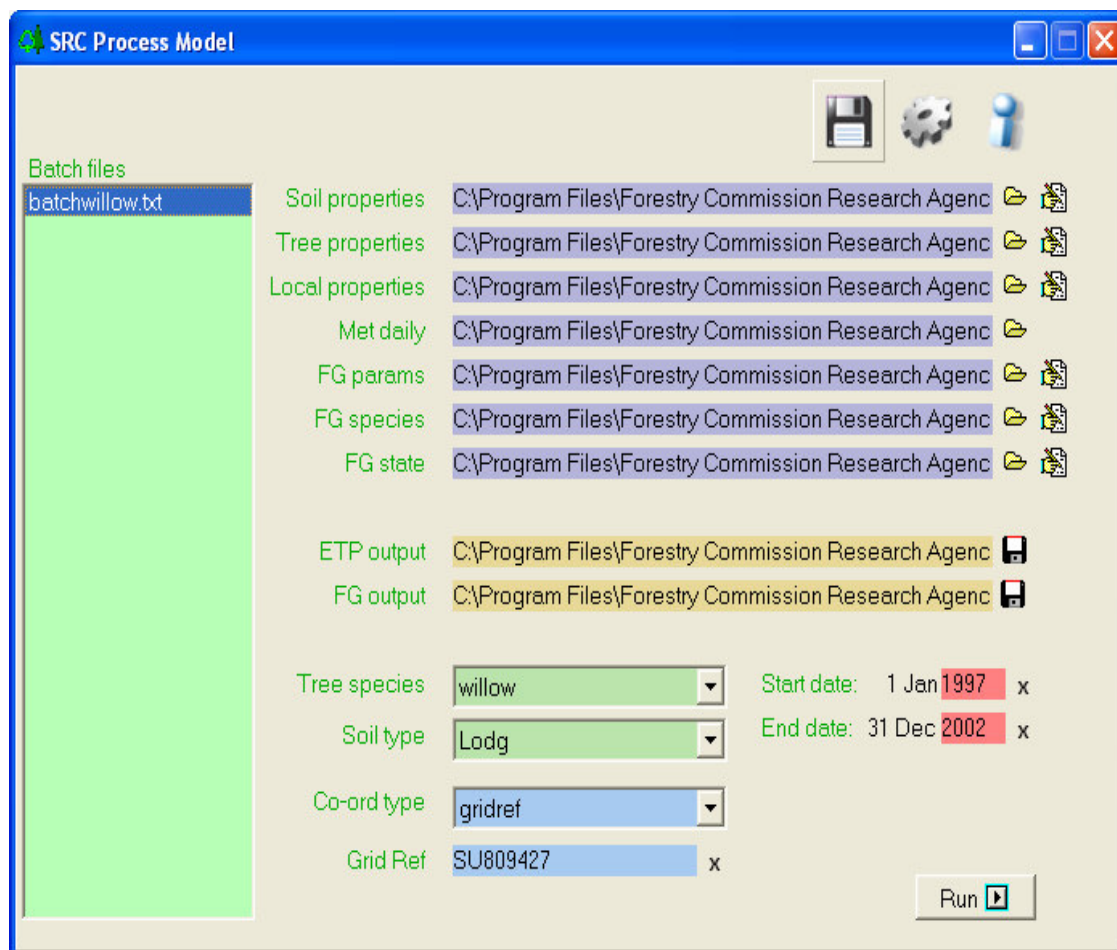
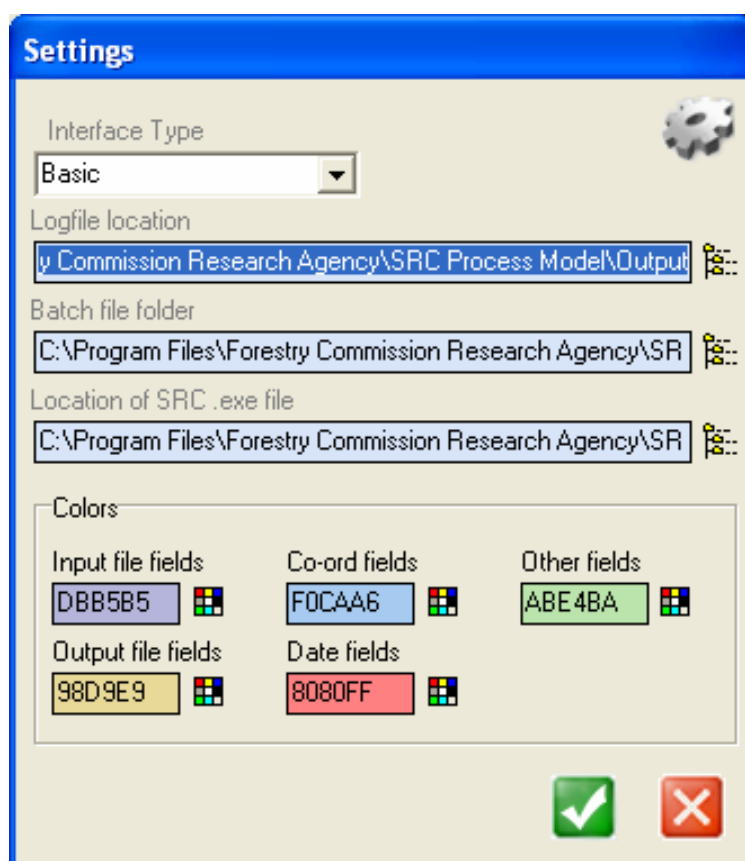
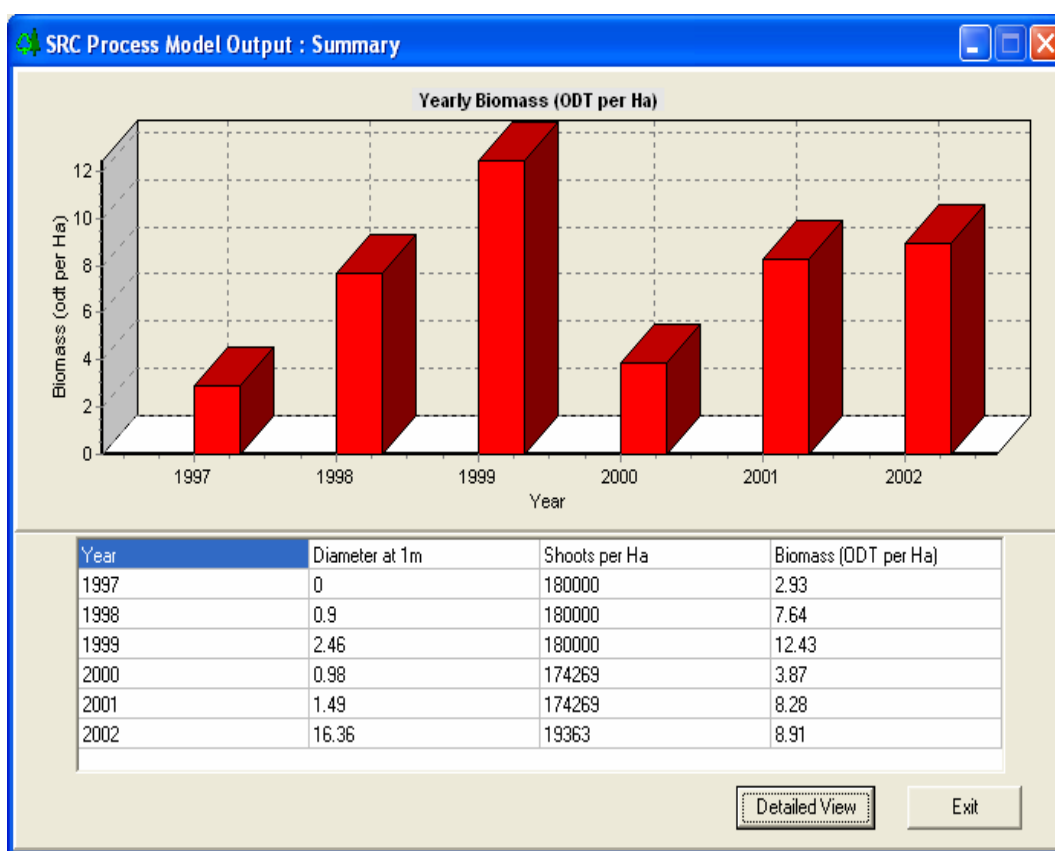
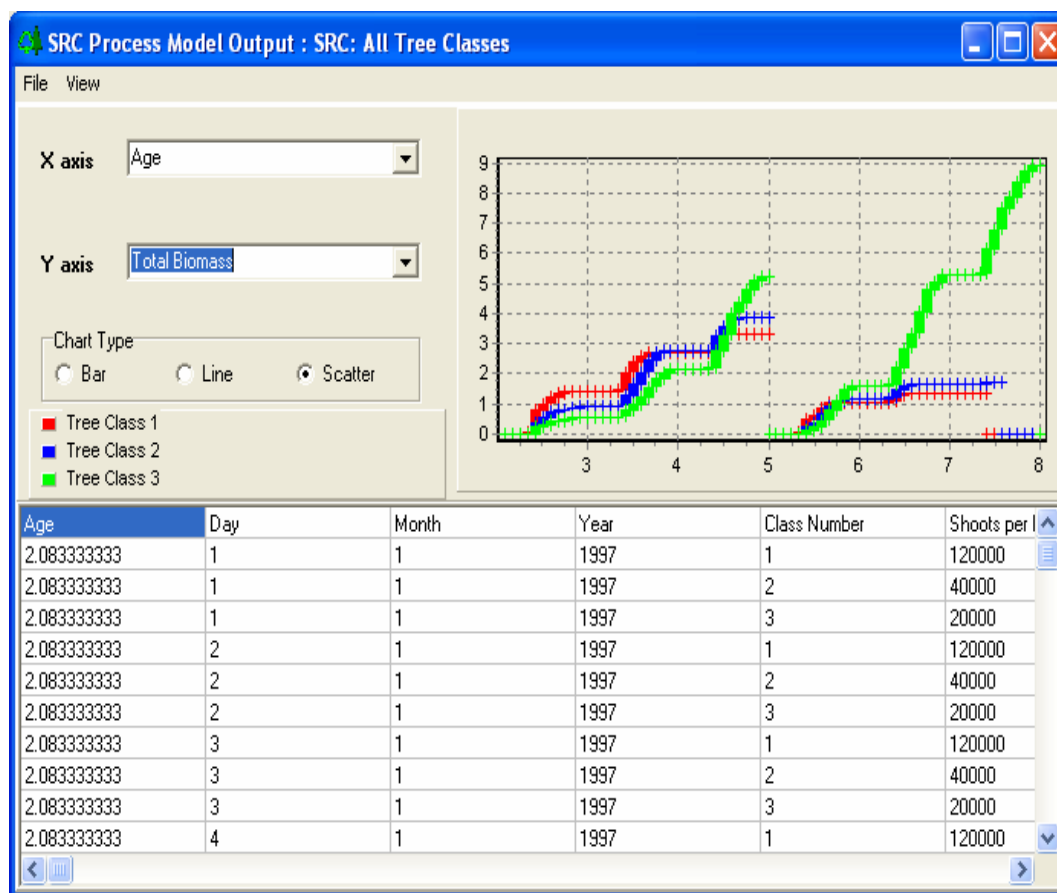


Figure 2.9: User level control window.

Once the user has selected their parameter files and defined their options, the model can be run. Two levels of complexity of outputs can be produced. The default output is a bar-chart of the biomass produced during the simulation (Figure 2.10).

Figure 2.10: Bar-chart output of the process model

Further information can be obtained by selecting the 'Detailed View' button which produces a further window (Figure 2.11). This window permits the user to examine many outputs produced by the model and also save the simulated data as a separate file, which can then be further explored using common tools such as Microsoft Excel™.

Figure 2.11: Additional investigative output screen

3. Simulations

Of the 50 sites in the field trials, 47 have been simulated. Three sites were excluded:

- Site 25 was not simulated due to suspect rainfall records; 71 mm and 134 mm were recorded in years 3 and 4 had respectively whereas the site would expect over 1000 mm per annum
- Site 45 was abandoned following soil survey (Table 1.1): Initial indications identified this as a suitable site, but the survey revealed it was a 'man-made' soil, containing building hardcore and industrial waste.
- Site 50 was abandoned for the trials (Table 1.1): this site had poor establishment, survival and growth, possibly due to a soil incompatibility with the coppice varieties.

3.1. Poplar

The clonal varieties *Trichobel* and *Ghoy* were simulated with the process model. *Trichobel* (in the field studies) was a productive clone yielding over 24 odt ha⁻¹ at many sites at the end of rotation. In comparison the variety *Ghoy* typically yielded around 15 odt ha⁻¹ at the end of rotation. The **ONLY** changes between these simulations were Leaf Size 0.005 m² and 50 leaves per layer for *Trichobel* and Leaf Size 0.0012 m² and 100 leaves per layer for *Ghoy*. These outputs compare well with the data obtained from the empirical standing biomass estimates, having a mean yield of 25-26 odt/ha, and 14-17 odt/ha for *Trichobel* and *Ghoy* respectively (Evans et al, 2007a).

To demonstrate the effect of elevated CO₂, we simulated the yield of *Ghoy* grown in an ambient CO₂ concentration of 500 ppm cf. typical current ambient CO₂ is 370 ppm. No other inputs were changed - meteorological data including temperature and rainfall were unchanged and no additional physiological responses to elevated CO₂ were assumed. Improved productivity was predicted, with biomass increasing between 20 and 30% in year one, reaching 20-40% by year 3 (Figure 3.6). This amount compares well to the range reported by Liberloo et al. (2004) at the EUROFACE sites, who found a biomass increase of up to 25% at year one.

3.2. Willow

Less information was available to differentiate willow varieties for the model parameterisation therefore simulations used a generic willow. The main difference is the description of willow and poplar. Is that the willow have more shoots per stools, and that the dimension of the shoots are smaller.

We performed 400 simulations taking into account the uncertainty in geometry of the shoot, leaf nitrogen content, below- ground carbon storage, and root allocation. The total coefficient of variation of the simulated yield is < 20 %.

In general the yields estimated by the process-based models were consistent with those from the fitted empirical models. On the other hand, the inter-site biomass variability simulated by the process-based model is too small and can only be partly explained by the local pest impact.

3.3. Yield maps of willow and poplar varieties

In order to present the yield data from 47 sites in an easy-to-interpret manner, colour coded maps of the UK were produced (using Genstat). The biomass value for each 20 x 20km grid square is an average of the biomass estimates for sites located within 60km of the grid. The site estimates were weighted inversely to the distance of the site from the centre of the grid. Biomass estimates were assigned different colours according to their magnitude or 'yield class'. In each simulation the range of predicted yield was grouped into five yield classes (therefore the same colour need not represent the same yield). Unshaded areas identify areas of the UK which are too distant from the field sites for estimates to be made.

Figure 3.1. Willow standing biomass of shoots for rotation 1, year 1 (top left) and 2 (top right); and rotation 2, year 3 (bottom left).

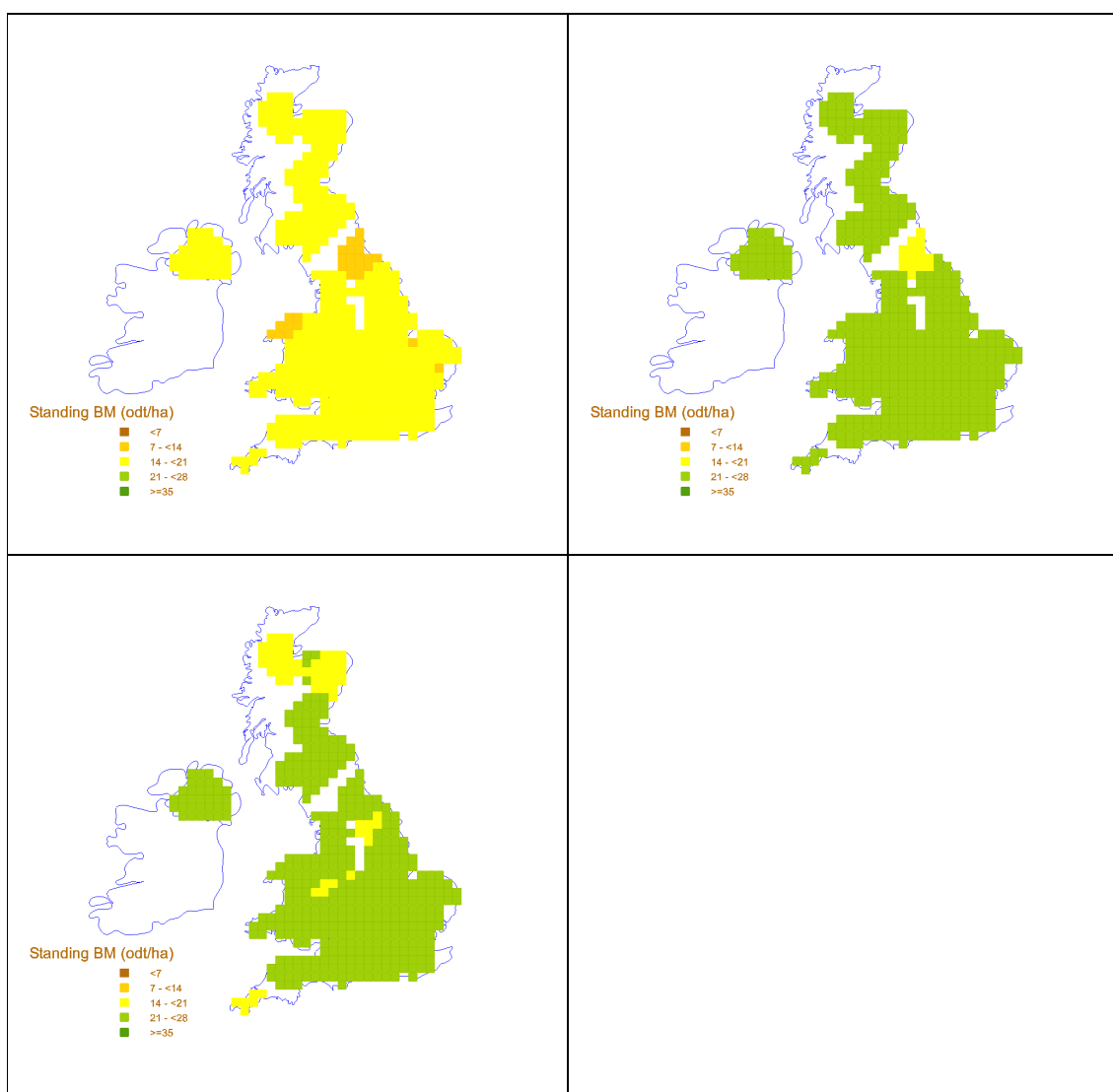


Figure 3.1 demonstrates the yield of Willow. However, it should be noted that the transition between rotations (carbon storage) was poor in the model – this led to the second rotation being weaker than the first.

Figure 3.2: Process-based model estimation of standing biomass of shoots for the poplar variety *Trichobel*. First rotation (top left, age 1; top right, age 2; bottom right, age 3). Note change in scale through the sequence.

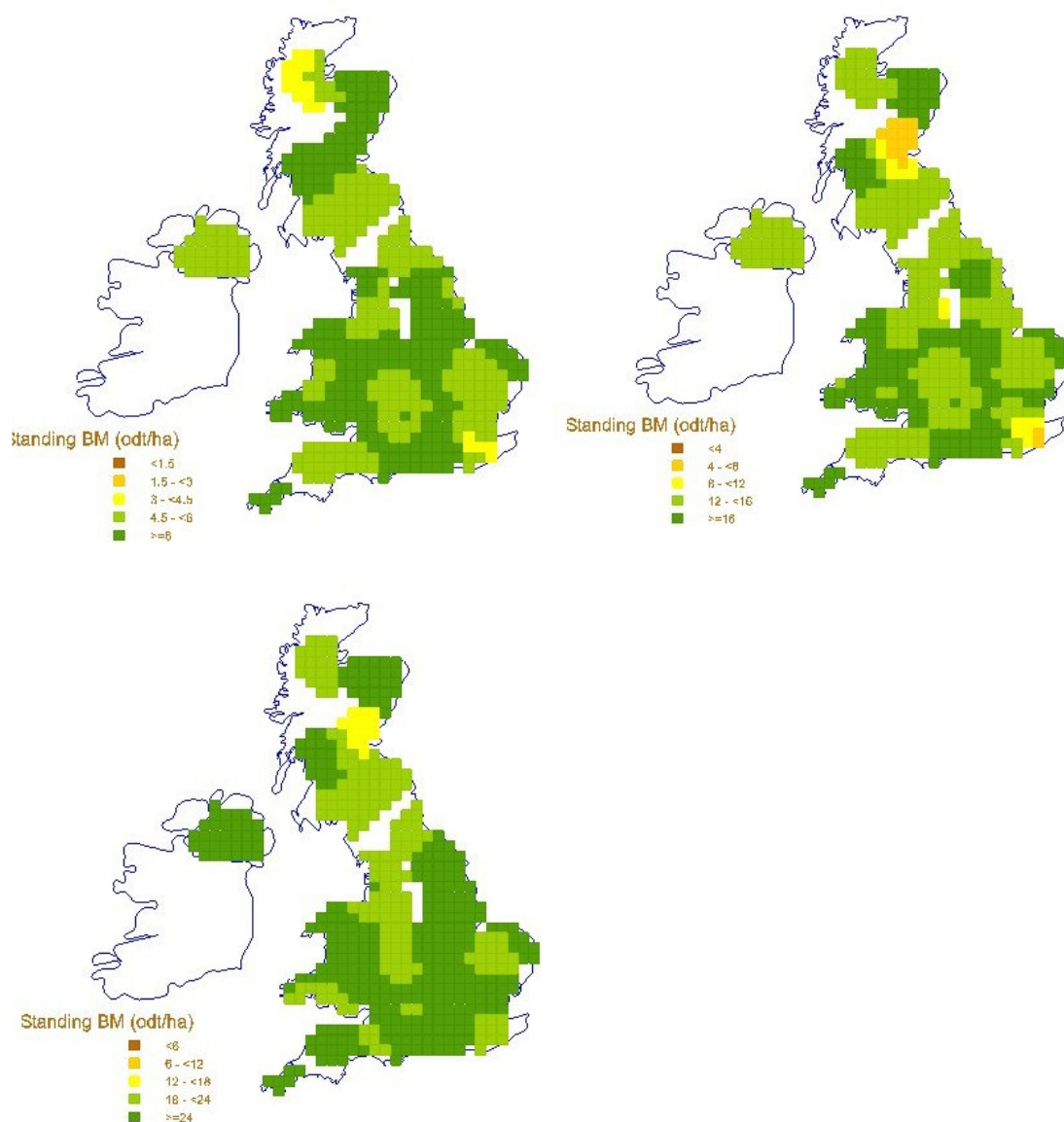


Figure 3.3: Process-based model estimation standing biomass of shoots for the poplar variety *Trichobel*. Second rotation (top left, age 4; top right, age 5; bottom right, age 6) Note change in scale through the sequence.

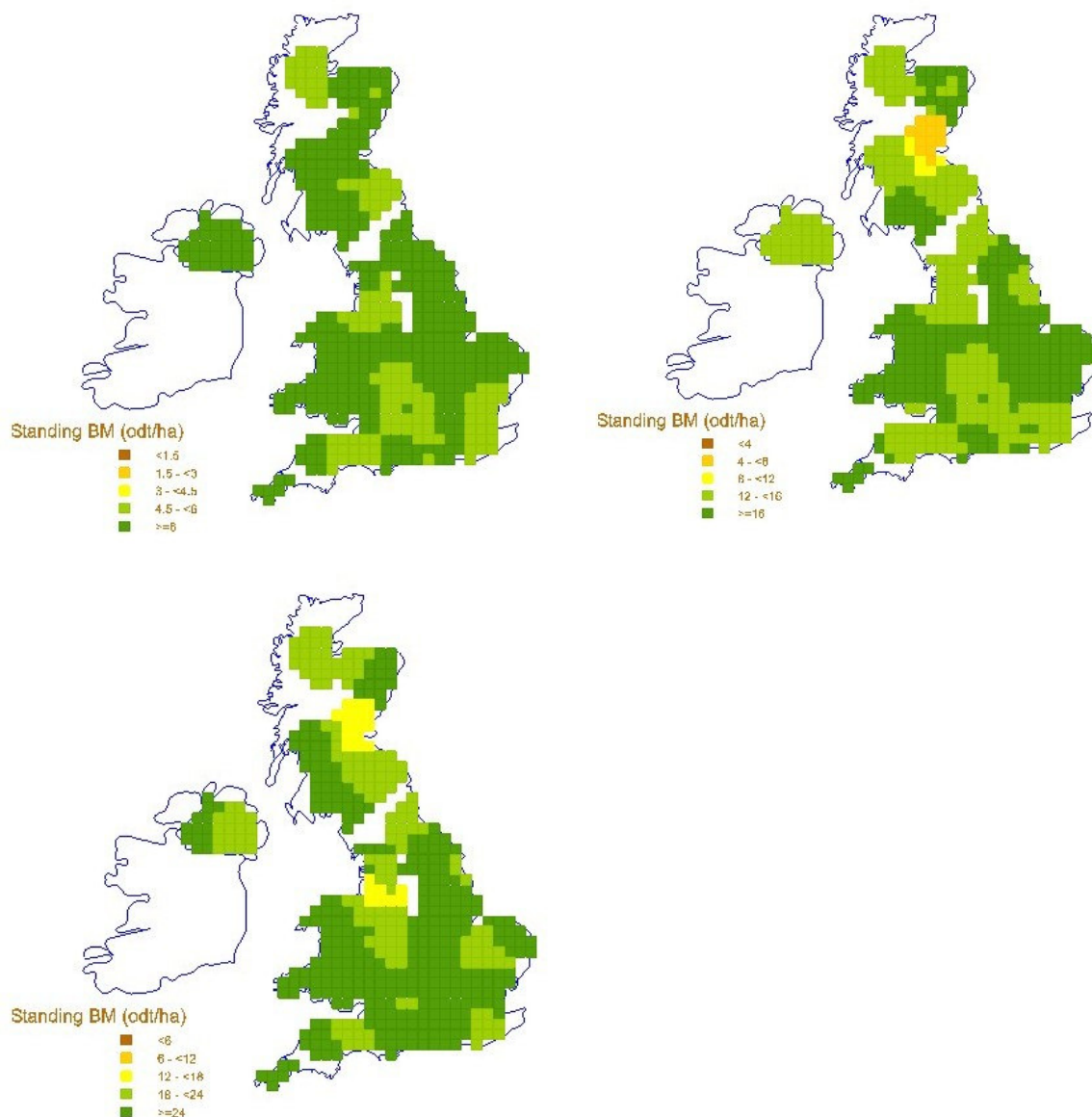


Figure 3.4. Process-based model estimation of the standing biomass of shoots for the poplar variety *Ghoy*. First rotation (top left, age 1; top right, age 2; bottom right, age 3) Note change in scale through the sequence.

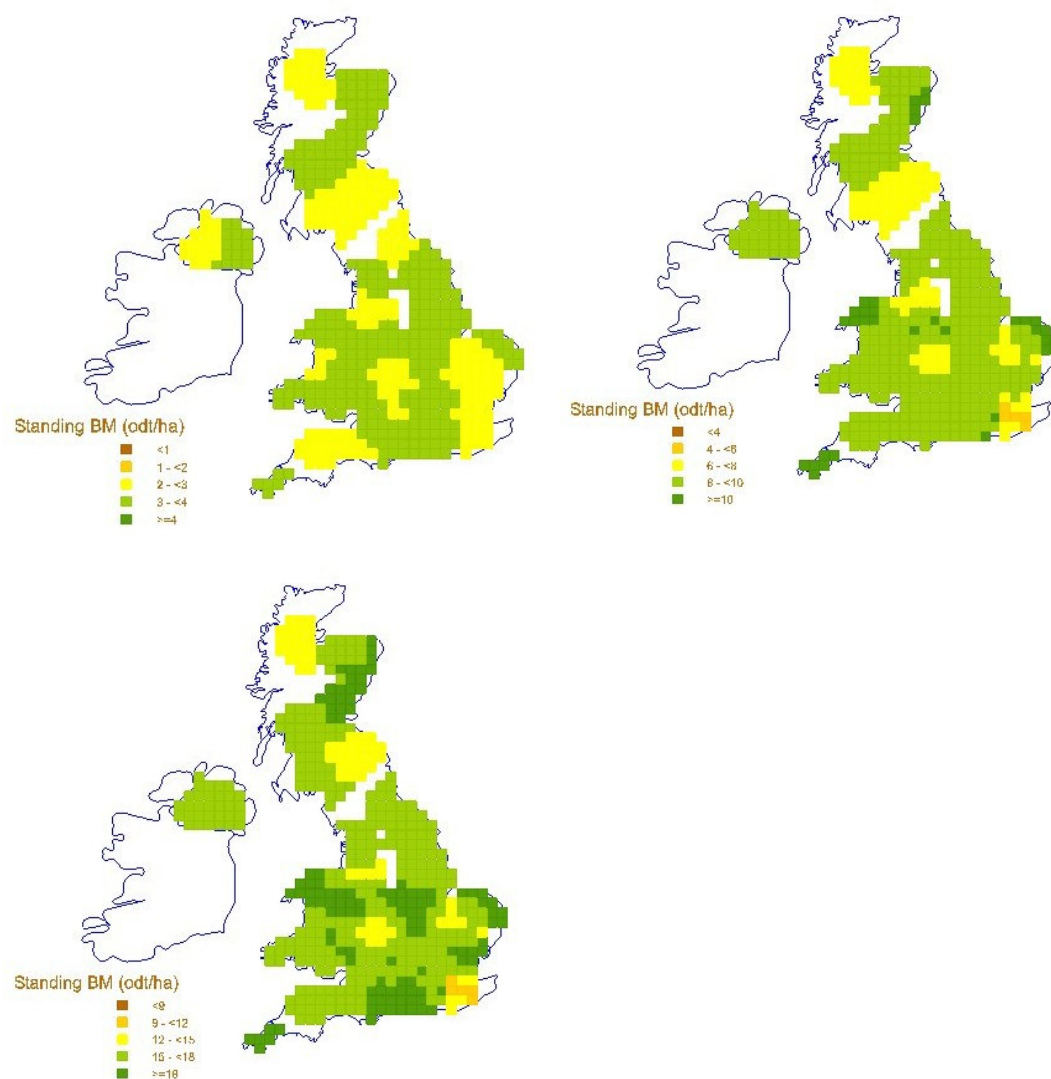


Figure 3.5. Process-based model estimation standing biomass of shoots for the poplar variety *Ghoy*. Second rotation (top left, age 4; top right, age 5; bottom right, age 6). Note change in scale through the sequence.

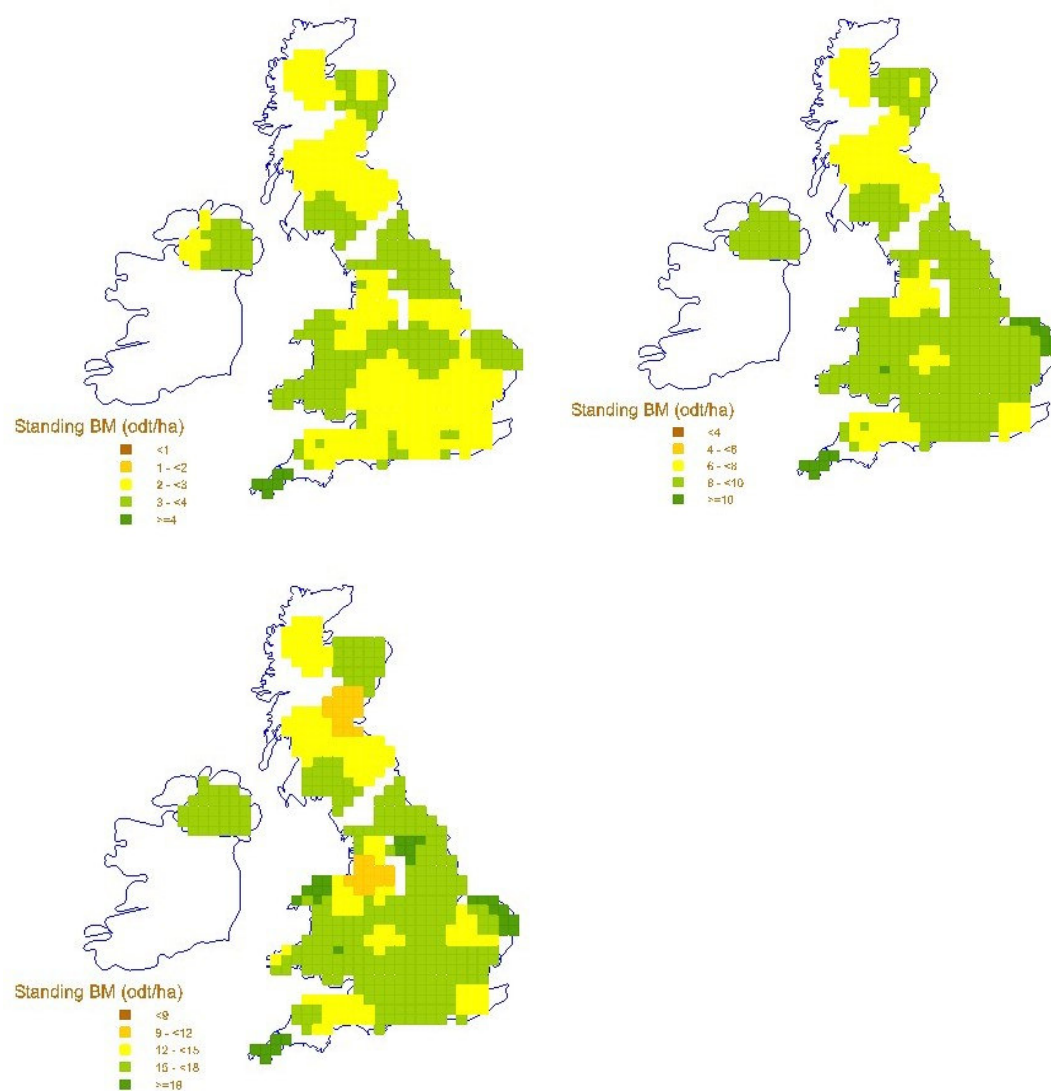
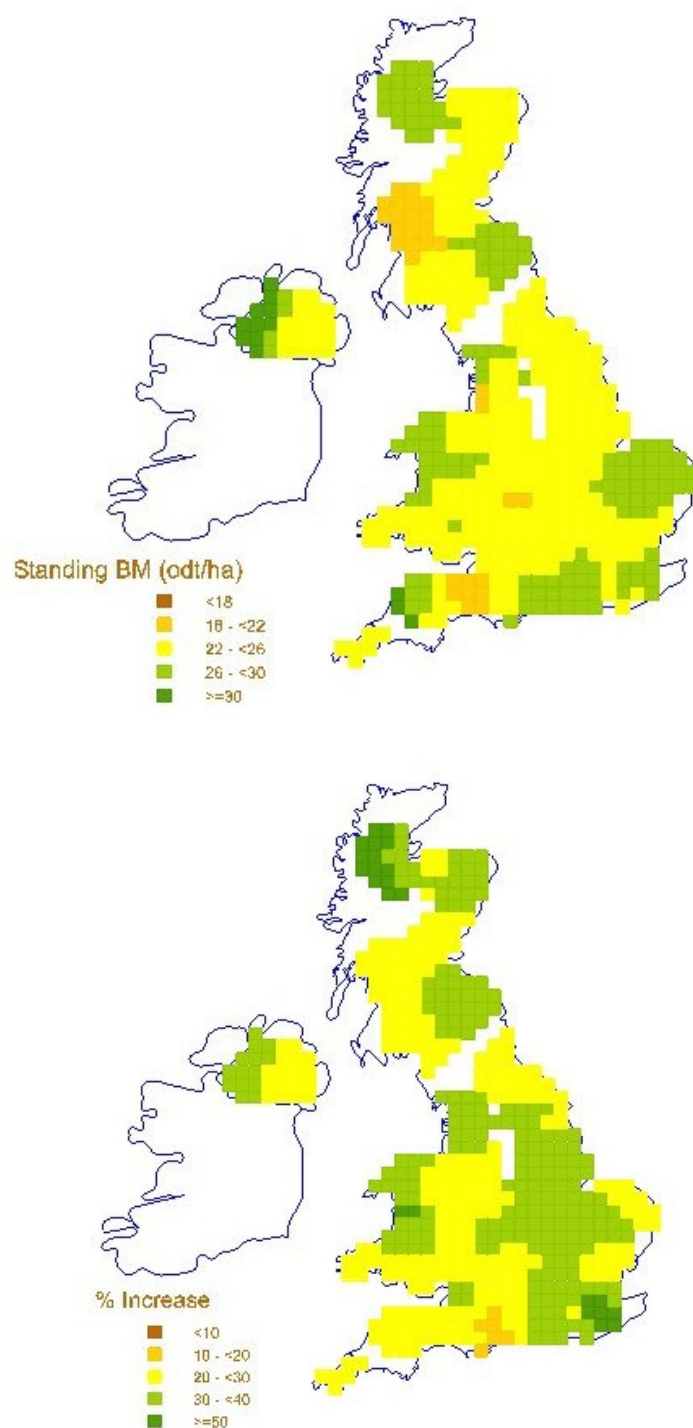


Figure 3.6. Response, as percent increase, of poplar variety *Ghoy* when ambient CO₂ levels are increased from 370ppm to 500ppm (top graph, first rotation, age 1 in odt ha⁻¹; bottom graph, first rotation, age 3 as % increase)



4. Pests and diseases

Both poplar and willow coppice are prone to disease, though the severity depends greatly on the variety and location. Probably the most significant damage is caused by rust fungus (*Melampsora* spp), which can cause substantial defoliation. This has been reported in Volume A, Section 4.

We have not attempted to model pest and disease intensity or frequency within this project. However, as pests and disease effects can be of commercial importance, a simple alternative method of exploring their impacts on yield has been provided whereby the user can defoliate the crop to various degrees. This approach takes no account of any response that a plant may make in response to attack. It is assumed that any defoliation event will affect all foliage equally (i.e. not be centred on a particular part of the canopy). There is no capacity to vary the defoliation on a year by year or rotation by rotation basis, although this could be subsequently built into the model.

The defoliation is defined by three parameters: the start of defoliation, the intensity and the duration.

Start day: this is defined by a day of year value. It should be borne in mind that lost foliage may be replaced if the canopy is still developing (see section 2.4) whereas later in the season this is not the case as defoliation will only reduce the amount of assimilate available for storage.

Intensity: This is an indication of the defoliation rate. It is expressed as a percentage per day. However, as the canopy is probably reducing in size, the amount lost day by day will decrease in a decay manner (Figure 4.1)

Duration: this parameter defines the duration of attack.

Figure 4.1: Effect of defoliation intensity on canopy status (assuming no replacement of foliage occurs)

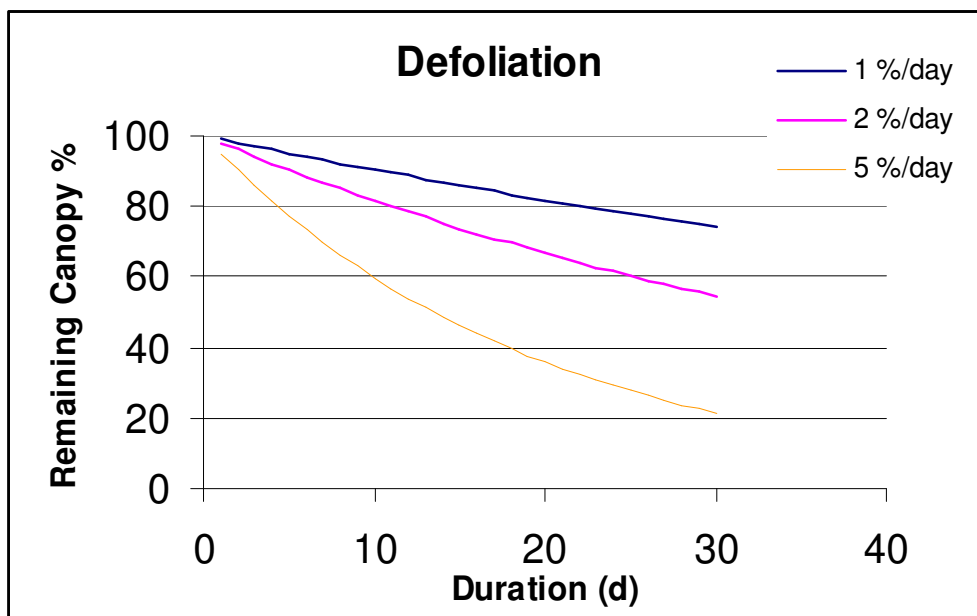
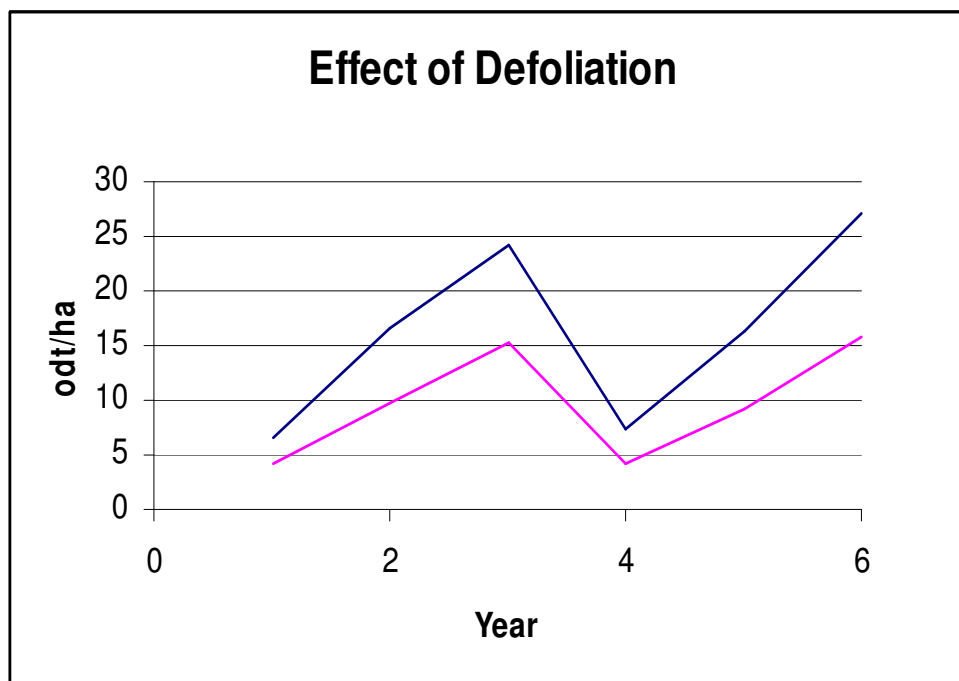


Figure 4.2 shows the modelled effect of a defoliation event in the first year with Start day 220, Duration 30 days, and 5% per intensity which causes a reduction in standing biomass of some 50%. An ongoing cumulative effect is caused by the reduced growth and subsequent lessened storage. It is likely that in reality the effect of such intensity would be even more severe. As a result modelled defoliation will have to be increased to account for the additional effort that would be made by the plant in combating the attack. In the case below (5%/day, 30 days), Figure 4.2, would be the equivalent of a 50-60% defoliation due to rust.

Figure 4.2: Simulated effect of defoliation on standing biomass production. Defoliation is set to occur at day 220 for 30 days at an intensity of 5 % /day (blue line indicates no defoliation; pink indicates defoliation).



5. Critical review of the process-based model

The network of 49 sites provided only limited coverage of the variation in soil types and climate found in the UK. This restricted the accuracy of the predictive model. On the other hand an increased number of sites would have added considerably to the cost of the project.

Only limited validation of the standing biomass estimates and output from the predictive model was been carried out. It would have been advantageous to have taken plot weights at the end of both cutting cycles in order to compare estimated and observed yield.

The process-based model goes some way to provide yield estimates for new varieties and environmental conditions that are outside our current experience; both are issues that cannot be addressed by the empirical models. A number of assumptions were made, most importantly that the physiology changes little between clonal varieties and that the main drivers are the leaf and canopy morphology. A particular limitation is that no account is taken of varietal differences in tolerance to harsh environmental conditions, e.g. drought.

One of the most critical sets of parameters for the process-based model is carbon storage both as an initial condition and throughout the simulation - stored carbon is used to create growth after cut-back. This is a difficult set of parameters to estimate and experimental data were not substantially collected. (A limited amount of root sampling was made, but this was not fully analysed due to resource constraints and the perceived limited value the data would provide since this was carried out over a small number of sites and species).

Poplar coppice was simulated well. In contrast the willow simulations were inconsistent; the inter-site variability was small; and growth in the second rotation was often less than the first rotation – perhaps a result of incorrect carbon storage. The more realistic simulation of poplar growth was a consequence of the more detailed physiological and morphological data provided through this programme and the international literature, which concentrates more on poplar than willow.

Although physiological measurements have been carried out on a limited number of clonal varieties, not all varieties have been characterised. Furthermore, during the course of the experimental work, the importance of the canopy and foliage morphology became apparent (Casella and Ceulemans 2002; Casella and Sinoquet 2003). These parameters are not difficult to obtain but the recording of such data was not envisaged at the outset of the project. Further data values of this type would enable a more detailed exploration of the model's range.

Soil data were sub-optimal for the process model, particularly with respect to the water availability.

Even when these limitations are taken into account, the model produced a comprehensive set of potential yield estimates. Furthermore the software provides growers and stakeholders with a useful guide to what yield may be achieved in different scenarios including many aspects of climate change.

The yield model software provides growers and stakeholders with a useful guide to what yield may be achieved in different parts of the country provided effective weed control is carried out and browsing animals are excluded from the crop.

6. Conclusions and deliverables

- The network of 49 sites provided only limited coverage of the variation in soil types and climate found in the UK. This restricted the accuracy of the predictive model.
- The process-based model produced a comprehensive set of potential yield estimates and goes some way to provide predictions for new varieties and environmental conditions that are outside our current experience; both are issues that cannot be addressed by empirical models.
- Only limited validation of the standing biomass estimates and output from the predictive model was been carried out. It would have been advantageous to have taken plot weights at the end of both cutting cycles in order to compare estimated and observed yield.
- A number of assumptions were made, most importantly that the physiology changes little between clones and that the main drivers are the leaf and canopy morphology.
- A particular limitation is that no account is taken of varietal differences in tolerance to harsh environmental conditions, e.g. drought.
- Carbon storage was one of the most critical sets of parameters for the process-based model both as an initial condition and throughout the simulation - stored carbon is used to create growth after cut-back.
- Poplar coppice was simulated well. In contrast the willow simulations were inconsistent, inter-site variability was small, and growth in the second rotation was often less than the first rotation – perhaps a result of incorrect carbon storage. The more realistic simulation of poplar growth was probably a consequence of the more detailed physiological and morphological data provided through this project and the international literature, which concentrates more on poplar than willow.
- Physiological measurements were carried out on a limited number of clonal varieties: 3 poplar & willow: Beaupre, Ghoy, Tirchobel and Jorrunn, Germany, Q83 (Volume C, appendices L, M; Evans et al, 2007b)
- The importance of the canopy and foliage morphology became apparent during the experimental work. These parameters are not difficult to obtain and further data would enable a more detailed exploration of the model's range.
- No attempt was made to model the process of pests and diseases outbreaks but defoliation was included as a surrogate to explore their impacts on yield.
- Soil data were sub-optimal for the process-based model, particularly in terms of water availability.
- Provided effective weed control is carried out and browsing animals are excluded from the crop, the software provides growers and stakeholders with a useful guide to potential yields under different scenarios including many aspects of climate change.

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