Yield Models for the Energy Coppice of Poplar and Willow

Project Summary
(Phase 4)

ABSTRACT

The overall objective of Phase IV[1] of the ***Yield Models for Energy Coppice of Poplar and Willow*** project (1996-2005) is to develop **models relating yield from energy coppice of poplar and willow to site factors and clonal characteristics.** This objective is being achieved by:

- Managing 51 sites planted with 32 poplar and willow clones established to simulate commercial plantings of short rotation coppice with no artificial irrigation, nutrition, fungicide or insecticide inputs.
- Monitoring growth and biomass accumulation and performance in the poplar and willow SRC clones over two 3-year rotation cycles using destructive and non-destructive techniques.
- Collecting detailed environmental data characterising site conditions and their relationship with growth and yield through physiological studies.
- Collecting qualitative data on the incidence of pests and diseases affecting willow and poplar SRC species.
- Using experimental and monitoring data from the project sites to develop 2 models, one empirical and one process-based, operating at the plot scale.

Principal results to date include:

1. Establishment and management of 51 experimental sites across England, Wales, Scotland and Northern Ireland. Following completion of the 2nd rotation the experimental component of the project is largely complete
2. Harmonised, protocol-based data collection at the experimental sites to evaluate growth and yield performance, pest and disease, soil properties and meteorology using non-destructive and destructive techniques.
3. Harmonised, protocol-based data collection at selected sites on relevant physiological processes of growth, such as above- and below-ground allocation, plant ecophysiology, respiration, sapflow and canopy architecture dynamics.
4. Harmonised, protocol-based data collection at the experimental sites on the intra- and inter-annual variability of the incidence of relevant pests and diseases.
5. Establishment of a quality-assured relational database containing inter-annual project data.
6. Development of a preliminary yield model providing annualised predicted yields at the UK and regional scales. Provisional yield estimations for each clone at each site are available for each year in the first rotation and for the first year in the second rotation (for Phase 1 sites only).
7. Development and initial validation of modules of a process-based model, coupled with the project database, describing the growth performance and yield of SRC poplar and willow species. The model will describe growth and yield, as well as encompassing mechanistic understanding of the growth observed in field trials and any significant variation between sites and clones.
8. Technology transfer to researchers, industry and other stakeholders through site visits, a project help-desk, information notes (FC Practice Note 7 and FC Research Information Note 294), conference proceedings, presentations, scientific papers in international peer-review journals and a dedicated web site (www.forestry.gov.uk/src).

[1] *This project is co-funded by DEFRA-DTI-Forestry Commission and DARD-NI.*

AIMS AND OBJECTIVES

The overall objective of the project is **to develop models relating yield from energy coppice of poplar and willow to site factors and clonal characteristics**.

This objective will be achieved by:

- Managing 51 sites where clones of poplar and willow are grown that will provide plant material for destructive and non-destructive data collection to inform model development. Sites have been managed with fixed planting pattern, the avoidance of irrigation and no use of pesticides to manage control of pests and/or diseases.
- Monitoring biomass accumulation in SRC clones over two 3-year rotation cycles.
- Collecting detailed environmental data characterising site conditions and affecting growth.
- Collecting qualitative data on the relative incidence of pests and diseases affecting SRC that will be used to assess the impact of insurgence on SRC yield. These data will be used in development of the empirical model, given the subsidiary project aim to assess UK growth performance of clones with the avoidance of fertilisers, irrigation and pesticides to manage control of pests and/or diseases.
- Developing 2 models, an empirical and a process-based model, operating at the plot scale; the process model will operate at the daily timestep, summarising yield at the annual timestep. The models will forecast biomass production of short rotation coppice species (willow and poplar) in the UK. The process model will simulate relevant physiological processes determining the yields observed in field trials and any significant variation between sites and clones. Given the proposed structure the process model will be suitable for predicting yield at new sites or relevant site-clone interactions and thus will be predictive beyond the range of the empirical model. Model outputs will be suitable for upscaling through a Geographical Information System [GIS], requiring the appropriate spatially references datasets to do so. Assessment of the predictive accuracy of the process-model will be achieved through a model inter-comparison exercise with the empirical model.

The principal deliverable is a modelling system that accounts for the variability in biomass accumulation observed between and within poplar and willow clones at the field experiments established by the project. Through the development of a process-based model, the system will explicitly account for site and environment interactions on the observed growth rate of clones.

In order to achieve this overall objective the programme has the following specific aims:

1. Increase understanding of the relationship between growth and site conditions in clones of poplar and willow for renewable bio-energy using an integrated network of sites, based on a nested sampling design to provide representative cover of the climatic and soil conditions in the UK.

2. Increase understanding of the mechanistic relationships underlying growth variation at sites and clones through a combination of the non-destructive and destructive analyses on stand structure and physiological characteristics at specific sites developed for this purpose.

3. Construct, calibrate and validate an empirical and a process-based model of growth and yield in SRC species that will describe growth and yield, as well as encompassing mechanistic understanding of the growth observed in field trials and any significant variation between sites and clones. This will be achieved using data collected under objectives 1 and 2. The process model will be based on widely accepted functions in an innovative modular structure.

METHODOLOGY

The project is progressing in three phases using the existing experimental infrastructure developed by the project that establishes a harmonised network of field sites across the UK. Together these sites provide the experimental infrastructure used for model development and model refinement.

Phase 1 aims to characterise the relationships between clones, site conditions, growth and yield across the UK can be achieved by:

- Monitoring growth and yield at clonal level at a representative range of sites in the UK.
- Monitoring of biomass at the intensive and extensive sites so as to examine and relate changes in growth to changes in allocation to tree compartments (leaf, branches, stems, stools, fine and coarse roots), as a function of crop age, cutting cycle and clone.
- Sampling individuals to relate morphological and biophysical properties to site conditions and growth.
- Selecting individuals so as to examine and relate changes in growth to changes in biomass across a range of clones.

Phase 2 Develops empirical models summarising the range of variability in growth and yield at clonal level and across the UK by:

- Developing and calibrating appropriate numerical functions for inclusion in empirical models summarising growth and yield as a function of crop age, cutting cycle and clonal groupings of poplar and willow and accounting for site conditions.
- Examining the numerical functions expressing model sensitivity to the factors being manipulated and use the experimental results to further refine the numerical functions.

Phase 3.

Developing a process-based model that account for the variation in growth responses resulting from natural and artificial genotypic and phenotypic selection processes in poplar and willow by:

- Developing a range of modules that, by simulating relevant physical, biophysical and biological processes operating at the plot scale and the daily timestep, account for the variation in growth responses observed between clones of poplar and willow.
- Assessing the predictive performance of the process-model through a model inter-comparison exercise with the empirical model.

The work-plan can be separated into:

- Monitoring Component
- Laboratory Component
- Data Management Component
- Modelling Component.

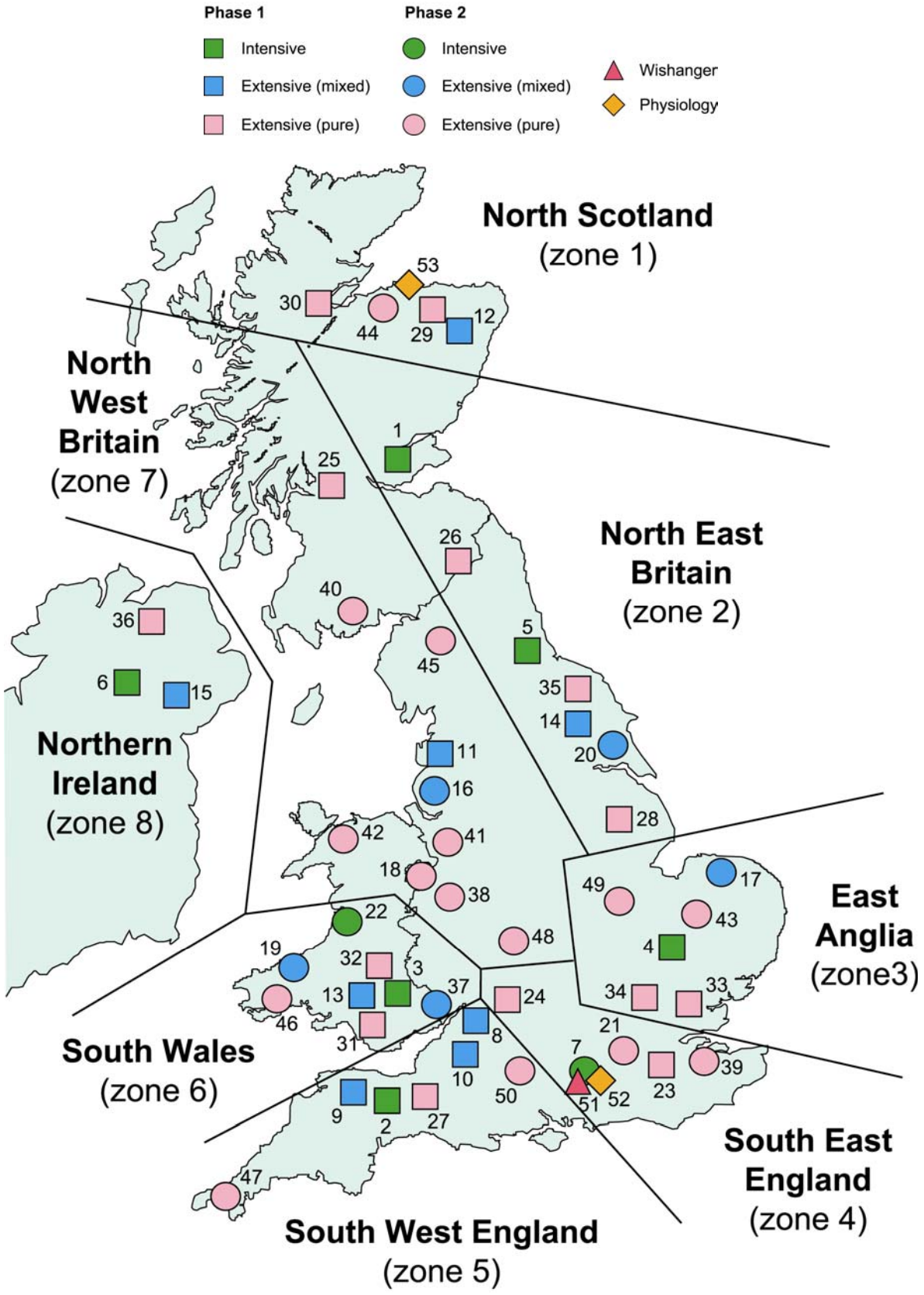
Monitoring Component

This is designed to characterise the relationships between site conditions, growth and yield prediction and how this varies between clones and across sites. It combines field measurements of site conditions and coppice species growth with detailed studies of relevant physiological, architectural and biophysical processes that will inform the modelling component. A nested approach has been developed using a combination of intensive, extensive and physiological sites, as described below. The distribution of sites is shown at Figure 1 overleaf.

The data collected at the experimental sites will be used for the following purposes:

a. To generate a database on the growth and yield of poplar and willow clones in UK conditions.
b. To provide calibration and validation data for models.
c. To inform the development of an empirical model.
d. To develop new mechanistic understanding underpinning the development and calibration of a process model.

Figure 1. Distribution map of project sites.



Laboratory Component

This uses established laboratory infrastructure and procedures to characterise biochemical properties at leaf level relevant to the modelling component described below.

Destructive sampling will be carried out on non-monitored individuals adjacent to the monitored plots, to monitor:

a. Evolution of leaf area index (mean canopy leaf area, maximum and minimum individual leaf area), morphology (leaf width, length) and ontogeny.
b. Canopy C-N profiles.
c. Leaf optical properties (leaf reflectance and transmittance) (Milne et al. 1992).
d. Carbon allocation in 6 compartments: foliage, branches, stem, stools, structural roots and fine roots.

Data Management Component

This handles and organises the data collected resulting from the specific activities carried out at the field sites, as detailed above. Data will be quality assured prior to input into a stand-alone database that will become the source for the calibration and validation data that will be used by all models. The database will be in the latest version of MS-Access; as part of this database, clonal libraries will be developed where the relevant physiological, morphological and phenological characteristics of clones will be stored (Host et al. 1990).

Modelling Component

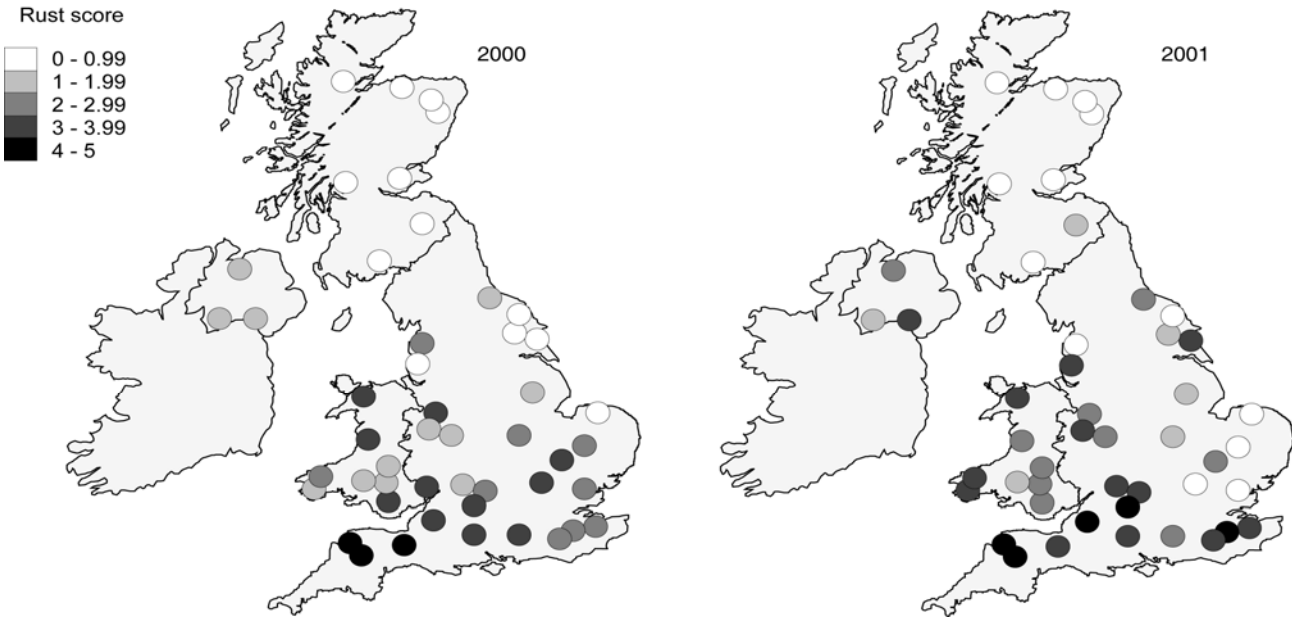
This builds upon existing state-of-the-art empirical and process-based modelling approaches, simulating yield at the plot scale derived from in-house expertise, and relevant approaches used in perennial crops and agroforestry, where appropriate. Model outputs will be suitable for upscaling through a Geographical Information System [GIS], requiring the appropriate spatially references datasets to do so.

Results

Principal results achieved to date are briefly summarised below.

- Site maintenance has allowed the collection of harmonised from the project's 51 experimental sites over two 3-year rotations. The majority of sites have now been closed, with a small number being retained for further targeted investigations supporting specific aspects of model development.
- Data collection, following inter-calibration courses for field staff, has been carried out at all sites using standard sampling protocols.
- Quality-assured data have been placed in a relational database developed using ORACLE and front-ended by Microsoft Access. Since 2000, CD-ROMs have been produced annually as attachments to annual reports.
- Data have been collected on the relative intra and inter-annual incidence of relevant pests and diseases across the experimental sites as shown, for example in the figure 2 below. These data provide a framework for understanding the relative impacts on growth performance of the poplar and willow varieties under study.

Figure 2. Geographic distribution of poplar rust in September 2000 and September 2001. Combined mean rust score (RUST-L) for 'Beaupre', 'Ghoy' and 'Trichobel' at each site.



- Development of a preliminary empirical model that can be used to predict annualised biomass yields both as UK average (see tables below) and for 8 regions. Data shown below in tables 1-2 are preliminary and should not be quoted, published, or relied upon for decisions.

TABLE 1. Predicted annualised biomass yield as a UK average for poplar varieties.

Poplar Variety	Annualised yield (oven dried tonnes per hectare per year)			
	1	2	3	4*
1. Beaupré	4.6	7.0	7.7	5.8
2. Ghoy	3.6	6.0	6.8	5.6
3. Trichobel	3.1	6.5	9.0	7.0
4. Boelare	3.9	6.2	7.4	4.5
5. Unal	4.8	7.6	8.6	-
6. Raspalje	-	7.1	7.6	5.7
7. Gaver	4.6	7.1	7.7	6.2
8. Gibecq	4.0	5.8	6.1	4.1
9. 69039/4	3.8	6.2	-	-
10. 69038/6	4.1	7.5	-	-
11. 71009/1	-	3.3	3.6	-
12. 71015/1	3.1	5.3	6.5	5.4
13. 71009/2	2.7	4.0	5.1	-
14. TT32	2.3	5.6	7.0	-
15. Fritzi Pauley	2.7	5.6	-	6.2
16. Columbia River	2.4	5.5	7.0	5.7

* first year of the second rotation.

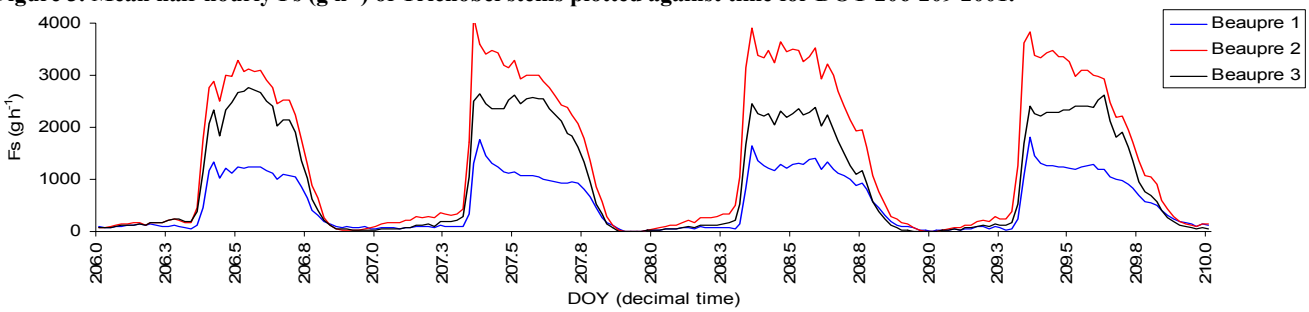
TABLE 2. Predicted annualised biomass yield as a UK average for willow varieties.

Willow Variety	Annualised yield (oven dried tonnes per hectare per year)			
	1	2	3	4*
1. Jorunn	7.1	9.1	9.8	15.1
2. Germany	3.5	6.3	7.8	7.9
3. Q83	3.4	6.1	7.7	11.2
4. Spaethii	3.1	6.8	-	11.1
5. Dasyclados	5.4	7.3	-	-
6. ST/2481/55	3.8	6.3	-	-
7. Delamere	-	-	-	-
8. Bebbiana	2.4	5.6	-	-
9. V789	3.4	4.6	-	-
10. Ing 00010	6.7	8.9	-	-
11. Ing 00011	6.4	9.7	-	-
12. Jorr	5.7	7.7	-	-
13. Bjorn	6.6	-	-	-
14. Tora	5.7	8.2	-	-
15. Orm	4.9	7.2	-	-
16. Ulv	4.4	7.2	-	-
17. Bowles Hybrid	-	-	-	-

* first year of the second rotation.

• Development of new process understanding on relevant plant physiological processes (e.g. see figure 3 below). These data will be used to inform process-model development and calibration.

Figure 3. Mean half-hourly Fs (g h^{-1}) of Trichobel stems plotted against time for DOY 206-209 2001.



• Development of new process understanding on above-ground carbon allocation dynamics and a three-dimensional canopy architecture model. These data contribute to the development of the process-model and preliminary outputs describing simulated canopy dynamics during the growing season are provided at figures 4a and 4b below.

Figure 4a. Simulation of 'Trichobel' architecture, May

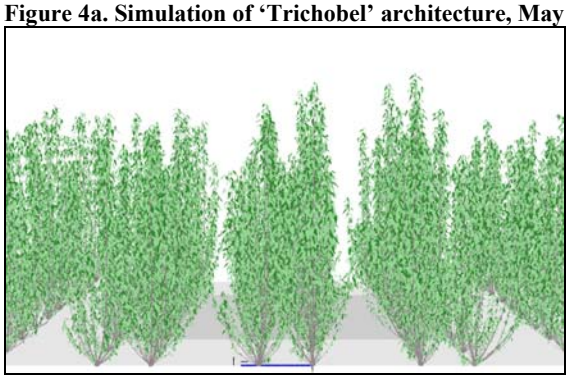
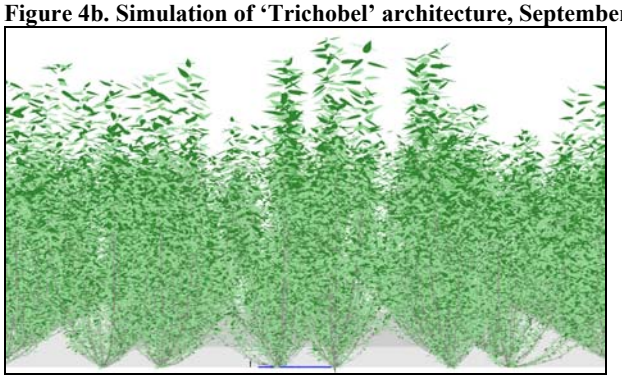
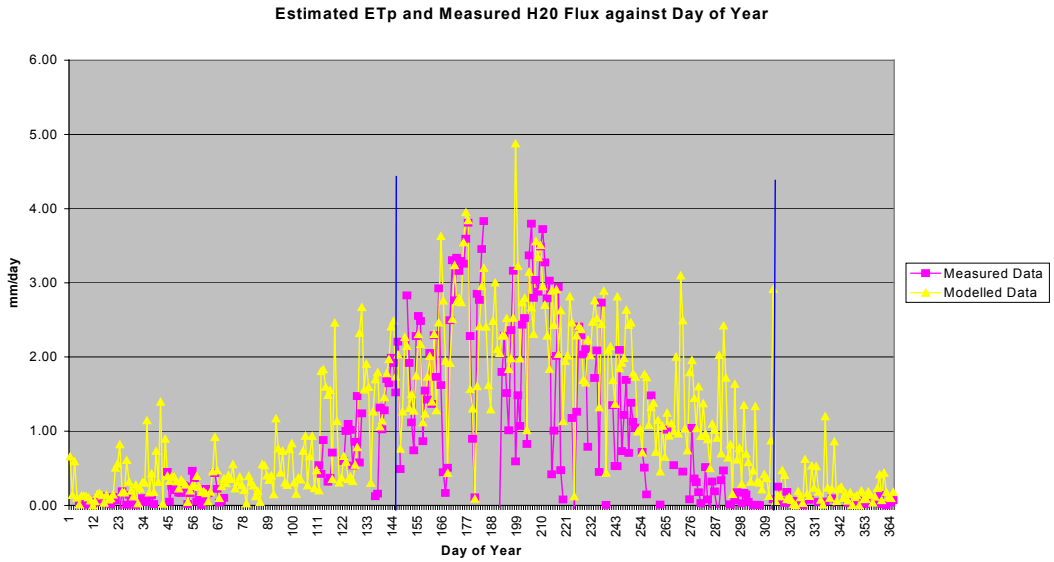


Figure 4b. Simulation of 'Trichobel' architecture, September



• Development of a preliminary process-based model summarising key biological and biophysical processes relevant to plant growth. The modular design of this model allows aggregation of model components to achieve the desired end-state and will be validated using data held in the project database. An example of model outputs, comparing simulated and measured H_2O canopy fluxes are at figure 5 below.

Figure 5. Estimated evapo-transpiration and eddy-covariance measurements of H_2O flux at the Headley site.



Technology transfer to researchers, industry and other stakeholders through site visits, a project help-desk, information notes (FC Practice Note 7 and FC Research Information Note 294), conference proceedings, presentations at energy crop seminars and forestry shows, scientific papers in international peer-review journals and a dedicated web site (www.forestry.gov.uk/src).

PROJECT RELEVANCE TO THE DEFRA POLICY RATIONALE

Rationale. Poplar and willow are amongst the most promising fast-growing tree species for short rotation coppice. Large genotypic differences amongst clones, hybrids and species (Barker et al. 1999) have already been demonstrated in productivity (Heilman & Stettler 1985, 1990; Ceulemans et al 1997; Dickson et al. 1998; Scarascia-Mugnozza et al. 1999), leaf area index (Ceulemans 1990) and other growth characteristics. Research has shown a strong dependency of the growth rates of particular clones on site climate and soil fertility, whilst exhibiting a high genotypic variability in survival rate, growth, resprouting and resistance to pests and diseases. Annual yields are typically between 8 and 12 tonnes dry matter per hectare on fertile soils. Several pests and *Melampsora* spp. rust cause risks to the plantations, which leads to a recommendation of clone mixture plantation. To date, growth and genetic variation experiments have mostly concentrated on determining the differences in biomass production and on the characterisation of physiological characteristics (DeBell et al. 1996, Deraedt & Ceulemans 1998, Laureysens et al. 2001, Laureysens et al. 2000).

Co-funded by DEFRA, DTI, FC and DARD-NI, this project is a national-scale programme that:

(a) is monitoring the growth performance of 32 fast-growing poplar and willow clones over two 3-year rotations at 51 UK sites, and;

(b) is providing models able to represent variation in growth, canopy architecture and physiological responses expressed by the varieties under observation, as well as new varieties being selected by breeding programmes.

Project results are therefore central to assisting delivery of the UK's bioenergy policy, supported by the Energy Crop Scheme, on identifying alternative, profitable uses for land released from surplus production. Principally, the project addresses the requirement to identify those poplar and willow varieties most suitable for biomass production in the UK, based on their potential inter-annual productivity (spanning the UK's climate and environmental range) and accounting for the relative incidence of pests and diseases. The development of robust empirical and process-based predictive models will allow the forecasting of potential productivity at high spatial resolution and as a function of the UK's climatic and environmental variability. The project's outcomes will therefore assist in determining the most economical systems for growing biomass for bioenergy using poplar and willow varieties, contributing to the development of a competitive farming industry that assists in reducing the UK's energy inputs.

REFERENCES

Barker JHA, Matthes M, Arnold GM, Edwards KJ, Ahman I, Larsson S and Karp A 1999. Characterisation of genetic diversity in potential biomass willows (*Salix* spp) by RAPD and AFLP analyses. Genome 42: 173-183.

Ceulemans R, G. E. Scaracia-Mugnozza, P. E. Heilman, J. G. Isebrands, R. F. Stettler, and T.M. Hinckley 1997. Production physiology and morphology of *Populus* species and their hybrids grown under short rotation. II. Biomass components and harvest index of hybrid and parental species clones. Canadian Journal of Forest Research 27: 285 – 294.

Ceulemans, R. 1990. Genetic variation in functional and structural productivity determinants in poplar. Thesis Publishers, Amsterdam, 100 pp

DeBell, D.S., G.W. Clendenen, C.A. Harrington and J.C. Zasada. 1996. Tree growth and stand development in short-rotation Populus plantings: 7-year results for two clones at three spacings. Biomass and Bio-energy 4: 253-269.

Deraedt, W. and R Ceulemans. 1998. Clonal variability in biomass production and conversion efficiency of poplar during the establishment year of a short rotation coppice plantation. Biomass and Bio-energy 15: 391-398.

Dickson RE, M. D. Coleman, D. E. Riemenschneider, J. G. Isebrands, G. D. Hogan, and D. F. Karnosky 1998. Growth of five hybrid poplar genotypes exposed to interacting elevated CO_2 and O_3. Canadian Journal of Forest Research 28: 1706 – 1716.

Heilman PE and Stettler RF 1990. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. IV. Performance in short rotation coppice. Canadian Journal of Forest Research 20: 1257.

Heilman, P.E. and R.F. Stettler. 1985. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. II. Biomass production in a 4-year plantation. Canadian Journal of Forest Research 15: 384-388.

Host G.E., Rauscher H.M., Isebrands F.G. and Michael D.A. 1990. Validation of the photosynthesis production in ECOPHYS, an ecophysiological growth process model of *Populus*. Tree Physiology 7: 268-296.

Laureysens I., E. Casella, W. Deraedt and R. Ceulemans 2001. High-density coppice culture of poplar: clonal differences in growth, mortality and biomass yield after a three-year rotation. In Biomass for Energy and Industry. James and James Publ., London, (*in press*).

Laureysens, I., E. Casella and R. Ceulemans. 2000 Productivity, basal area and shoot density of different poplar clones in a coppice culture. In Topics in Ecology: Structure and Function in Plants and Ecosystems. Ceuleman R., Bogaert, J., Deckmyn G. and Nijs I. Eds., University of Antwerp UIA, Wilrijk, pp 29-38.

Milne, R., M. Sattin, J.D. Deans, P.G. Jarvis and M.G.R. Cannell. 1992. The biomass production of three poplar clones in relation to intercepted solar radiation. Forest Ecology and Management 55: 1-14.

Scarascia-Mugnozza GE, T. M. Hinckley, R. F. Stettler, P. E. Heilman, and J. G. Isebrands. 1999. Production physiology and morphology of *Populus* species and their hybrids grown under short rotation. III. Seasonal carbon allocation patterns from branches. Canadian Journal of Forest Research 29: 1419 – 1432.