Yield models for short rotation coppice of poplar and willow

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INTRODUCTION

For more than 20 years Forest Research has been testing combinations of tree species and silvicultural systems suited to the production of large volumes of woodfuel or wood fibre. This has lead to the development of reliable yield assessment techniques capable of quantifying wood production in novel silvicultural systems. Early species trials showed that willow and poplar varieties planted at very close spacing and managed as a regularly and frequently harvested coppice stand provided some of the highest yields per given area of land. Woody crops managed in this way are known as short rotation coppice (SRC).

Biomass crops and production systems are now recognised as serious options in agriculture and forestry. In England, the establishment of commercial plantations of willow and poplar SRC (Figure 1), along with other energy crops such as Miscanthus (elephant grass), is supported by the Energy Crop Scheme (ECS) administered by the Department for Environment, Food and Rural Affairs (Defra). Similar grants administered by the FC are available in Scotland. Additionally, as from 1 April 2009, the UK-wide ‘Renewables Obligation’ managed by the Department of Trade and Industry (DTI) will ensure that power generators wishing to co-fire coal with non-fossil fuels will source at least a proportion of this fuel from dedicated biomass crops and forests. In return, power generators receive tradable ‘Renewable Obligation Certificates’ (ROCs).

Government support for biomass

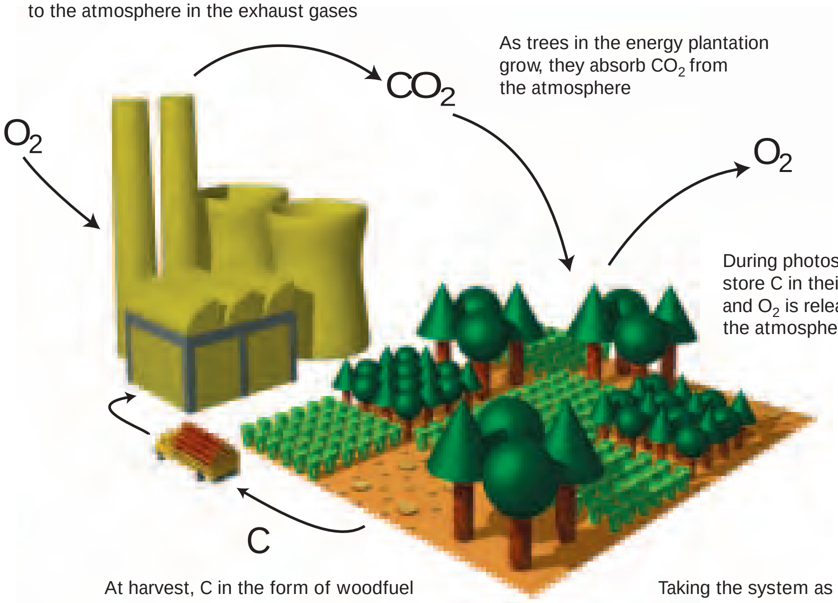
Government support is given to sustainably managed energy crops because they are 'carbon lean' (see Figure 2), i.e. compared with fossil fuels, only small quantities of greenhouse gases are emitted per unit of energy produced from the biomass. This contributes towards government meeting its ambitious and, following the ratification of the Kyoto Protocol, legally binding commitments to reduce CO_2 emissions by 10 % (based on 1990 emission levels) by 2010. Further international support for the development of biomass derived heat and power was given at the G8 summit held at Gleneagles in 2005, where the intention to create a Global Bioenergy Partnership was announced.

Unlike some other renewable and carbon lean technologies such as wind and wave farms, the potential energy within woodfuel can be stored and used 'on demand'. Woodfuel is also transportable and can be used in several forms including woodchips, wood powder, pellets or, after processing, liquid fuel. However, as with many other fuel and fibre producing systems, in order to maximise land use efficiency, biomass production and financial return, suitable combinations of species and site need to be identified and reliable techniques for monitoring and predicting yield are required. Such information is of use to a large range of energy crops 'stakeholders' including existing and potential government grant assisted energy crop producer groups, independent growers, fuel users and project planners.

Figure 1

A short rotation coppice willow plantation.

As the wood is burned the carbon (C) stored combines with the oxygen (O_2) to produce carbon dioxide (CO_2), emitted back to the atmosphere in the exhaust gases



As trees in the energy plantation grow, they absorb CO_2 from the atmosphere

During photosynthesis the trees store C in their woody tissues and O_2 is released back into the atmosphere

At harvest, C in the form of woodfuel is transported from the plantation to the heat or power generating plant

Taking the system as a whole, only small amounts of carbon are emitted through consumption of fossil fuels to cultivate and transport the biomass and to maintain the power station

Figure 2

The carbon cycle of a woodfuelled heat or power generation system (adapted from Matthews and Robertson, 2002).

The site/yield research programme

Against this background, in 1994 the Forestry Commission (FC), Defra, DTI and the Department of Agriculture and Rural Development, Northern Ireland (DARDNI) funded a research programme aimed at establishing relationships between site characteristics and variations in performance amongst a selection of willow and poplar varieties. The principal objectives of this programme were to:

- Establish field experiments at a wide range of sites across the UK
- Develop a minimally destructive method of assessing standing biomass
- Monitor insect pests and fungal pathogens
- Collect soil and meteorological data and relate these to variations in yield
- Create a database to hold the information collected
- Develop empirical and process based yield models
- Develop suitable graphic user interfaces for the completed models.

Sites and varieties used

In spring 1995, 24 experiment sites were successfully established and in the following year a further 25 sites were planted (Figure 3). Three experimental designs were used. The first and most numerous type contained two sub-experiments. The first sub-experiment contained three poplar varieties exhibiting different growth and form characteristics. Each variety was grown in three monoclonal plots containing 100 individuals. The second sub-experiment contained three willow varieties, also developed from different parent species, planted according to the same experiment design. Data from these sites, known as ‘Extensive Pure’ trials, were used to assess the suitability of the chosen varieties on a wide range of site types, and to provide the main source of information for the development of minimally destructive yield assessment methods.

The second experimental design also contained monoclonal plots of three willow and three poplar varieties. In addition plots containing a mixture of the same three willow or three poplar varieties were

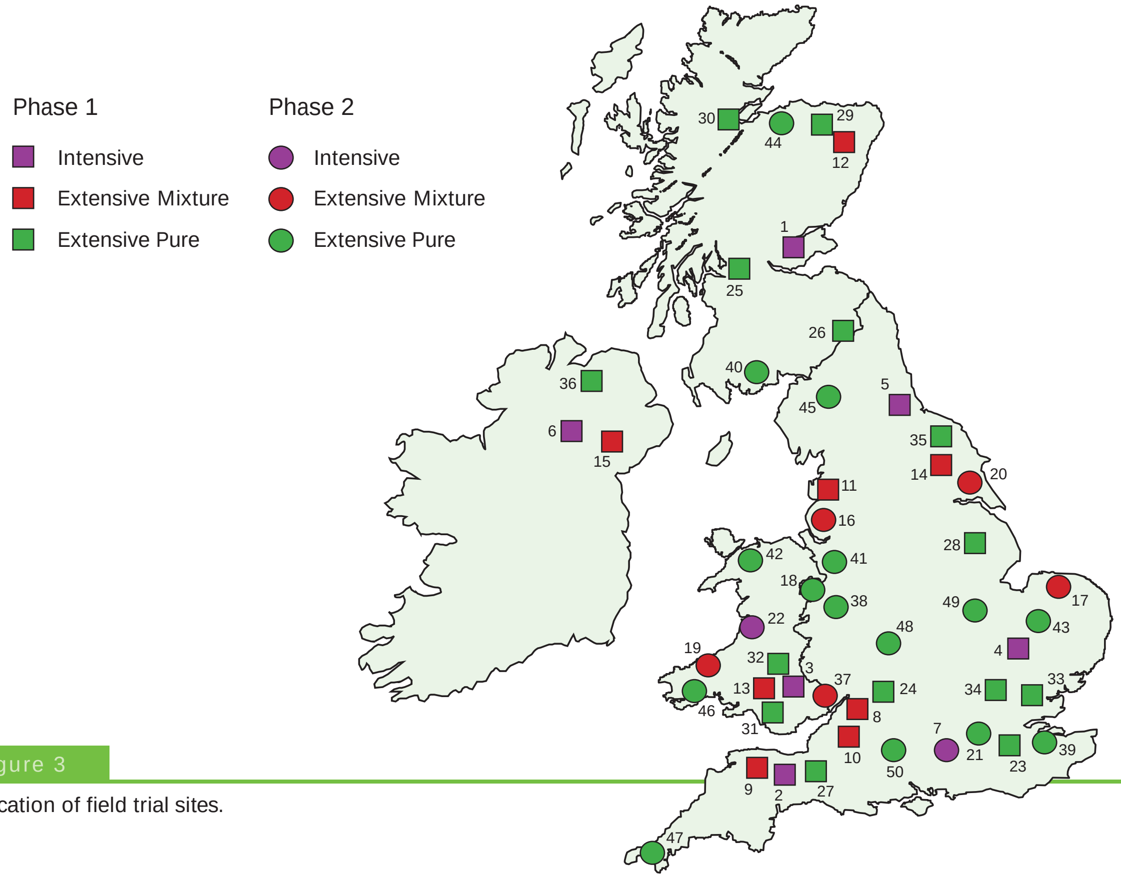


Figure 3

Location of field trial sites.

Table 1

Willow and poplar varieties used in the field experiments.

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

* Variety present in all experiment types. Varieties without this symbol were planted at the ‘Intensive’ sites only.

established. Data from these plots were used to investigate the effect of multi-clonal mixtures on the incidence and severity of insect and disease infestations along with differences in yield between single variety and multi-variety plantations. Sixteen ‘Extensive Mixture’ sites of this type were established.

The third and final experimental design contained 16 willow and 16 poplar varieties derived from a wide range of parent species. The varieties used at the other two site types were included to act as ‘benchmarks’ against which other varieties could be compared. Data from these large experiments was used to inform the calibration of yield models to represent a wide range of growth characteristics. This is important as new willow and poplar varieties become commercially available on a regular basis as plant breeders develop higher yielding or pest resistant clones. Seven of these large ‘Intensive’ sites were established. The varieties used in all three experiment types are shown in Table 1.

In addition to these field based experiments, trials were also established in nurseries at Headley in Hampshire and Newton in Morayshire. At these sites fertiliser, irrigation and pesticides were applied judiciously to remove some of the environmental factors that could limit plant growth in the field and mask the inherent production potential of the varieties tested. A range of physiological measurements including shoot respiration, sap flow and gas exchange was taken on the three willow and three poplar clones planted. These data were used during the parameterisation of process based yield models.

Crop silviculture

At each site, pre-planting ground preparation was carried out using standard agricultural ploughs and power harrows. Chemical weed control was used to minimise the effect of weed competition on the developing coppice. Once a suitable seed bed had been created 25 cm long willow and poplar cuttings were planted by hand in spring/early summer. Planting followed a twin row design, reflecting commercial practice. Planting density was just less than 10 000 cuttings per hectare, again following commercial practice at the time (commercial plantations are now generally established at around 15 000 cuttings per hectare). At the end of the first growing season all above ground growth was cut back to approximately 10 cm above ground level. This operation, the essence of coppicing, encourages the development of multiple stems in the following spring.

The coppice was then managed on a three-year cutting cycle with harvests occurring at the end of the third and sixth growing season following cut back. At the end of the second cutting cycle, final assessments were made and the experiments closed. A commercial harvester was used at one of the larger 'Intensive' sites at the end of the second cutting cycle (Figure 4).

Figure 4

Harvest at the end of the second three-year cutting cyle.

Data collection and storage

An extensive range of crop and site variables were quantified at each site. Data were collected mainly by staff from the Technical Support Unit. The variables assessed can be classified into four groups, as shown in Table 2. Data were stored in a dedicated database, purpose designed for this project.

Table 2

Assessments and surveys carried out at field and nursery based experiment sites.

Shoot allometry	Site characteristics	Crop architecture	Crop physiology
Coppice stool survival	Air and soil temperature	Above and below ground carbon allocation	Shoot respiration
Number of shoots per stool	Rainfall	Canopy development	Root respiration
Shoot diameter	Relative humidity		Leaf nitrogen content
Shoot length	Solar radiation		Gas exchange
Shoot dry weight	Soil chemistry (i.e. nitrogen, potassium, phosphorus content)		Sap flow
	Soil physical properties (i.e. sand, silt and clay content)		

Minimally destructive yield estimation

The assessments shown in the first column of Table 2 are fundamental to the monitoring of growth patterns, biomass accumulation and ultimate yield in crops such as SRC. These data enable modellers to construct site, clone and age-specific relationships between shoot diameter, shoot length and shoot dry weight (Matthews, 1995; Matthews *et al.,* 2002). Once these relationships are established it is possible to estimate the total shoot oven-dry biomass present in research plots. These results are then up-scaled into more tangible estimates of oven-dry tonnes. To date, limited validation has shown that these estimates are accurate to within +/- 10% when applied to research scale plots.

This work is of fundamental importance as it allows researchers, growers and suppliers to estimate the standing biomass of a crop prior to harvest. Without the development of these relationships it would not be possible to make annual assessments of above ground biomass production, which are essential for the development of growth models.

Empirical modelling

Once a full set of standing biomass figures was available for each site/variety/age combination, statisticians were able to investigate the large variation in yields observed over the life time of the field experiments. Examples of variations in standing biomass amongst sites and varieties is shown in Table 3. Data collected during the site characterisation monitoring and assessment process (column 2, Table 2) were used to explain this variation. The models developed can account for approximately 70% of the variation observed in the field. However, this analysis has shown that variation in yield cannot be explained by quantifying and analysing a limited number of simple measurements such as rainfall and nutrient availability. Instead, yield is governed by complex interactions amongst a large number of site variables that will prove impractical for a grower to quantify. Despite these limitations the models generated represent the current state-of-the-art predictive SRC yield models available to growers and planners and provide a solid foundation for future development.

Process modelling

Whereas the standing biomass and empirical models developed during this research programme are likely to be of immediate use to SRC growers and producer groups, a process model based on data collected during crop architecture and physiology assessments (columns 3 and 4 in Table 2) may be of more interest to researchers and plant breeders. Process models can be used to explore how crops respond to climate change or help evaluate new varieties prior to commercial release. The downside is that these models require comprehensive parameterisation for each variety of interest. This can lead to time consuming and costly data collection programmes. During this programme the ForestGrowth process model originally developed by Evans *et al.* (2005) for use with high forest species was parameterised for

Table 3

Examples of variations in standing biomass between sites, varieties and crop ages.

Site	Clone	Standing biomass, oven-dry tonnes per hectare					
		Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
1	Bjorn	11.2	29.3	34.8	12.2	21.6	47.5
1	Stott10	12.1	35.2	43.7	13.3	21.6	46.2
1	Germany	10.5	35.7	41.5	12.7	17.8	45.4
6	Bjorn	5.0	18.5	28.0	6.9	15.9	25.9
6	Stott10	9.4	25.6	33.3	5.6	13.1	20.5
6	Germany	4.8	14.2	22.2	3.2	6.0	9.9
7	Bjorn	3.4	11.7	21.1	8.9	22.4	31.3
7	Stott10	3.4	12.1	20.1	6.9	11.8	19.4
7	Germany	2.1	8.9	15.9	3.0	6.5	13.9

several SRC varieties using data collected from both the field-based and nursery-based experiments.

One of the most important aspects of the development of this model for use on SRC was the adaptation of the canopy architecture module to account for differences observed in canopy structure and carbon allocation between high forest and SRC canopies. This module also needed to accommodate the frequent harvesting and re-growth associated with SRC. As originally configured, this module was unable to re-create the complex, multi-layer canopy found in SRC plantations. However, using field data and the 3D-CPCA validation tool developed by Casella and Sinoquet (2003) as part of a European funded research project, a new light interception module was constructed. A comparison of output from 3D-CPCA and ForestGrowth canopy models is shown in Figure 5.

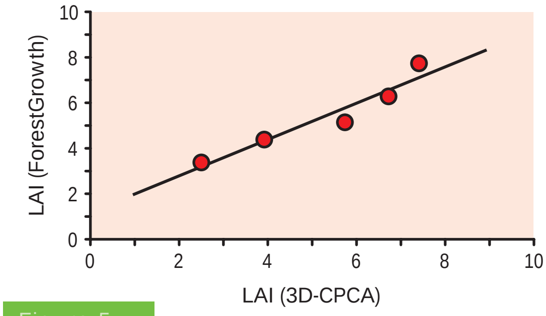


Figure 5

Comparison of leaf area index (LAI) values for short rotation coppice generated by 3D-CPCA (*x* axis) and ForestGrowth (*y* axis) canopy models.

Key outputs

One of the most important outputs from this research programme are standing biomass estimates for more than 3000 site, variety and age combinations. These estimates are of great interest to coppice growers and researchers and form the basis for empirical predictive yield models. Growers are similarly interested in summaries of the incidence of insect and disease infestation generated using possibly the largest SRC pest dataset collected to date. Examples of disease summary maps for rust (*Melampsora* spp.) are shown in Figure 6.

Finally, the development of user interfaces that allow SRC growers to use data collected from their own plantations to make estimates of standing biomass and predict yield represents a significant step forward and could assist with on-farm cash flow predictions, crop management and the planning of renewable energy projects. A screen shot of one of the current user interfaces is shown in Figure 7.

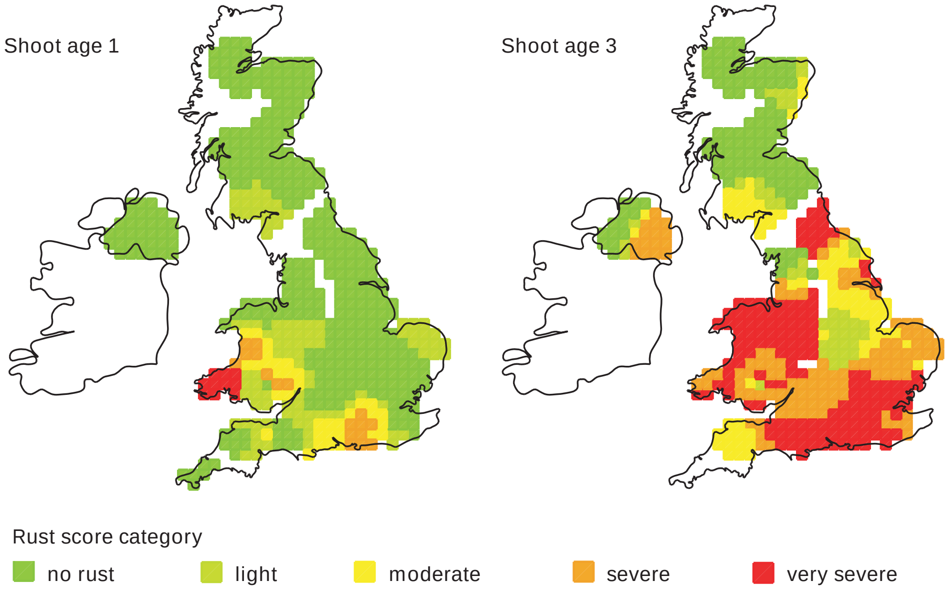


Figure 6

Maps showing the incidence of *Melampsora* spp. on the foliage of 1-year-old and 3-year-old shoots of the poplar variety ‘Beaupré’. The estimates presented on a 20 x 20 km square grid are based on a statistical analysis of the survey data.

Figure 7

Screen shot of a yield model user interface during the development phase.

The future

The methods devised to estimate yield at the experiment level can be used with reasonable confidence on very small stands of SRC, however further development is required before models can accurately reflect variations of crop survival and vigour found in larger, more variable commercial plantations. Consultation with industry is required to ensure that future developments are relevant and applicable to the commercial world. For example, since the conception of this research programme commercial planting densities have increased and some growers are moving away from the standard 'cut back after one year, then leave for three years' silviculture in an attempt to reduce management costs and improve farm cash flow.

Some of the varieties used in this research programme have been planted commercially but are being superseded with new willow varieties offering increased yield, improved insect and disease tolerance or greater drought resistance. These varieties may open up site types that were previously unsuitable or only marginal for SRC production. The yield models constructed during this research programme could be reparameterised to incorporate these new varieties.

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