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YIELD MODELS FOR ENERGY COPPICE OF POPLAR AND WILLOW

Volume A – Empirical yield models

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Volume A – Empirical models

Contract No: B/W2/00624/00/00

Contractor: **Forest Research**

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Executive summary

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 CO_2 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. Once established, and following consultation with SRC growers and industry stakeholders, these relationships were incorporated into easy-to-use software able to predict the biomass production of a range of willow and poplar varieties. This report summarises the development of these empirical yield models along with yield estimates for the site and variety combinations tested and information from pest and disease surveys carried out at each site.

Project Objectives and work summaries

This 10 year research programme was comprised of four consecutive contracts aimed at establishing and managing field trials, data collection, data analysis, model development and reporting. Each of the contracts or ‘phases’ contained distinct objectives and tasks.

Phase 1 (1 November 1994 – 31 March 1995)

Objectives

- To establish six sites on a range of soil types and climatic conditions and to measure intensively the site/clone interactions of a range of willow and poplar clones
- To establish 22 experimental sites with a smaller number of clones but on a wider range of soil types and climatic conditions and to validate and extend the data from the 6 intensive sites
- To ensure that the clones planted are identical across the experiment by carrying out DNA analysis
- To develop minimal destructive sampling techniques
- To carry out a literature review to assist process modelling techniques

Work summary

During this period a total of 27 field trial experiments were established. Of these 21 were small 'extensive' trials containing three willow and three poplar, six were larger 'intensive' sites planted with 16 willow and 16 poplar varieties. Due to poor growth four of the extensive and two intensive trials were either fully or partially replanted or had stump back delayed for 12 months. These trials were subsequently treated as 'Phase 2' sites.
Minimally destructive sampling techniques were developed and reported on by Matthews (1995).
Only limited genetic analysis was carried out on planting material and reported on by the Institute of Arable Crop Research, Long Ashton. A literature review was not produced. Four out of the five objectives were fully or partially met.

Phase 2 (1 June 1995 – 31 May 1998)

Objectives

- To maintain and manage 20 new (Phase 2) and 28 established (Phase 1) experiments in order to:
  a) refine non-destructive sampling methodology in the light of new data and
  b) make yield assessments and assemble a database of yield information which can be used for yield modelling
- To monitor insect damage and fungal pathogens in all experiments and assess any impact on yield
- To collect soil and meteorological data from all experimental sites to relate to variability of yield

Work summary

Twenty new extensive experiments and one new intensive experiment were established during this time period. New equipment (digital calipers) for assessing shoot diameter was tested in the field and bespoke software developed allowing the its use in these

field trials. Data collected with this equipment was stored in a dedicated database and used to generate yield estimates.
A survey of 24 damaging biotic and abiotic agents was made at each site twice annually from September 1996 onwards.
Physical and chemical soil surveys were carried out at each site at the time of establishment. Weather monitoring equipment was set up at each field trial site or the use of locally held data secured. All of the objectives of this phase were met.

Phase 3 (1 June 1998 – 31 May 2004)

- To maintain all established experiments
- To refine non-destructive sampling methodology in the light of new data
- To make yield assessments and assemble a database of yield information which can be used for modelling
- To monitor insect and fungal pathogens in all experiments
- To collect meteorological data from all experimental sites

Work summary
All 49 field trials and associated data logging equipment were maintained during this period. Non-destructive and minimally destructive sampling protocols were employed at the sites. Detailed analysis of shoot allometry was conducted on data collected using these protocols. A summary of this analysis was and reported on (Matthews et al., 2002). Insect and disease surveys were carried out twice each year of the field trials life. Data from these assessments was stored in dedicated database along with data collected by weather monitoring equipment. All objectives were met.

Phase 4 (June 1999 – 31 May 2005)

Objectives
- To maintain all established experiments
- To refine non-destructive sampling methodology in the light of new data
- To make yield assessments and assemble a database of yield information which can be used for modelling
- To monitor insect and fungal pathogens in all experiments
- To collect meteorological data from all experimental sites
- To collect physiological information to characterise clonal difference
- To collect information on the relationship between cutting cycle, spacing and yield from a spacing experiment at Wishanger
- To analyse and describe the data-sets produced
- To use the information to construct easy-to-use computer models relating clone, site and climatic factors to expected yields

Work summary
All experiment maintenance and data collection objectives were met at the intensive and extensive field trials. Physiological data was collected at dedicated experiments established at nurseries near Alice Holt, Hampshire and Elgin, Morayshire; fertiliser and irrigation was applied to the three willow and three poplar clones planted at these sites. Non destructive and minimally destructive sampling protocols were modified during this period in light of new information emerging from data analysis. Models based on

empirical relationships between variety, site and climatic variables have been constructed following consultation with SRC industry stakeholders and representatives from other research groups. Work on process based yield models developed during this project will be reported on in Volume B of this report.

This report focuses on the development of empirical yield models and summaries yield estimates and data collected during pest and disease surveys. Details of site selection, site management, experimental design, data collection and database construction will be found in separate sections included in Volume C of this report.

Conclusions and deliverables

- A network of 49 trial sites across the UK was successfully established and managed for two, three year cutting cycles.
- A database containing information on site specific environmental variables, insect and disease loads and plot level biomass estimates was constructed.
- The number of environmental variables that significantly effect SRC yield is large but no single variable is able to explain a large proportion (>5%) of the variation in yield observed amongst varieties, sites and years.
- Models able to account for 68.9% of the variation in shoot diameter observed amongst willow varieties, sites and years and 70.3% of the variation in shoot diameter observed amongst poplar varieties, sites and years were constructed.
- Software able to predict the yield of 16 willow and 13 poplar varieties managed as SRC was constructed.
- Limited validation using data from commercial plantations suggests that yield estimates generated by this software are within 1 to 6.5 odt.$ha^{-1}yr^{-1}$ of observed yield figures.
- ‘Yield maps’ of willow and poplar SRC have been produced which show variations in yield amongst varieties, location and crop age and indicate which areas of the country are most suitable for the establishment of SRC
- The poplar varieties tested are unlikley to provide economically viable yields at sites in Northern Ireland.
- Willow and poplar varieties that perform well in the first cutting cycle may not continue to do so in subsequent cutting cycles.
- The incidence of pest and disease in SRC on a country scale changes significantly and rapidly over time.
- SRC pest and disease levels are currently low in Scotland.
- Varieties that are currently resistant or tolerant to disease may not remain so.
- The standing biomass estimation software produced during the course of this project provides the basis for the development of a commercial, non-destructive yield estimation tool.

Recommendations for further work

- In order to test their robustness, further comparison of yield predicted by models constructed during this project with yields obtained in commercial plantations should be carried out.
- Poplar should not be planted as an SRC crop in Northern Ireland due to low yields.
- Beaupré, Hoogvorst, Hazendans and other related poplar clones should not be planted as SRC due to disease susceptibility problems
- The standing biomass estimation software devised during this project should be developed to provide growers with a tool able to estimate the standing biomass of existing SRC plantations in a cost efficient manner.
- Permanent samples plots should be established within commercial plantations to facilitate the monitoring of long term yield reliability, the affect of mixtures on yield and pests, soil fertility, and the incidence of potentially damaging agents including *Melampsora* spp, skeletonising insects and stem aphids.

Contents

1. Introduction

1.1. Background

As a result of high oil prices in the mid-1970s, many European and Scandinavian countries initiated research programmes investigating fuel production from energy crops. Initial studies were aimed at identifying suitable crop systems. One of the systems tested involved planting coppicing tree species at high densities (around 10,000 stools per hectare) and harvesting above ground growth every two to five years. This system was termed 'Short Rotation Coppice' (SRC). In the UK, numerous coppicing tree species were tested using this system (Potter, 1990). Examples include *Salix viminalis* clones, *Populus interamericana* clones, *Eucalyptus archeri*, *Alnus cordata*, and *Northofagus procera*. Willow and poplar clones emerged favourably from these trials, producing high yields without succumbing to disease or frost. Other research programmes concentrated on developing harvesting, processing and power generation equipment that could cope with biomass produced by a variety of crop systems including SRC. Political backing for SRC was shown on 20 December 1994 when the UK minister for Energy announced government support for three power generation projects using woodfuel gasification technology. These projects were expected to 'stimulate substantial commitment to coppicing'.

1.2. Objectives

Although informative, results from early research programmes could not predict the yield of willow or poplar SRC under different environmental conditions. Without this information planners could not make informed decisions as to where SRC plantations and power generation plants should be sited in order to maximise yield and land use efficiency. Growers also needed information on likely yields achievable by different site/clone combinations, in order to estimate their financial return from these crops. For these reasons the Department of Trade and Industry (DTI), the Ministry of Agriculture, Fisheries and Food (now incorporated into the Department of the Environment, Farming and Rural Affairs [Defra]) and the Forestry Commission (FC) sought to quantify and model the yield potential of a diverse range of willow and poplar clones grown as SRC on agricultural sites across the UK. This report describes the techniques used during the development of predictive empirical yield models and summarises yield estimates and pest and disease data collected during the course of this project.

1.3. Overview of experimental methods

The research programme 'Yield models for energy coppice of poplar and willow' was supervised by Future Energy Solutions (now AEA Energy Environment) and carried out by Forest Research (FR) and the Department of Agriculture and Rural Development, Northern Ireland (DARDNI, formally Department of Agriculture, Northern Ireland). The backbone of this research programme was a network of 49 field trials established on agricultural land throughout England, Scotland, Wales and Northern Ireland. Data collected from these sites was used to develop empirical yield models and process based predictive yield models capable of estimating the productivity of varieties grown under a range of environmental conditions.

Three basic experiment types were established:

- 'Intensive' sites planted with 16 poplar and 16 willow varieties grown in monoclonal plots. Seven of these sites were established.

- ‘Extensive (Pure)’ sites planted with three poplar and three willow varieties grown in monoclonal plots. Twenty-six of these sites were established.
- ‘Extensive (Mixed) sites planted with three poplar and three willow varieties grown in both monoclonal plots and polyclonal (mixed) plots containing either three willow or three poplar grown in alternating rows. Sixteen of these sites were established.

At each site planting density was 9875 stools per hectare. Cuttings were planted in the conventional ‘twin row’ manner. Inter-row spacing alternated between 0.75 m and 1.5 m with 0.9 m between cuttings within rows. Three replicates of each variety or mixture of varieties were planted at each sites. Each replicate consisted of either 36 (monoclonal plots) or 81 (mixed plots) coppice stools used for assessment surrounded by at least two ‘buffer rows’ of un-assessed coppice stools. Data collected at two spacing experiments established to a different experimental design were also used during the development of the models presented here. Details of these trials can be found in a separate report (Armstrong and Johns, 1997).

Figure 1.1 and Table 1.1 show details of the location and type of the experiment sites established. Table 1.2 gives details of the willow and poplar varieties used at each experiment.

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

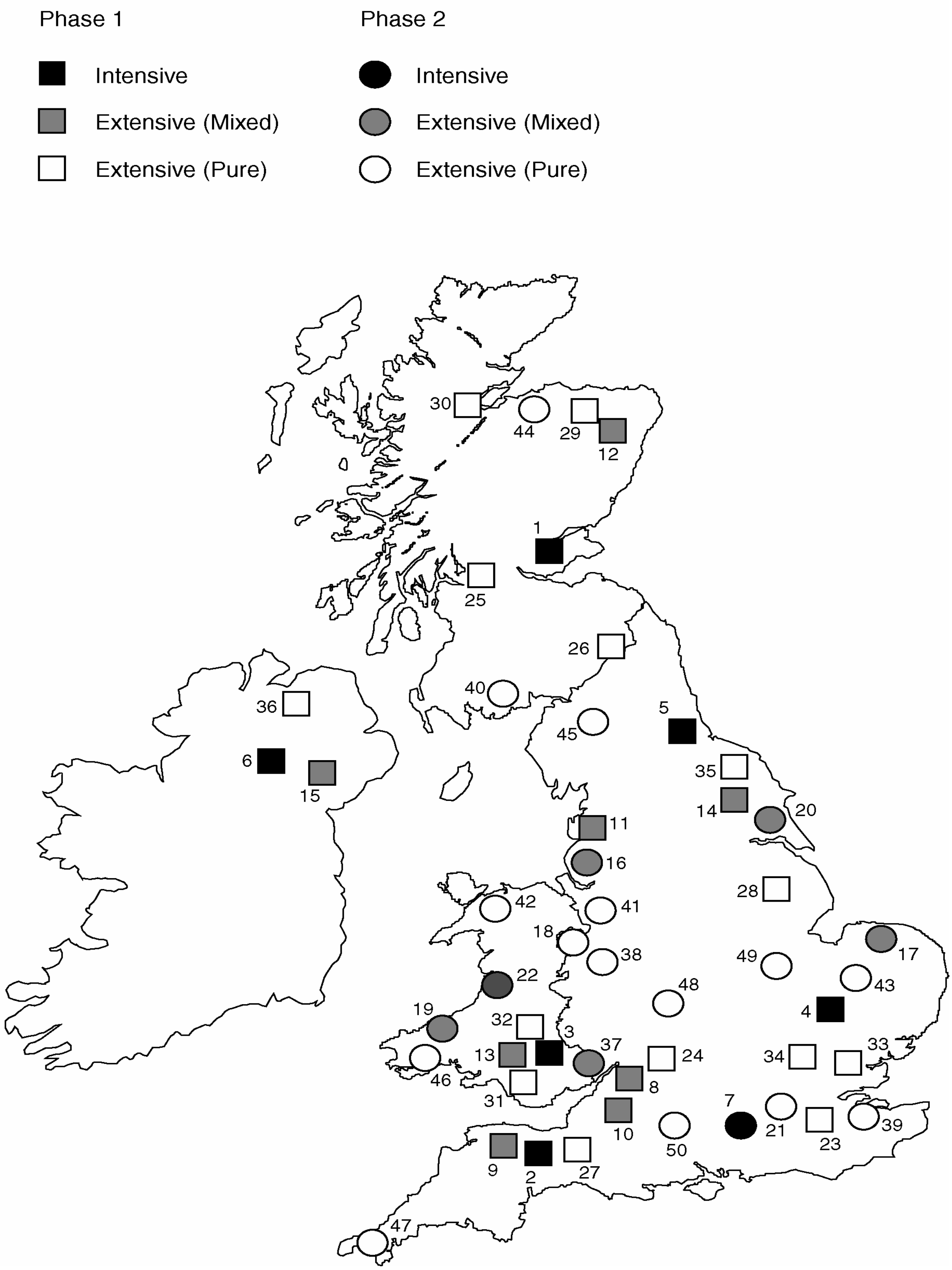


Table 1.1 Details of field trials established in project 'Phase 1' and 'Phase 2'.

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

Site 45 abandoned following soil survey.

Table 1.2 Willow and poplar varieties used at experiment sites

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

* 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. Empirical models for predicting yield of short rotation coppice

2.1. Introduction

The principal aim of the empirical modelling component of this project was to develop a tool to predict yield (biomass) at a specified crop age (1 – 6 years) for a given poplar or willow variety at any location in the UK and Northern Ireland.

To achieve this aim the empirical modelling component was divided into two parts. The first part generated a series of models using data collected during the project, including meteorological data and soil characteristics from each site. Appendix J describes this first set of models, developed to gain useful insights into the relationship between the growth of short rotation coppice of poplar and willow and soil and meteorological variables. For short-hand these have been referred to as ‘Science models’.

The second part of the modelling component generated a group of predictive models needed to develop the tool to predict yield. Insights obtained from the Science models were used to guide variable selection during construction of the predictive models. However, for the predictive models long term meteorological averages were used. In addition, feedback from stakeholders, including growers, provided the predictive modelling process with a selection of potential variables based on the grounds of practicality. A full list of variables considered during the predictive modelling process is described in the relevant sections of this chapter.

2.1.1. Structure of the predictive modelling suite

In order to develop the tool to predict yield a suite of connected models was developed. For the three willow and three poplar varieties planted at all 49 sites (referred to as the ‘extensive’ varieties), models relating shoot diameter at 1m (D100) and number of shoots per stool to site characteristics were constructed along with models relating shoot dry weight to the D100 values.

Far more data on shoot form was available for the three willow and poplar (extensive) varieties planted at all 49 sites than for the 13 willow and 13 poplar (intensive) varieties planted only at the 7 Intensive trial sites (see Figure 1.1 and Tables 1.1 and 1.2 for descriptions of the experiment sites and varieties used). This helped define the approach taken for developing the predictive yield model.

For the varieties grown at the seven ‘intensive’ sites only, information collected from the extensive varieties at these sites were related to the corresponding values for the intensive varieties. These models were then combined to produce a predictive yield model for all varieties. Refer to the user manual for the SRC Predictive yield model software Appendix P for details of the user input required for the predictive yield model.

In addition to the yield models, epidemiological models predicting the probability of severe *Melampsora* spp. rust fungus infecting the crop were developed.

Finally, the part of the model suite that predicts shoot dry weight from D100 values (section B3 & C3 below) was used in the development of a tool to estimate the standing biomass of existing SRC plantations from user provided D100 values. Refer to the user manual for the SRC Standing yield model in Appendix O for more details.

Predictive Modelling Stages

A. For the three willow and poplar extensive varieties planted on 49 sites:

1. Model the mean D100 values for each variety and crop age using site level variables (section 2.2.1).
2. Model the relationship between D100 and dry weight of individual shoots (section 2.2.2).
3. Model the number of shoots per stool using site level variables and D100 values (section 2.2.3).
4. Model the probability of severe rust using site information (section 2.2.4)
5. Model the relationship between the extensive and intensive varieties using information from the seven Intensive sites.

B. Given the component models above, predict the yield (biomass) for the three extensive poplar or willow varieties by:

1. Predicting the mean D100 values for a given variety, location, crop age combination.
2. Predicting the number of shoots per stool for a given variety, location and crop age.
3. Computing the estimated mean dry weight per shoot.
4. Computing the estimated biomass in tonnes per hectare from the estimated mean dry weight per shoot and the predicted number of shoots per stool using an adjustment for number of stools per hectare planted.

C. For the additional Intensive site varieties:

1. Predict the D100 values for the three extensive varieties for the location and crop age.
2. Estimate the D100 values for the intensive varieties using the three extensive variety predicted D100 values.
3. Estimate the mean dry weight per shoot from the D100 values.
4. Predict the number of shoots per stool for the three extensive varieties for the location and crop age.
5. Estimate the number shoots per stool for the intensive varieties using the predicted number of shoots per stool for the three extensive varieties.
6. Compute the estimated biomass in tonnes per hectare from the estimated mean dry weight per shoot and the predicted number of shoots per stool using an adjustment for number of stool per hectare planted.

Datasets

The development of the empirical models used several data sets describing the form of coppice shoots growing in the field trials. The data sets used during the predictive empirical modelling phase covered by this report are listed in below (Table 2.1).

Table 2.1 Datasets used for predictive modelling

Dataset	Scale	Collection frequency
Shoot diameter 1m above ground (D100)	All shoots on all plots	Annually – 2 cutting cycles
Number of shoots per stool	All stools on all plots	Annually – 2 cutting cycles
Shoot Dry Weights (& corresponding D100)	≥1 shoot per variety at each site	Annually – 2 cutting cycles

Further data sets covering aspects of each trial site, e.g., physical and chemical soil properties and 30 year averages of meteorological information along with recordings of pests and diseases were also available. The protocols followed during the assessments are described in Appendix A.

All models were fitted using GenStat (GenStat®, 2005). In particular linear regression models, generalised linear models and the REML functionality were used. Multivariate methods such as cluster analysis and principal co-ordinate analysis were also used to explore the structure of the data. Detailed information of the analyses used during each stage of the modelling process is given in the relevant section.

N.B. All modelling output including Tables, Figures & Appendices refer to the poplar and willow varieties as clones.

2.2. Empirical models – description and results

2.2.1. Shoot diameter at 1m above ground level (D100) model

This model was developed to provide a prediction of the mean D100 for the extensive poplar and willow varieties from a set of input variables. Part of the modelling process was to try and explain the site effects in terms of site variables. For the more detailed 'science' modelling, described in Appendix J, these variables were recorded as part of the experiments. For the predictive yield modelling the following criteria were used to select site variables for inclusion in the models:

- Site information that is likely to be readily available to the grower (SRC stakeholders were consulted on this issue)
- Weather information should be medium term averages (30 years) rather than any prediction of future weather or any of the short-term site-specific information collected for the project.
- The variables should be closely related to variables that have been shown to have explanatory power in the 'science' model.

In addition, as there are only 49 sites within the experiment only a relative small number of potential explanatory variables could be considered at the formal model selection stage to avoid over fitting by the inclusion of chance effects.

The variables considered were:

1. Latitude (decimal minutes)
2. Longitude (decimal minutes)
3. Number of frost days between March and May
4. Total growing season rainfall (Mar-Oct for willow and Apr-Oct for poplar)
5. Annual rainfall
6. Growing degree days (GDD) in a growing season
7. Mean daily maximum temperature – June to August average
8. Soil pH [$]
9. Soil extractable phosphorus (P)
10. Soil extractable potassium (K)
11. Soil extractable nitrate (N)
12. Soil texture category - Clay, Loamy, Sandy.*

[$] Labelled 'pH2' in all modelling output as two methods of measuring pH were used during soil surveys carried out at each site. 'pH2' was assessed following methods used by ADAS.
* The 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.

Individual shoot D100 values were available for all shoots on three plots of each of the three extensive poplar and willow varieties on 49 sites for six years, a total of 2646 plot/years for each species. However, data were not available for some of these plot/years due to stand death, problems in data collection etc. The individual shoot data would effectively have applied different weights to plot level data (mean D100 per plot) depending on the number of shoots and the relative sizes of the within and between plot/years variation. Analysis using REML (GenStat®, 2005) showed that there was no advantage in using the individual shoot data so the modelling was carried out at the plot/years mean level.

The distribution of the D100 values was skewed but could be approximately corrected using a natural log transformation (log). All models considered for D100 used the log-transformed values (log-D100). The two key factors were variety (labelled 'clone') and crop age (1 – 6 years). The six level factor for crop age could have been broken down into rotation (1 or 2) and shoot age (1 – 3 years), with shoot age quantitatively modelled. However, as there were significant rotation by shoot age interactions and the need for (at least) a quadratic term to model the relationship between shoot age and log-D100 there was no advantage in this decomposition.

Linear regression was used to fit models to the log-D100 values. Models containing the main effects and interactions of the variety and crop age factors and the variables listed above were considered. The percentage variance accounted for (adjusted R^2 statistic) and Mallows' Cp Statistic (measure of prediction error) were used to evaluate the fit of each model. A term was included in the model provided it was significant (p-value $\leq$ 0.05) and made at least a 0.5% contribution to the R^2 value. Residual plots were examined to validate the assumptions of the model.

It is possible that under some uses of the model the nitrogen, phosphorus and potassium values (NPK) may not be known, therefore models with and without NPK values were evaluated. In addition, NPK values were not available for all sites so including NPK terms in a model reduced the number of observations available.

The following results for the three extensive poplar and willow varieties were obtained.

Willow
Significant variables included in the model: total growing season rainfall, annual rainfall, growing season GDD, soil pH and soil texture. No N, P, or K variables were significant.

Table 2.2 Summary of models used to describe yield variation amongst three willow varieties

Model	No. Parameters	R^2 value
Clone*Crop Age	18	63.5%
Selected model	52	68.9%
Selected model + Site	92	78.4%

The ratio of the change in R^2 for the two selected models compared to the Clone*Crop Age model shows that the site variables explain about 36% of the between site variation.

Poplar
Significant variables included in the model: latitude, number of frost days (Mar-May), soil pH, NPK and soil texture.

Table 2.3 Summary of models used to describe yield variation amongst three poplar varieties

Model	No. Parameters	R^2 value
Clone*Crop Age	18	58.9%
Selected model	62	70.3%
Selected model + Site	91	81.3%

The simpler model without NPK terms gave an R^2 value of 67.4%, or 79.9% with Site included. For poplar the site variables explain about 51% of the between site variation.

Table 2.4 A summary of the model terms, including interactions (shown as ‘x’), used to predict log D100

Willow	**Poplar without NPK**	**Poplar with NPK**
Clone	Clone	Clone
Crop Age	Crop Age	Crop Age
Clone x Crop Age	Clone x Crop Age	
Annual Rain		
Annual Rain x Crop Age		
Season rainfall		
Season rainfall x Clone		
Season rainfall x Crop Age		
	Frost Days	Frost Days
	Frost Days x Crop Age	Frost Days x Crop Age
GDD		
GDD x Crop Age		
	Latitude	Latitude
	Latitude x Clone	Latitude By Clone
	Latitude x Crop Age	Latitude By Crop Age
pH	pH	pH
pH x Clone	pH x Clone	pH by Clone
pH x Crop Age	pH x Crop Age	pH by Crop Age
Texture	Texture	Texture
Texture x Clone		
	Texture x Crop Age	Texture x Crop Age
		Potassium
		Potassium x Crop Age
		Nitrate
		Nitrate x Clone
		Nitrate x Crop Age
		Phosphorus
		Phosphorus x Crop Age

Further details are given in Appendix C and associated coefficients can be obtained from the model functions listings in Appendix H.

The values of log-D100 for the three extensive varieties of poplar and willow and the relationship between the extensive and intensive varieties were used to model the log-D100 values for the 13 varieties of each species grown at the intensive sites.

Using a principal co-ordinate analysis an ordination of the D100 values for willow and poplar varieties was produced. For willow the two-dimensional ordination represented 65% of the variation, while for poplar it was 58% (Figure 2.1 and 2.2).

Figure 2.1 Ordination for Willow D100 values (varieties w1, w2, w3 were present at all 49 sites, remaining varieties were planted at intensive sites only)

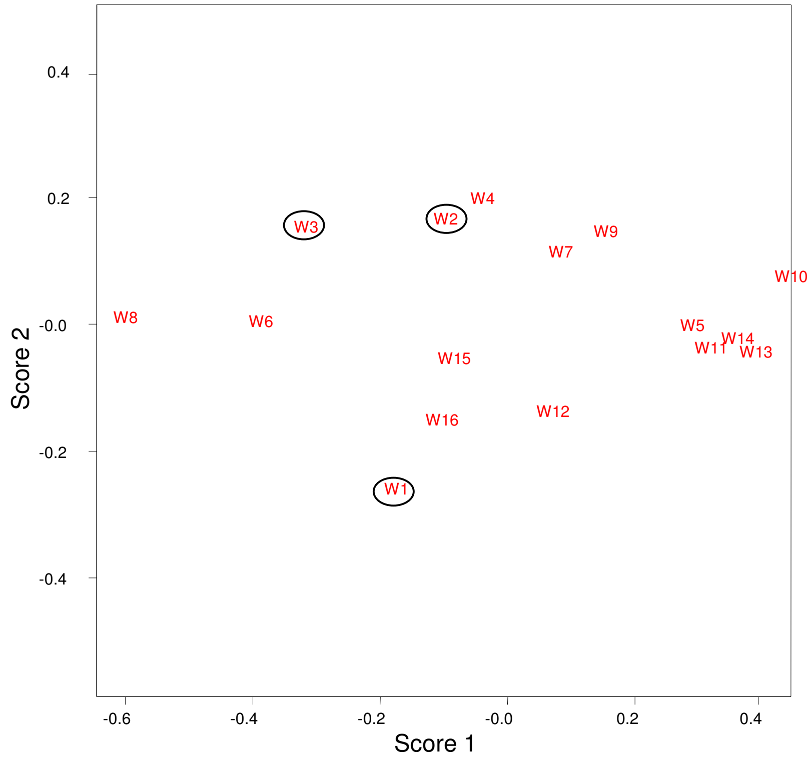
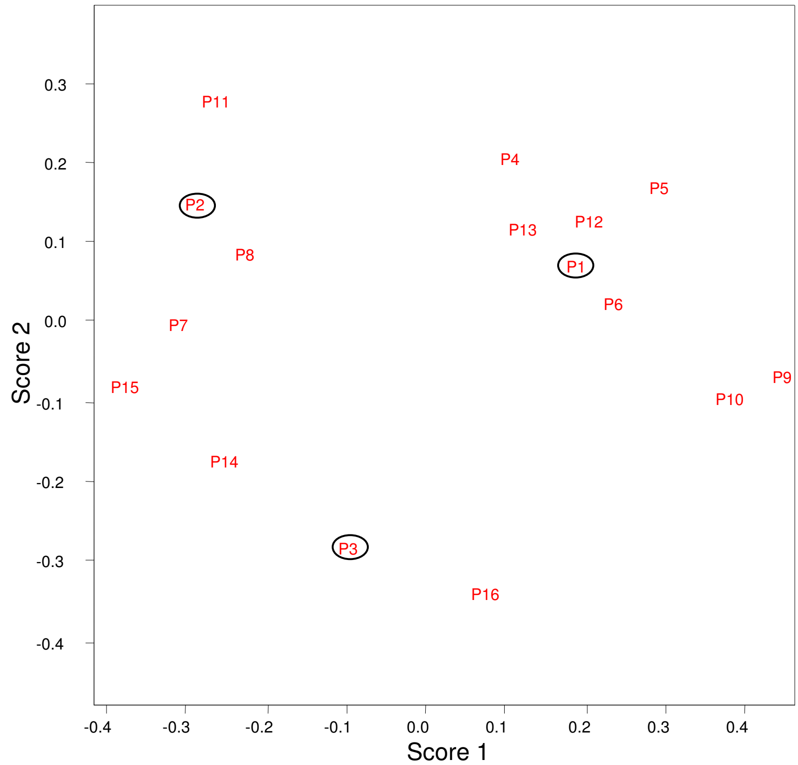


Figure 2.2 Ordination for Poplar D100 values (varieties p1, p2, p3 were present at all 49 sites, remaining varieties were planted at intensive sites only)



For poplar, the three extensive varieties give a reasonable coverage of the space. For willow the coverage over the second dimension is good but the coverage over the first dimension is poor.

Linear regression was used to relate the log-D100 values of the intensive varieties to the log-D100 values of the extensive varieties using data from the common sites. Significant terms only were included in the models.

Willow
For willow, in addition to the three extensive varieties (W1 = Jorunn, W2 = Germany, W3 = Q83) it was necessary to include a crop age by variety interaction term in the model. The coefficients for the three extensive varieties are shown in Table 2.5.

Table 2.5 Coefficients for the three extensive willow varieties

Clone	W1	W2	W3	R^2 (%)
W4		0.41	0.20	84.5
W5	0.50	0.31		80.0
W6	0.36	0.32	0.16	86.1
W7	0.36	0.32	0.18	85.4
W8	0.30	0.16	0.23	84.6
W9	0.09	0.29	0.28	88.7
W10	0.37	0.45	0.31	85.9
W11	0.28	0.25	0.19	89.1
W12	0.80	0.24		87.9
W13	0.62	0.23		84.6
W14	0.64		0.36	83.1
W15	0.89	0.34		82.3
W16	0.77		0.25	84.1

Poplar
For poplar only the extensive varieties (P1= Beaupré, P2 = Ghoy, P3= Trichobel) were needed in the model. The coefficients for the three extensive varieties are shown in Table 2.6.

Table 2.6 Coefficients for the three extensive poplar varieties.

Clone	P1	P2	P3	R^2 (%)
P4	0.64		0.38	81.6
P5	1.02			89.8
P6	0.68		0.35	89.8
P7		0.56	0.42	92.7
P8	0.22	0.49	0.29	89.8
P9	0.70		0.35	85.6
P10		0.27	0.80	77.8
P14	0.30		0.65	75.4
P15	0.31		0.62	71.5
P16	0.15		0.88	88.9

Varieties P11, P12 and P13 (v710091, v710151 and v710092) not included due to universally poor growth and lack of commercial potential.

2.2.2. Dry weight models

The protocols followed to collect data used for estimating the dry weight from diameter and length measurements are described in Appendix A. Two approaches to computing dry weight from diameter at height 1 m (D100 values) have been considered in the project.

1. An allometric approach that develops the relationship in 3 stages. At each stage suitable models were developed including site and crop age factors. The stages were:
   - The relationship between D100 and the diameter at 0.1 m (D10 values).
   - The relationship between D100, D10 and length of the shoot.
   - The relationship between D100, D10, length of shoot and the dry weight.

2. A predictive approach that finds the best (linear) predictor of shoot dry weight from D100 values. This approach required only a single model.

The first approach has the advantage of a theoretical underpinning and the modelling can use a hierarchy of data sets. The second has the advantage of simplicity and, under certain assumptions, provides the optimal predictor for dry weight. For the first version of the empirical yield model it was decided to use the predictive approach. If further refinements of the allometric model are successful and it proves superior to the predictive model it may be incorporated into future versions of the yield model.

For willow there were 1820 observations of shoot diameter at a point 1 m above ground level (D100 values) and shoot dry weight. For Poplar there were 1788 similar observations. Data for the extensive varieties were available from all 49 sites; data for the intensive varieties was collected at seven sites. The distribution of observations between crop age and variety shows that despite the large number of observations there are relatively few for each site by variety and age combination (see Table 2.7). This means that assumptions have to be made about the consistency of the relationship between dry weight and the D100 value and these cannot be fully validated.

Table 2.7 Summary of the number of observations of shoot diameter (D100) and shoot dry weight for the 32 willow and poplar varieties tested

Willow Clone	Crop Age (Years)						Poplar Clone	Crop Age (Years)					
	1	2	3	4	5	6		1	2	3	4	5	6
W1	63	66	59	59	49	28	P1	63	63	59	56	55	36
W2	61	66	57	60	49	29	P2	61	62	58	59	49	29
W3	62	66	58	59	50	27	P3	61	62	62	58	47	28
W4	7	13	15	14	8	7	P4	7	10	15	14	7	7
W5	7	13	14	14	17	12	P5	7	11	14	12	7	7
W6	7	13	15	14	8	7	P6	6	11	18	16	6	8
W7	7	13	16	14	8	7	P7	7	11	19	15	6	8
W8	5	13	15	15	8	7	P8	7	11	17	15	6	8
W9	7	13	15	14	8	7	P9	7	11	18	14	6	7
W10	7	13	16	15	8	7	P10	5	11	17	15	7	7
W11	7	13	16	14	8	7	P11	6	9	13	14	6	7
W12	7	13	15	15	8	7	P12	6	11	12	15	7	7
W13	7	13	15	13	8	7	P13	6	11	13	15	7	7
W14	7	13	15	14	8	7	P14	7	11	18	15	16	14
W15	7	13	16	15	8	7	P15	7	11	16	16	7	8
W16	7	13	16	15	8	7	P16	7	11	16	15	7	8

Data exploration of the relationship between the dry weights (response variable) and the D100 values (explanatory variable) highlighted two important features:

1. The variance of dry weight values increased with size, showing a skewed distribution (Figure 2.3b & 2.4b); this increase could be approximately corrected (variance stabilisation) by a cube-root transformation.
2. The relationship was curved; this could be approximately corrected (linearisation) by a cube-root transformation.

As the same transformation was suitable for both variance stabilisation and linearisation a transformed linear regression approach could be used rather than a generalised (non-linear) regression approach in which the variance and response relationships are modelled separately.

Figure 2.3 Distribution of Willow shoot D100 and Dry Weight values

a) **b)**

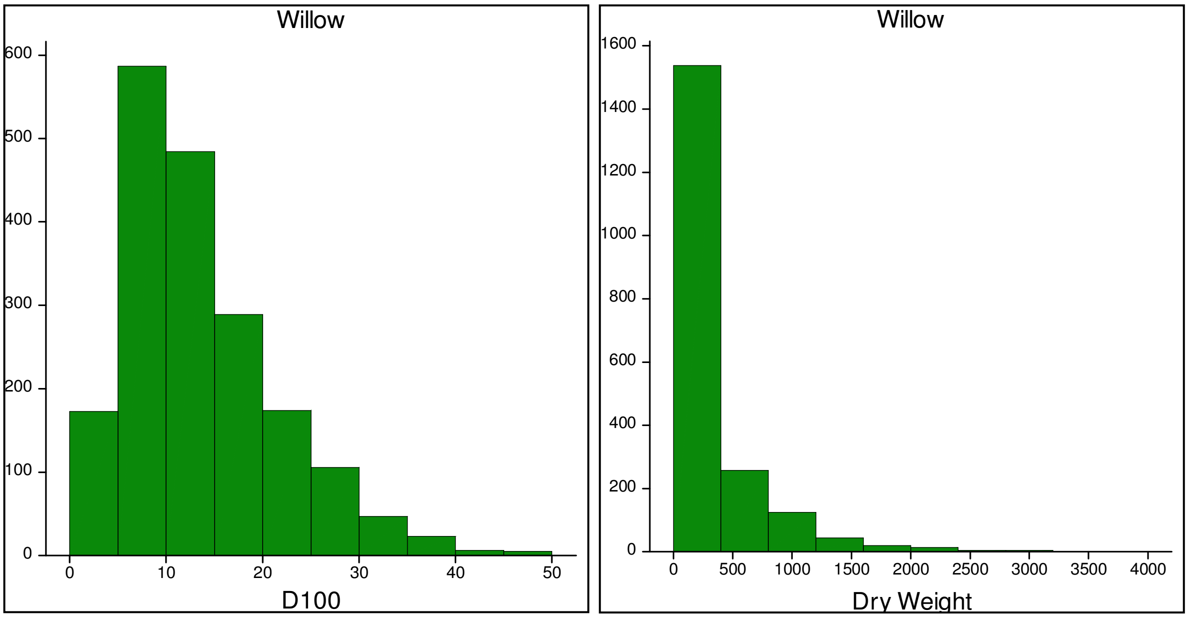
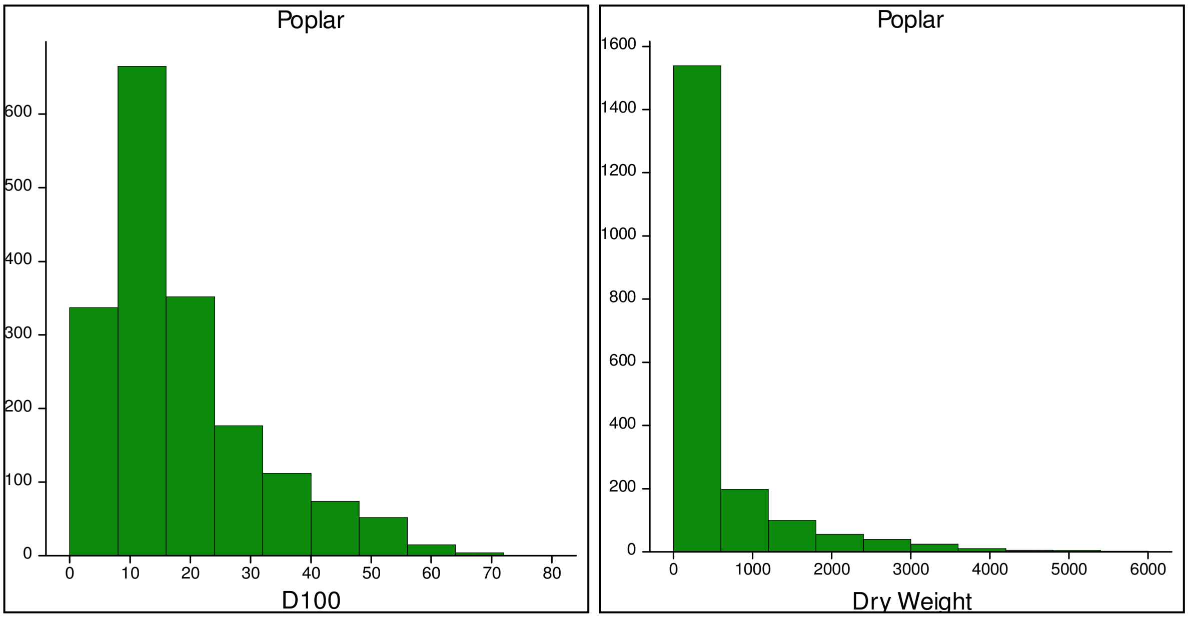


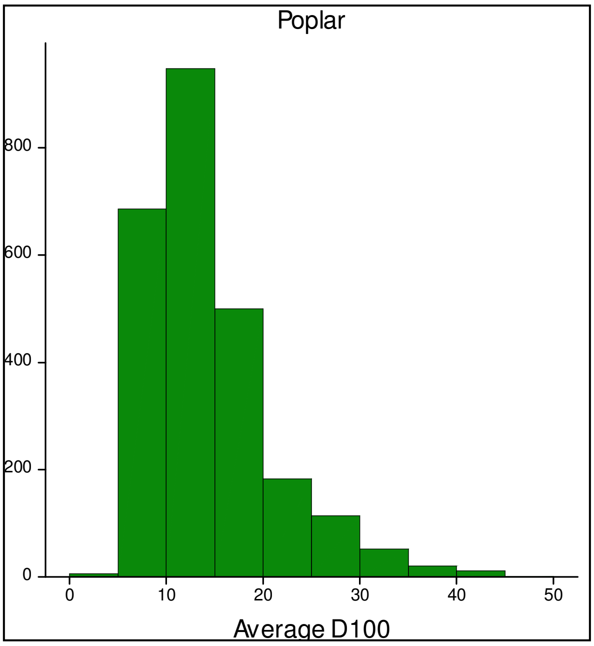
Figure 2.4 Distribution of Poplar shoot D100 and Dry weight values

a) **b)**



The cube-root transformation was not ideal, as can be seen from the Figures 2.6 and 2.7, and alternative non-linear models were considered. The weak fit of the poplar model is most visible where there are high ratios of D100/Dry weight with a D100 value greater than 50. There are relatively few values in this region (Figure 2.3a & 2.4a), and a large amount of variability, so it would be difficult to find and validate a non-linear model that would clearly give a better fit. In addition, since the purpose of the model is to predict mean dry weight from mean D100 values and the plot mean D100 values from the experiments show no mean values fall into this category (Figure 2.5) this region will generally not be considered.

Figure 2.5 Experiment Plot mean D100 values



Having adopted the transformed cube-root model for both willow and poplar, the next stage was to explore the relationship with variety, crop age and dry weight. The interaction terms were tested for significance and their contribution to the model fit, as measured by both the R^2 value and the Akaike Information Criterion (AIC) statistic, was assessed.

For both willow and poplar the variety x D100 and crop age x D100 interactions were significant and made a major contribution to the model fit. Quadratic effects did not contribute to the model fit; Site effects were also found to be significant. A summary of model fits is given in Appendix D.

The fit of the models is illustrated in Figures 2.6 and 2.7 in which, for simplicity only, the marginal variety models (i.e., averaging over crop age and sites) are shown.

Figure 2.6 Transformed dry weight models using D100 and variety effects only for willow and poplar varieties

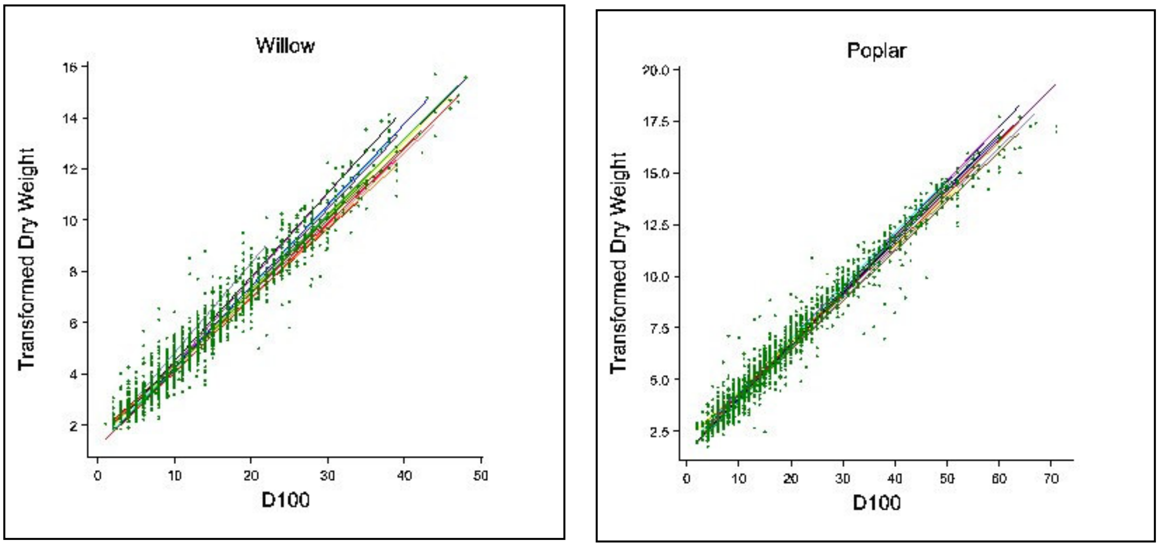
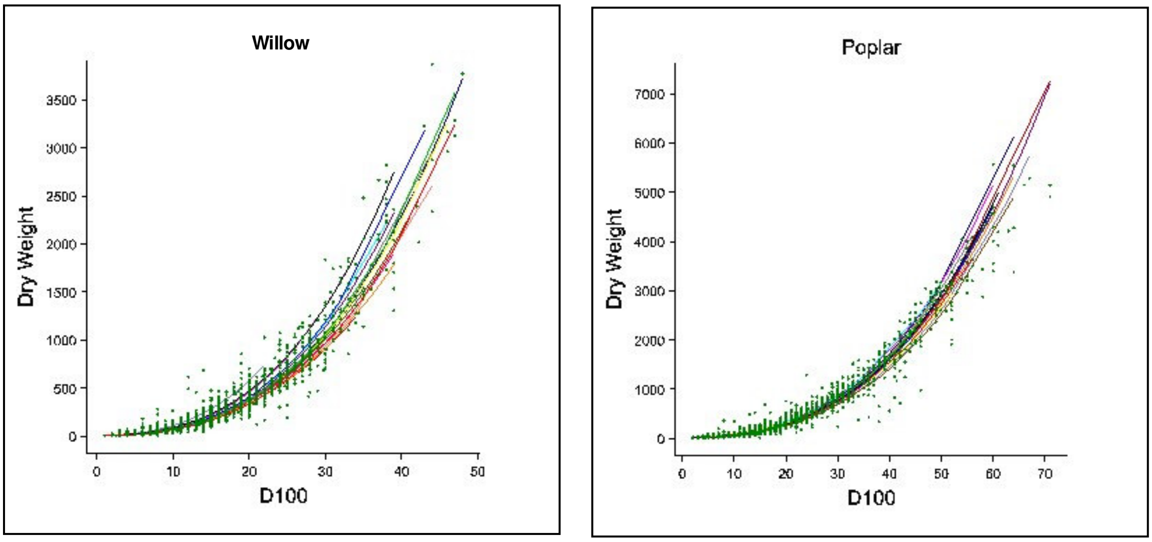


Figure 2.7 Dry weight models for D100 and variety effects only for willow and poplar varieties



For the predictive yield model the fixed site effects were replaced by site characteristics that could be generalised to other sites, similar to the predictive log-D100 model above. Using the three extensive willow and poplar varieties, across all 49 sites, predictor variables were tested for significance using Wald tests within a REML mixed model analysis. However none of the variables considered for the log-D100 model, except for pH for willow ($p < 0.01$), was significant. The effect of pH for willow on the R^2 value was very small and it was decided not to proceed with a model with just this term in. Models for willow and poplar were therefore fitted with the site effects as random effects in a mixed model fitted by REML. The coefficients for the fixed effects in the model, that is D100, variety and crop age and their interactions with D100 were then used in the appropriate functions for the SRC Predictive Yield and the SRC Standing Biomass models.

As the model is on the transformed cube-root scale the dry weights had to be computed by back-transformation. For individual shoots this procedure is reasonable but poses problems when means are used, as for a non-linear function the expected value (mean) of the function is not the function of the expected value. i.e. (the mean of observations)^3 $\neq$ mean of the (observations)^3. To counteract the bias two correction factors were used.

To correct for the cubic transformation the correction term derived from a quadratic approximation of the function is:

$$\frac{2_{\text{nd}}\,\text{Derivative}}{2} \times \sigma^2$$, which for the cubic transformation is $3 \times \mu \times \sigma^2$,

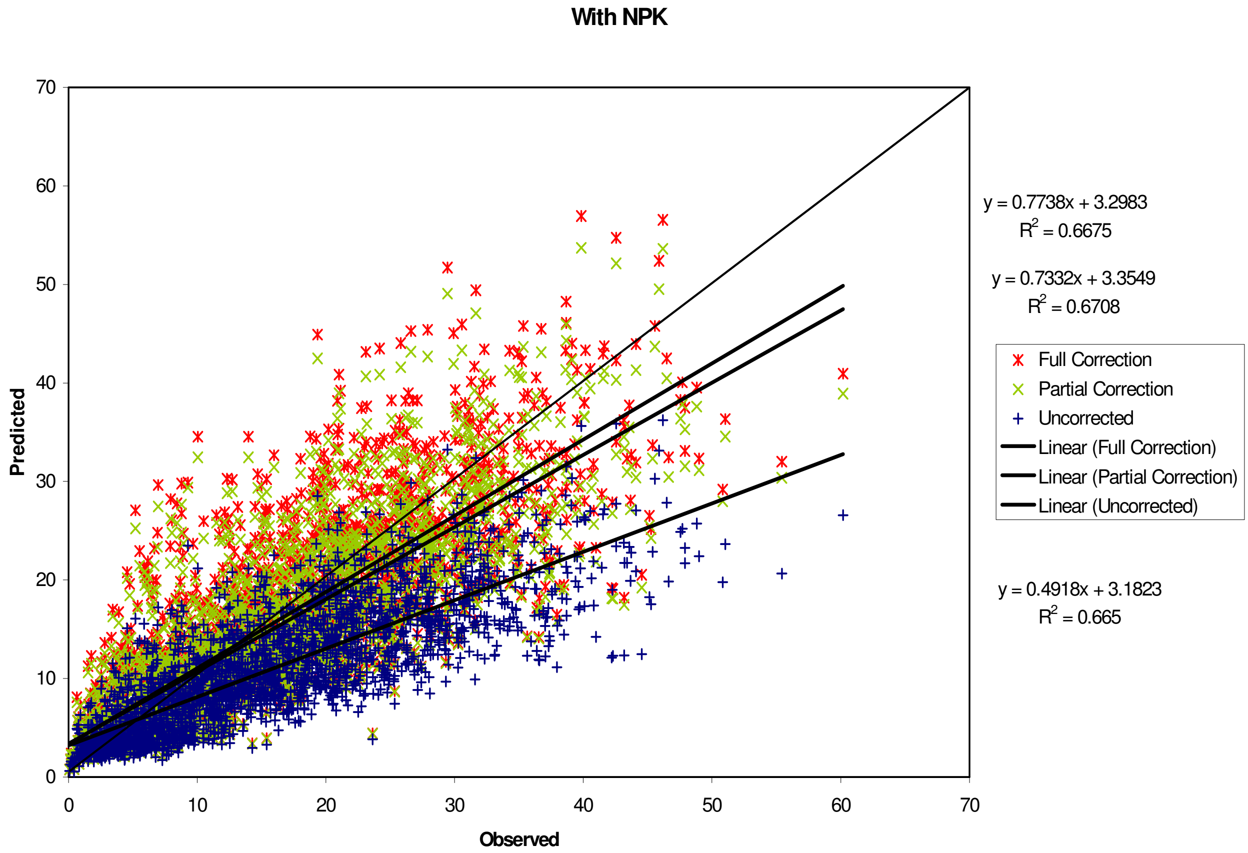
where the mean (μ) and variance (σ^2) are for the linear transformation of the D100 given by the model, i.e., *a* + *b*(D100).

A further correction to account for the skewness of the D100 values was also considered. The D100 values were found to be approximately log-normally distributed. For the log-normal distribution an estimate of the skewness can be derived from the estimated mean (μ) and variance (σ^2). The skewness can be used in the cubic term $\left(\frac{3_{\text{rd}}\,\text{Derivative}}{6} \times \text{Skewness}\right)$ of an approximation of the function.

For the cubic transformation this term reduces to just the Skewness, which for a log-normally distributed variable is $\frac{\left(\sigma^2\right)^2}{\mu}\left(\frac{\sigma^2}{\mu^2} + 3\right)$.

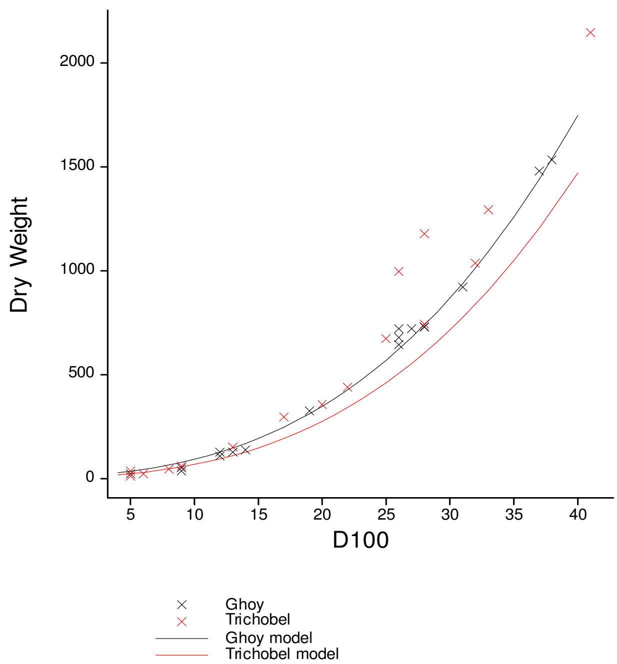
The majority of the bias was accounted for using the first correction. The second correction also improved the bias but slightly increased the range of residuals. In any model there is always a need to balance robustness with accuracy, thus, only the first correction was used in the predictive model, but the full correction has been used for the standing model. This is due to actual D100 measurements being used by the standing model, compared with the smoothed predicted values used by the predictive model. The effects of the corrections can be seen in Figure 2.8, where the full corrected version contains both correction for variance and skew, and the partial correction contains only the variance correction.

Figure 2.8 Comparison of observed and predicted yields and the effects of correcting predicted yields for variance and skew present in the D100 dataset



As well as validation checks during the modelling the models were validated against additional data collected for shoot age 3 of rotation 3. An example of the comparison is shown below (Figure 2.9).

Figure 2.9 Validation checks for Ghoy and Trichobel Yield models



This shows a good fit for the Ghoy (P2) model. The Trichobel (P3) model gives a poorer fit but is within the variation to be expected given the different rotation and years from the original fitting data.

2.2.3. Shoot number models

The model for shoot numbers followed a similar procedure to that for the D100 models. The number of shoots was modelled using a Poisson generalised linear model with a log link. Adjustments were made for over-dispersion when testing for the significance of terms.

It is expected that inter-shoot competition causes a close relationship between D100 values and the number of shoots. Either measure could be used as a predictor of the other. The approach adopted in the project was to express the relationship as a model for number of shoots rather than D100 values, that is the D100 values were used as an explanatory variable for number of shoots but number of shoots was not used as an explanatory variable for D100.

As noted in Appendix A in an attempt to cut costs on some occasions only alternate stools were measured and number of shoots recorded. Adjustments to shoot numbers per plot were made for these observations.

The explanatory variables, apart from log-D100, were those described in the D100 models. Significant terms only were included in the models. The final models are summarised in table 2.8.

Table 2.8 Summary of variables included in models used to predict shoot number

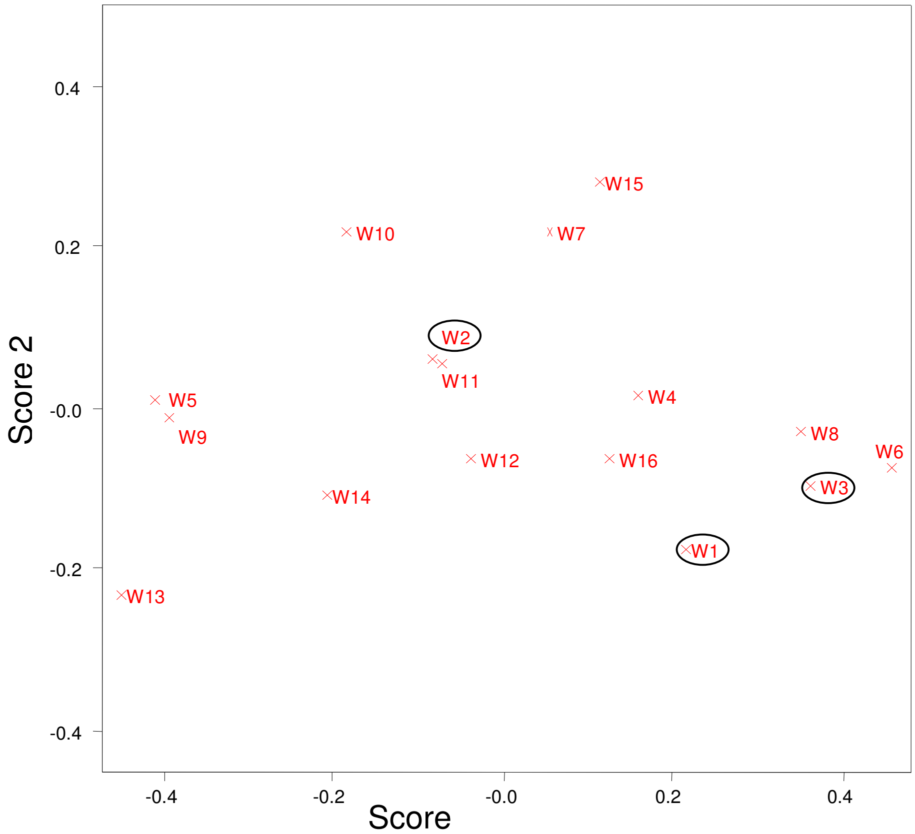
Willow without NPK	**Willow with NPK**	**Poplar without NPK**	**Poplar with NPK**
Clone	Clone	Clone	Clone
Crop Age	Crop Age	Crop Age	Crop Age
Clone x Crop Age	Clone x Crop Age	Clone x Crop Age	Clone x Crop Age
Frost Days	Frost Days	Frost Days	Frost Days
Frost Days x Clone	Frost Days x Clone		
		Frost Days x Crop Age	Frost Days x Crop Age
GDD	GDD	GDD	GDD
GDD x Crop Age	GDD x Crop Age	GDD x Crop Age	
		Longitude	Longitude
			Longitude x Clone
		Longitude x Crop Age	Longitude x Crop Age
		pH2	pH2
			pH2 x Crop Age
Texture		Texture	
Clone x Texture		Clone x Texture	
Texture x Crop Age			
			Potassium
	Nitrate		Nitrate
			Nitrate x Clone
			Nitrate x Crop Age
			Phosphorus
			Phosphorus x Crop Age
LogD100	LogD100	LogD100	LogD100

Further details are in Appendix E and associated coefficients can be obtained from the model functions listings in Appendix G.

As for the D100 models the information from the extensive varieties was used to predict the number of shoots for the intensive varieties. A Poisson generalised linear model with a log link was used and the log-shoot numbers for the extensive varieties and plot mean log-D100 values were included as explanatory terms in the model.

Willow
Using a principal co-ordinate analysis an ordination of the shoot numbers for willow extensive and intensive varieties was produced. The two-dimensional ordination represented 62% of the variation, the coverage over the first dimension is reasonable but over the second dimension is poor.

Figure 2.10 Ordination for Willow Shoot Numbers (varieties w1, w2, w3 were present at all 49 sites, remaining varieties were planted at intensive sites only)



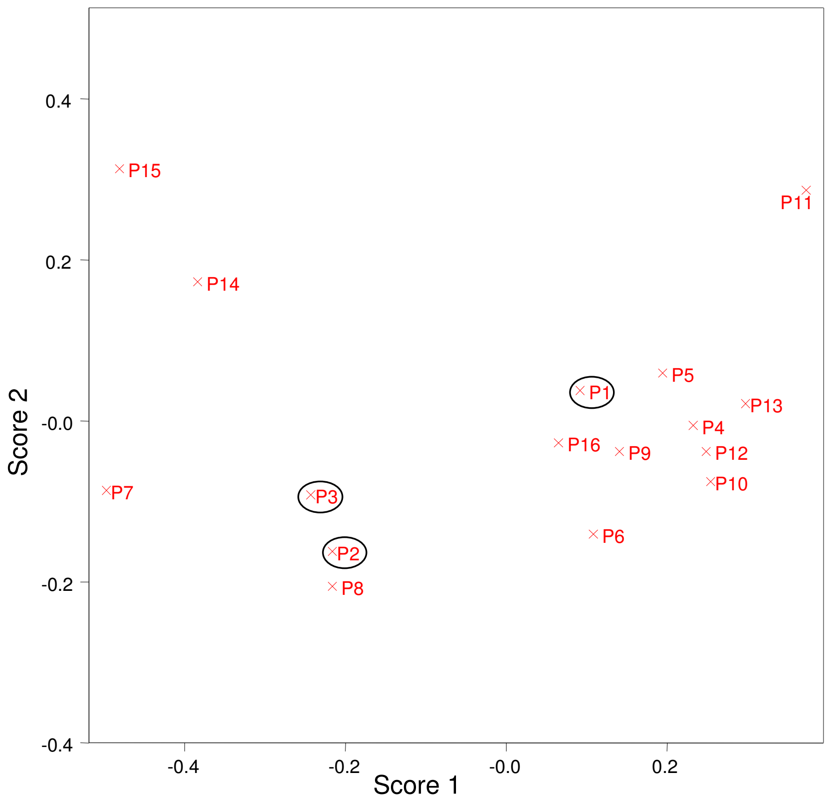
For all intensive varieties the three extensive variety values were significant. Only the log-D100 value for clone 10 (Stott 10) was not significant. The coefficients for the three extensive variety log-shoot number estimates and log-D100 are shown in Table 2.9.

Table 2.9 Coefficients for willow variety specific log-shoot number estimates and corresponding log D100

Clone	W1	W2	W3	LogD100
W4	0.46	0.16	0.36	0.03
W5	0.50	0.15	0.23	0.08
W6	0.53	0.09	0.44	-0.08
W7	0.50	0.18	0.37	-0.14
W8	0.48	0.14	0.43	-0.07
W9	0.46	0.14	0.27	0.07
W10	0.37	0.48	0.12	0.00(ns)
W11	0.45	0.27	0.18	0.17
W12	0.59	0.15	0.22	0.04
W13	0.84	0.03	0.11	-0.21
W14	0.59	0.13	0.27	-0.11
W15	0.66	0.29	0.14	-0.21
W16	0.51	0.10	0.29	0.23

Poplar
Using a principal co-ordinate analysis an ordination of the shoot numbers for poplar intensive and extensive varieties was produced. The two-dimensional ordination represented 63% of the variation, the coverage is better over the first dimension than the second.

Figure 2.11 Ordination for Poplar Shoot Numbers (varieties p1, p2, p3 were present at all 49 sites, remaining varieties were planted at intensive sites only)



Fitting the models gave the following coefficients for the log of the number of shoots and log-D100:

Table 2.10 Coefficients for willow variety specific log-shoot number estimates and corresponding log D100.

Clone	P1	P2	P3	Log D100
P4	0.49	-0.01 (ns)	0.40	0.10
P5	0.52	-0.15	0.57	0.03
P6	0.30	0.21	0.46	-0.03
P7	0.07	0.39	0.54	0.09
P8	0.21	0.29	0.52	-0.01 (ns)
P9	0.17	-0.14	0.91	0.03 (ns)
P10	0.74	-0.07 (ns)	0.27	-0.03
P14	0.10	0.32	0.46	0.30
P15	0.17	0.01 (ns)	0.70	0.36
P16	-0.03	0.20	0.84	-0.13

Varieties P11, P12 and P13 (v710091, v710151 and v710092) not included due to universally poor growth and lack of commercial potential.

For some of the intensive varieties, extensive variety P2 is not significant and has small coefficients.

2.2.4. Leaf rust models

Details of the rust assessments are given in a separate report Appendix F. When the effect of rust was added to the log-D100 selected models it was significant but made a low contribution to the R^2 value. Rather than attempt to include a prediction of rust score within the yield prediction model it was decided to produce a separate 'warning' model for rust. While it may be possible to model the risk of severe rust it is difficult to model the rust score itself as that will depend on a range of local factors including the presence of the pathogen in the area, local short-term weather etc. Predicting the effect of rust is also difficult as in some cases it could kill the crop while in others it may only led to temporary damage.

The plot mean rust scores were dichotomised into above and below a score of 3.5, with a score above 3.5 being considered severe. Logistic regression models were then constructed to predict the probability of severe rust for the three extensive varieties for each species. Only significant terms were included in the models. The models tested are shown in Table 2.11.

Table 2.11 Summary of models used to predict the probability of severe rust Infection on willow and poplar coppice

Willow	Poplar
Clone	Clone
Crop Age	Crop Age
Clone x Crop Age	Clone x Crop Age
Latitude	Latitude
Latitude x Clone	
Latitude x Crop Age	Latitude x Crop Age
Longitude	
Longitude x Crop Age	
	Season rainfall
	Season rainfall x Crop Age

Further details are in Appendix F and associated coefficients can be obtained from the model functions listings in Appendix H.

For the intensive varieties, the most appropriate predictor extensive variety was chosen by examining the errors in the 2 x 2 matrix shown in Table 2.12. The table shows the similarity among intensive and extensive varieties for severe rust presence, i.e. when b + d is small then similarity is high. The most appropriate predictor variety for a particular intensive variety was defined to be the extensive variety with the lowest value for b + d.

Table 2.12 Matrix used to select suitable extensive poplar 'predictor' for modeling the incidence of rust on the 'intensive' poplar varieties. Errors = *b + d*.

Number of plots with severe rust		Predictor (Extensive)Variety	
		Absent	Present
Intensive Variety	Absent	*a*	*b*
	Present	*d*	*c*

The majority of willow varieties, including Jorunn (W1), had a very low incidence of rust, i.e. the majority of plots appear in cell *a* above. In these cases it was impossible to use the matrix to choose an appropriate predictor variety for each intensive variety. It was therefore decided to use Jorunn as the predictor, using the argument that if for a low risk variety (i.e. Jorunn) there is a high risk of rust then it is likely to be high for all other varieties.

The extensive willow and poplar varieties used to predict the incidence of rust on the intensive varieties in shown in Table 2.13. Varieties P11, P12 and P13 (v710091, v710151 and v710092) not included due to universally poor growth and lack of commercial potential.

Table 2.13 Intensive varieties and corresponding extensive 'predictor' varieties used to estimate the probability of severe infection by leaf rust.

Intensive variety	Number of plots with severe rust infection (out of 126)	Chosen Predictor variety	Number of errors
W4	17	W2	19
W5	3	W1	
W6	22	W2	23
W7	2	W1	
W8	0	W1	
W9	10	W1	
W10	22	W2	18
W11	17	W2	
W12	6	W1	
W13	0	W1	
W14	0	W1	
W15	8	W1	
W16	4	W1	
P4	62	P1	21
P5	47	P1	20
P6	44	P1	26
P7	11	P3	5
P8	20	P3	14
P9	21	P3	14
P10	20	P3	14
P14	14	P3	9
P15	25	P3	17
P16	9	P3	4

2.2.5. Adjustment for planting density

The entire experiment was carried out with the same planting densities (10000 stools per ha). However, as commercial plantations use various different spacings, adjustments based on other work had to be considered.

Four papers (Armstrong *et al.* 1999, Bullard et al. 2002, Armstrong and Johns 1997, Bergkvist and Ledin 1998) all concluded that coppice planted at closer spacing produced more biomass per hectare than less dense plantings for a 3 year rotation.

The two papers by Armstrong (Armstrong *et al.*, 1999; Armstrong and Johns, 1997) were based on the same experiments at Wishanger and Downham Market. The varieties used matched the varieties selected for the empirical model. Armstrong et al 1999 was of limited use as no direct relationship between spacing and any other variable was published other than to confirm a greater yield per hectare at closer spacing.

However, Armstrong and Johns (1997) provided data and a relationship between spacing and yield, as did Bullard *et al.* (2002). One species planted at two sites was common to both papers, *Salix x dasyclados* ('Dasyclados') at planting densities of 10,000 and 15,625 stems per hectare. Bullard provided yearly increment at one site, and Armstrong an annual increment at two sites.

As evidence from the papers showed that both the number of shoots per stool and the mean diameter of a shoot on a stool would alter with spacing, two forms of adjustment were considered.

Method 1
A standard simple model is that the yield per plant Y_p is related to the planting density (N) by

$Y_p = 1/(a + bN)$

Fitting the model to the Armstrong data gave coefficients:

a = 0.0003
b = 7E-8 (Wishanger), 10E-8 (Downham Market)

This implies a free growing stool value of 3kg per stool while at 10,000 p/ha it is 1kg (0.8kg) per stool and at 15,000p/ha it is 0.6kg (0.4kg) per stool.

This would suggest the following approach:

Use data to estimate maximum stool size for each variety and use this as an estimate of $1/a$, perhaps using a suitable prior.

Use the model prediction (Y_p, 10000) to estimate b, perhaps again using a suitable prior.

Method 2
Bullard described the relationship between annual yield and planting density for 'Dasyclados' on a triennial rotation as:

Annual yield per hectare = 4.67 + 0.208 * log (planting density per hectare).

That is a model of the form:

Annual yield per hectare = a + b * log (planting density per hectare).

As the intercept was more variable than the gradient, b, the gradient was fixed at the values obtained by taking the average of all the quoted gradients. The (Y_p, 10000) value from the model was then used to estimate the intercept, a, given the fixed value b, and the required yield for the requested spacing calculated.

It should be noted that the adjustments were not very large for the range of values of spacing likely to be encountered in practice. Method 2 has been implemented in the software.

2.2.6. 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 most appropriate model has been selected and, as far as possible, validated, 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; and more extreme weather conditions are possible.
3. Only one planting density was used in the experiments, extrapolation to other spacing can potentially lead to errors. Insufficient data was available to validate the spacing model used and to estimate the uncertainty associated with it.

From the analyses carried out it is known that there are inadequacies in the representation of site effects in the prediction models. For the observed 49 sites this can be quantified by the difference between the R^2 value when site is included in the model as compared to when only site variables are included in the model. These differences are shown in Table 2.14.

Table 2.14 Differences in R^2 values between models with and without 'site' included as a variables.

Model	Willow	Poplar
log-D100	36%	51%
$\sqrt[3]{\text{Biomass}}$	13%	13%
Shoot numbers	23%	29%

As the data sets used to fit the models are moderately large (about 2000 observations) the error in the parameter estimates will be small compared to the inherent variability assumed to be reflected in the residual variation. This assumption is supported by the low value of the mean leverage for the models fitted (typically about 2%).

The estimate of the uncertainty at each stage can therefore be approximated by the prediction error for a given model, i.e. the residual mean square. The error at each stage then needs to be combined to produce a final uncertainty estimate. As the components link in a non-linear way this will be an approximation. The residual mean squares associated with the models are shown in Table 2.15.

Table 2.15 Residual means squares (prediction error) associated with models of log-D100, $\sqrt[3]{\text{Biomass}}$ and Shoot numbers

Model	Willow	Poplar
log-D100	0.030	0.052
$\sqrt[3]{\text{Biomass}}$	0.258	0.0319
Shoot numbers	52.4	25.0

Combining this information requires a number of assumptions about the independence of the errors and the relationship between errors and the model values. Combining the errors using a Taylor's series approximation gives an estimated coefficient of variation for the predicted shoot dry weights of about 40%. However, as the yield will be the sum of a large number of shoots the between shoot percentage error will be reduced while the between site error will not. From Table 2.15 it would be reasonable to assume that about 30% of the error is between sites. So for a large number of shoots (i.e. >10,000) the coefficient of variation would be approximately 12%. Thus, an approximate estimate of the error in a prediction is ±25%.

2.3. Software realization of models

The models were combined using the process described above. The individual functions to calculate the predicted model values from their inputs were coded in C. The functions were composed from the coefficients extracted from GenStat. These functions were then tested using results generated by GenStat for the fitted models.

It was decided to not include poplar clones 11, 12 and 13 (v710091, v710151 and v710092) in the model software because of their universally poor performance in the field and lack of commercial interest.

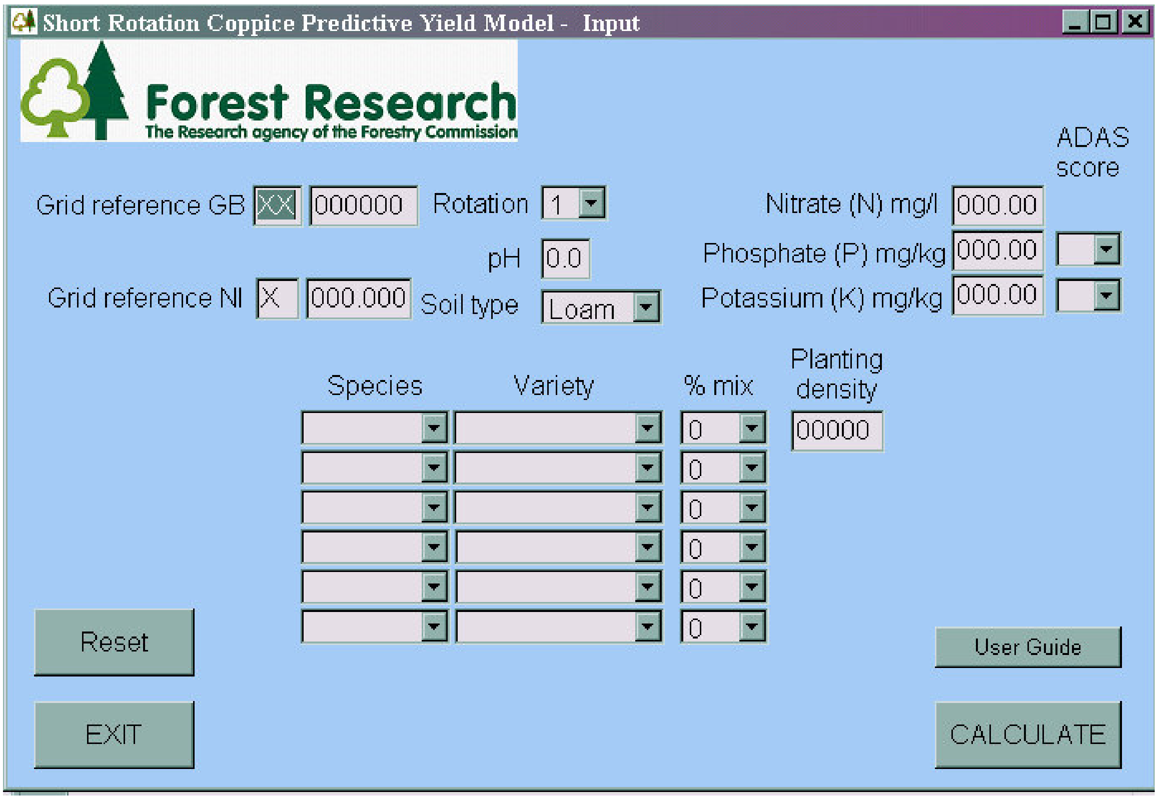
The list of functions used to perform the model calculations is given in Appendix G and the structure of the model, in terms of these functions, is given in Appendix H.
A mock up of a possible user interface was produced and demonstrated to industry stakeholders and other research groups. Feedback from these meetings helped to shape the function and look of the final product. Further details of the software are available in Appendix P.

A screen shot of the input page of the user interface is shown in Figure 2.12. By using drop down menus and entering data into input windows the user supplies the following information:

- Grid reference
- Soil type (from a choice of sand, loam or clay)
- Soil pH
- Rotation (either 1 or 2)
- Coppice species (from a choice of either poplar or willow)
- Variety (from a choice of 16 willow or 13 poplar varieties)
- The proportion of each variety within the plantation
- Planting density

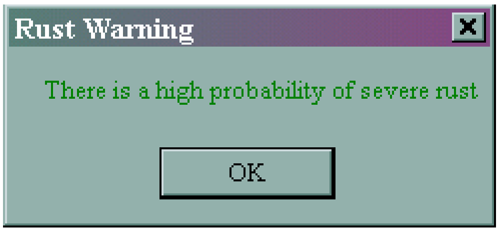
If the user know the N, P and K content of the site's soil, this may be entered. After this information has been entered the user clicks the 'CALCULATE' button.

Figure 2.12 Input page of the user interface of the predictive yield model



If the site and varieties chosen by the user are likely to suffer from high levels of rust infection, a pop up warning box appears, as shown in Figure 2.13

Figure 2.13 Pop up warning alerting the user to the likelyhood of serious rust infection on the site and varieties specified in the input form.

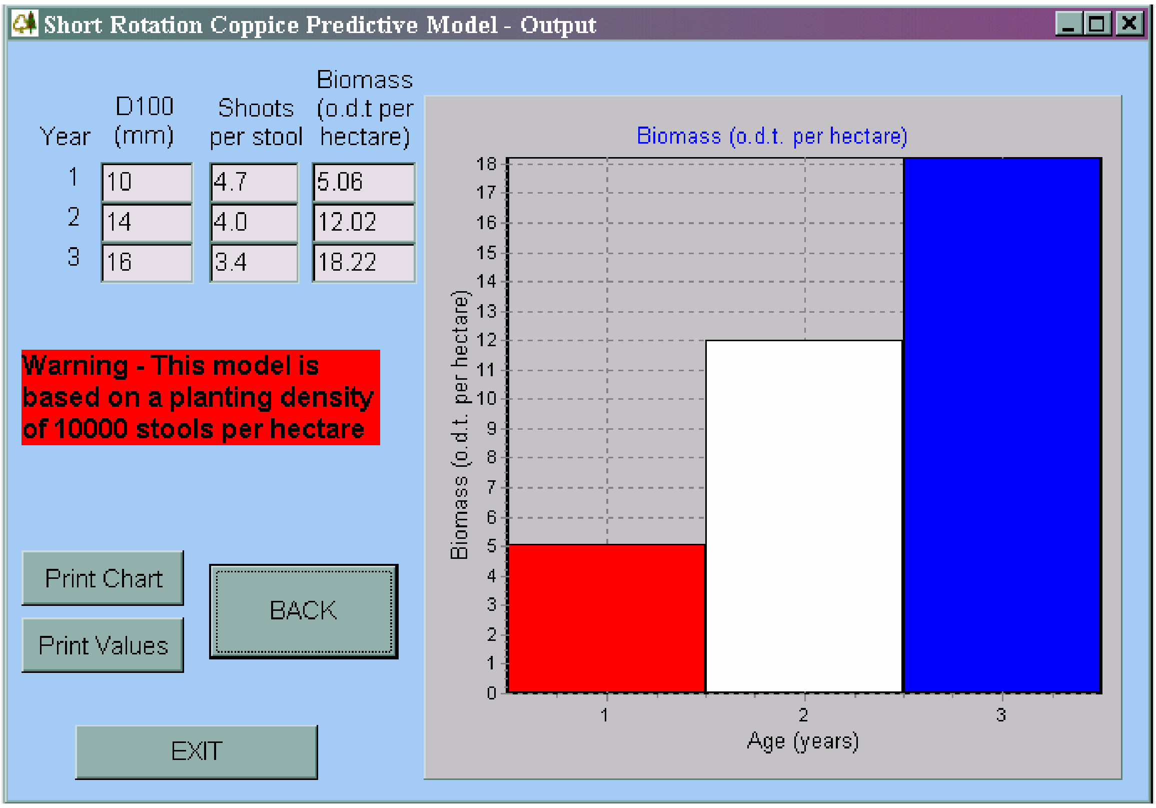


The output page of the software presents the following information for the site and varieties specified by the user:

- Standing biomass (odt ha^{-1})
- Number of shoots per stool
- Average shoot diameter at 1 m above ground level (D100)

This data is presented for each year of the rotation specified by the user.

Figure 2.14 Screen shot of the output page of the predictive yield model software



2.4. Validation of model and software

The individual components of the model were validated at the model fitting stage and their implementation at the software development stage, as described above. Further global validation was performed by checking the results of the model against the data used within the project. This constitutes an implementation validation and would show any gross errors in the translation of the fitted model into the software. None were found.

Because of the small area of SRC currently planted in Britain it proved difficult to obtain yield information from commercial plantations established using sites and varieties similar to those used during this research programme. Therefore comprehensive comparison of predicted and commercially realised yields was not possible. However, a limited amount of model validation has been carried out using data kindly supplied by Coppice Resource Limited. Details of 13 commercial SRC plantations were supplied to model developers for comparison with model output. Of these, five plantations could be broadly simulated using the predictive model described here. Details of the commercial plantations used in this exercise are shown in Table 2.16. The data were supplied as 'yield per year' and therefore equal yields per year are assumed throughout the rotation. The predictive model does not make this assumption and the modelling results presented are the final year cumulative yield divided by the number of years in the rotation.

Table 2.16 Details of site and used during model validation

Location	Crop age	Yield odt.ha^{-1}yr^{-1}	Variety mix	Soil type
Retford (A)	3	7.47	Bowles, Tora, Jorr, Jorrun, Orm, Ulv	reclaimed sand
Retford (B)	2	10.9	Bowles, Tora, Jorr, Jorrun, Orm, Ulv	reclaimed sand
Lound	3	6.91	Tora, Jorr, Jorrun, Orm, Ulv	reclaimed sand
Retford (C)	3	9.43	Bowles, Tora, Jorr, Jorrun, Orm, Ulv	clay
East Stockwith	3	7.17	Bowles, Tora, Jorr, Jorrun, Orm, Ulv	sand/loam

The model was run two times. On each occasion slightly different assumptions were made about site conditions and the proportion of each variety within the plantation. No information on pH or soil NPK content was available. Soil pH was assumed to be 6 and the model was run in the ‘no NPK data’ mode. Like wise no grid reference was available for these sites so the grid reference of the nearest town was used.

It should be noted that the predictive model could not accommodate Bowles Hybrid. This is a relatively low yielding variety. In the model, its place was taken by increasing the proportions of other varieties present within the plantations. As a result, it was thought likely that the model would over estimate yield.

The assumptions used in the two model runs were:

Case 1 – each variety was assumed to account for 20% of the total crop area
Case 2 – it was assumed that Tora made up 60% of the plantation area, Jorunn, Ulv, Jorr and Orm accounted for 10% each.

Predicted and observed results are shown in the Table 2.17. The predictions were within 1.0 and 6.5 odt ha^{-1}yr^{-1} of the observed yields, depending on site and set of assumptions used. For case two, three of the sites give acceptable results within the expected prediction error of ±25%. The remaining two (Retford A & Lound) are more extreme. For Lound, it was known that the plantation was subject to damage by browsing geese and this may have led to the large difference between the observed and predicted yields.

The first Retford site (A) observed yield seems to be out of line with the two other Retford values. It gives a total yield of 22.5 odt ha^{-1} for the 3 years, which is similar to the yield provided at Retford (B) for only a 2 year rotation (21.8 odt ha^{-1}). Conversely, the total yield for 3 years at Retford (C) is 28.2 odt ha^{-1}. It may be possible that further information about Retford (A) could explain this apparent reduction in observed yield.

Further data from commercial plantations established on agricultural, rather than reclaimed, land is currently being sought in order to carry out more validation checks.

Table 2.17 Comparison of observed and predicted SRC yield at five sites

Location	Cutting Cycle (Rotation)	Shoot Age (years)	Observed yield odtha^{-1}yr^{-1}	Predicted yield odtha^{-1}yr^{-1}		Absolute error (odtha^{-1}yr^{-1})		Prediction Percentage error	
				Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Retford (A)	1	3	7.5	12.6	12.1	-5.1	-4.7	-40.6	-38.4
Retford (B)	2	2	10.9	9.5	9.9	1.4	1.0	14.9	10.2
Lound	1	3	6.9	13.4	12.8	-6.5	-5.9	-48.4	-45.9
Retford (C)	1	3	9.4	11.8	11.1	-2.3	-1.7	-19.8	-15.3
East Stockwith	1	3	7.2	9.9	9.2	-2.7	-2.0	-27.5	-22.1

3. Summary of standing biomass estimates.

3.1. Extensive willow varieties

Yield estimates for over 2800 site, variety and age combinations were generated. A predictive yield model with fixed site effects was used to generate these estimates (see section 2.1.1 Modelling Stage A2). A complete set of these yield estimates is presented in Appendices K, L, M, N. A summary of mean standing biomass estimates for the three extensive willow clones grown at all 49 sites is shown in Table 3.1. Jorunn was the most vigorous variety in the first cutting cycle achieving an average annual increment of 9.6 $odtha^{-1}yr^{-1}$ compared to 7.5 and 7.4 $odtha^{-1}yr^{-1}$ achieved by Germany and Q83. Although growth rates of all three varieties in the first year of the second rotation were noticeable higher than that achieved in the first year of the first cutting cycle this increase was not repeated in subsequent growing seasons by either Jorunn or Germany. Only Q83 maintained an increased growth rate throughout the second cutting cycle producing an average of 9.9 $odtha^{-1}yr^{-1}$. This is equivalent to an increase of 7.5 $odtha^{-1}$ by the end of the second cutting cycle. Variations around these mean, annualised figures are large, for example at the end of the third year of the first cutting cycle Jorunn stood at 12.5$odtha^{-1}$ at the least compatible site and 42.6 $odtha^{-1}$ at the most compatible. At the end of the second cutting cycle worst and best yields achieved were 8.7 and 47.9 $odtha^{-1}$ respectively.

Table 3.1 Summary of mean standing biomass estimates for three willow clones established at 49 sites

	Standing biomass (oven dry tonnes per hectare)					
Variety	Cutting cycle 1, age 1	Cutting cycle 1, age 2	Cutting cycle 1, age 3	Cutting cycle 2, age 1	Cutting cycle 2, age 2	Cutting cycle 2, age 3
Jorunn	6.9	18.7	28.8	12.4	20.4	29.0
Germany	4.6	13.3	22.5	7.0	12.7	23.8
Q83	4.5	13.2	22.1	10.4	19.6	29.6

3.2. Intensive willow varieties

Some willow varieties planted at the larger Intensive sites achieved significantly higher yields than those achieved by the three extensive willow varieties. When data from all seven intensive sites are pooled, the three most productive willow varieties at the end of the first cutting cycle were Stott 10, Stott 11 and Tora (Table 3.3). Each of these varieties achieved an average annual increment of around 10 $odtha^{-1}yr^{-1}$. These varieties were bred specifically for use in SRC energy plantations and were not commercially available at the time this project commenced. However, by the end of the second cutting cycle the performance of Stott 10 and Stott 11 had slipped significantly when compared to many of the other varieties tested. Stott 10 was one of the two varieties that achieved a lower average standing biomass in the second cutting cycle than in the first. This may be due to increased susceptibility to rust or stem aphid attack and brings into question the long term reliability of this variety. Although the average figures are poor, Stott 10 did perform well in the second cutting cycle at sites in North East England, Fife and South Wales.

Table 3.2 Mean standing biomass achieved by 16 willow varieties grown at seven Intensive experiment sites

	Standing biomass (oven dry tonnes per hectare)					
Variety	Cutting cycle 1 shoot age 1	Cutting cycle 1 shoot age 2	Cutting cycle 1 shoot age 3	Cutting cycle 2 shoot age 1	Cutting cycle 2 shoot age 2	Cutting cycle 2 shoot age 3
v789	5.8	10.5	18.0	8.2	13.3	20.6
Germany	6.7	14.7	25.0	7.2	12.6	24.9
Dasyclados	6.8	14.6	21.1	8.1	15.5	25.0
Ulv	5.8	15.8	24.0	10.7	18.0	26.4
Jorunn	6.1	17.7	25.3	11.8	19.4	27.2
Orm	6.0	17.1	26.3	10.0	18.9	28.8
Stott 10	7.3	20.6	31.2	9.5	17.0	28.8
Q83	4.0	13.7	22.0	11.0	18.4	29.6
Delamere	3.8	14.5	23.4	9.7	18.8	29.6
Jorr	5.9	17.4	28.4	10.1	19.1	31.0
ST248155	5.7	12.8	22.3	11.1	19.5	31.3
Spaethii	4.5	14.2	23.8	10.7	19.8	32.0
Stott 11	6.8	20.5	31.5	10.9	20.1	33.3
Bebbiana	3.8	13.6	21.9	8.6	19.9	33.9
Bjorn	5.4	14.9	23.8	9.4	21.4	36.1
Tora	6.5	18.1	29.7	11.0	25.0	44.6
mean	*5.7*	*10.3*	*14.6*	*9.9*	*8.7*	*21.5*

The varieties Bjorn and Tora have also been planted commercially and Tora especially has proved to be a reliable performer (Hilton et al., 2005). Results achieved in these trials suggest that Tora is capable of achieving high yields at a wide range of sites. At the end of the second cutting cycle, at the most compatible site (site 4, near Cambridge), Tora achieved a standing biomass of 60 $odtha^{-1}$ at and yields of over 30 odtha-1 at the remaining 6 intensive sites. The older variety, Bebbiana performed well in the second cutting cycle despite a relatively slow start in the first cutting cycle. Interestingly this variety did not perform as well at site 4 as it did at sites 1, 7 and 3 (Fife, Brecon and Alice Holt) where yields of around 40 odtha-1 were achieved at the end of the second cutting cycle.

3.3. Summary of willow yield achieved in each of the countries.

Results from the field trials show that combinations of site and willow varieties capable of producing in excess of 10 odtha-1yr-1 exist in England, Scotland, Wales and Northern Ireland. The minimum, mean and maximum yields achieved by willow SRC at trials in each country are summarised in Table 3.3. By the end of the second cutting cycle 21 out of 37 (56%) site/variety combinations tested in Scotland achieved yields in excess of 10 odtha-1yr-1. Site 2, established on sheep pasture in Fife was particularly well suited to willow SRC, 13 out of the 16 varieties planted exceed the 10 odtha-1yr-1 benchmark in the second cutting cycle. Growth at this site was very poor during the first year of establishment, possibly as a result of root browsing by cranefly larvae (leatherjackets). As a result, cutback was delayed by one year. In Wales 16 site and variety combinations (40%) produced more that 10 odtha-1yr-1 in the second cutting cycle. Two combinations matched this level of productivity in the second cutting cycle in Northern Ireland although only three trials were established. In England 66 site/variety combinations (47%) exceeded 10 odtha-1yr-1.

Table 3.3 Minimum, mean and maximum standing biomass achieved by site/willow variety combinations in each country

		Standing biomass (oven dry tonnes per hectare)					
		Cutting Cycle 1 age 1	Cutting Cycle 1 age 2	Cutting Cycle 1 age 3	Cutting Cycle 2 age 1	Cutting Cycle 2 age 2	Cutting Cycle 2 age 3
Scotland (37 site/variety combinations)	min	0.6	3.7	15.2	0.8	3.6	8.9
	mean	6.2	19.7	27.9	10.6	18.4	32.5
	max	12.5	38.2	43.8	16.9	26.3	47.5
Wales (40 site/variety combinations)	min	1.4	3.3	8.7	1.3	1.1	2.1
	mean	4.9	12.6	20.8	9.7	18.0	26.8
	max	11.4	25.6	36.9	16.9	32.0	48.0
N. Ireland (22 site/variety combinations)	min	2.5	5.9	10.2	3.2	6.0	9.9
	mean	5.9	16.4	23.3	7.1	14.5	21.4
	max	9.7	25.6	33.3	12.0	22.3	31.2
England (139 site/variety combinations)	min	0.2	0.9	0.0	0.0	0.0	0.0
	mean	5.3	14.5	24.7	10.0	18.3	29.4
	max	23.6	32.9	49.0	21.6	34.3	60.2

3.4. Extensive poplar varieties

In the first cutting cycle yield achieved by the three extensive poplar varieties grown at all 49 sites was broadly comparable to that of the willows (Tables 3.1 and 3.2). Trichobel performed well, achieving an average increment of 9.1 odtha^{-1}yr^{-1}. Variation around mean standing biomass and annual increment estimates were again very large. By the end of the first cutting cycle Beaupre had died at site 2 in South West England, probably as a result of infection by *Melampsora* spp. rust fungus. All three poplar varieties died in the first cutting cycle at site 47, also in South West England. The most likely cause of death at this site was heavy water logged soils. At the other extreme Trichobel achieved a standing biomass of more than 40 odtha^{-1} by the end of the first cutting cycle at three sites in England. On average, neither Beaupré nor Ghoy performed as well in the second cutting cycle as they did in the first. The decrease in productivity of Beaupré, and to a lesser extent Ghoy, fits in with the increase in both the incidence and severity of *Melampsora* spp rust recorded on this variety (see figure 4.11 and 4.12).

Table 3.4 Summary of mean standing biomass estimates for three poplar clones established at 49 sites

	Standing biomass (oven dry tonnes per hectare)					
Variety	Cutting cycle 1, age 1	Cutting cycle 1, age 2	Cutting cycle 1, age 3	Cutting cycle 2, age 1	Cutting cycle 2, age 2	Cutting cycle 2, age 3
Beaupre	4.9	14.0	21.1	4.8	10.3	13.5
Ghoy	4.0	12.0	19.0	4.9	11.7	16.7
Trichobel	4.2	14.1	27.2	6.4	16.5	27.7

3.5. Intensive poplar varieties

The *Populus trichocarpa* varieties, Trichobel and Fritzi Pauley were the most reliable poplar varieties grown at the intensive sites (Table 3.5). The *Populus trichocarpa x*

Populus deltoides varieties v710092, v710091 and v710151 performed poorly, especially at sites in the southern half of the England. Other *Populus trichocarpa x Populus deltoides* varieties such as Beaupre, Boelare, 690386 and 690394 performed well in the first cutting cycle but declined in the second. These varieties became infected with a pathotypes of *Melampsora larici-populina* previously unrecorded in the UK. This disease is the likely cause of crop failure at site 2 during the course of this research programme and at sites 4 and 7 in the third cutting cycle. The *Populus deltoides x Populus nigra* varieties Ghoy, Gaver and Gibecq also declined slightly in the second cutting cycle.

Table 3.5 Mean standing biomass achieved by 16 willow varieties grown at seven Intensive experiment sites

	Standing biomass (oven dry tonnes per hectare)					
Variety	Cutting cycle 1 shoot age 1	Cutting cycle 1 shoot age 2	Cutting cycle 1 shoot age 3	Cutting cycle 2 shoot age 1	Cutting cycle 2 shoot age 2	Cutting cycle 2 shoot age 3
Beaupre	4.0	12.0	17.2	3.4	7.9	11.6
Ghoy	3.6	10.5	16.9	3.8	8.9	14.4
Trichobel	3.9	14.0	25.3	5.8	14.3	25.9
Boelare	5.2	13.7	19.4	4.0	9.4	13.8
Unal	3.7	11.0	16.0	2.4	5.7	8.9
Raspalje	4.8	14.0	20.1	3.5	8.5	14.2
Gaver	4.2	12.4	19.8	4.8	11.4	17.3
Gibecq	3.8	11.1	17.1	3.6	8.8	14.8
690386 (Hoogvorst)	3.7	14.5	26.5	4.6	11.8	19.4
690394 (Hazendans)	2.9	11.4	21.7	4.4	10.9	17.0
710091	1.6	5.7	8.3	1.5	2.6	5.4
710151	3.6	9.7	14.9	3.1	7.4	12.5
710092	2.6	7.8	12.7	2.6	6.3	10.5
Columbia	3.2	11.9	20.1	4.9	12.0	20.8
TT32/Balsam Spire	2.8	12.2	21.7	5.1	14.0	22.3
Fritzi Pauley	3.3	13.5	25.8	4.7	13.2	25.5

3.6. Summary of poplar yield achieved in each of the countries.

First cutting cycle yields of around 10 odtha-1yr-1 were achieved by the most productive combinations of poplar varieties and site in Scotland, Wales and England. Productivity in Northern Ireland was considerably lower, the best site and variety combination produced less than 7 odtha-1yr-1 in the first cutting cycle. Mean yield in the third year of the second cutting cycle was considerably reduced compared to yield in the third year of the first cutting cycle in all countries. It is likely that infection by *Melampsora* spp. rust fungus played a significant part in this reduction especially in England, Wales and Northern Ireland. Sites and varieties in Scotland suffered lower incidences of rust although second cutting cycle yield was still slightly reduced. In England one of the most reliable varieties test was Trichobel. Nine out of the ten highest yielding site/variety combinations in the third year of the second rotation contained Trichobel. In Wales seven out of the ten most productive combinations contained Trichobel. In Scotland Trichobel only appeared twice in the ten most productive combinations, possibly as a result of reduced disease pressure allowing other faster growing but less disease tolerant varieties to perform well.

Table 3.6 Minimum, mean and maximum standing biomass achieved by site/poplar variety combinations in each country

		Standing biomass (oven dry tonnes per hectare)					
		Cutting Cycle 1 age 1	Cutting Cycle 1 age 2	Cutting Cycle 1 age 3	Cutting Cycle 2 age 1	Cutting Cycle 2 age 2	Cutting Cycle 2 age 3
Scotland (37 site/variety combinations)	min	0.0	2.9	9.7	1.7	5.3	0.0
	mean	3.5	14.9	25.2	4.7	13.7	24.6
	max	7.4	24.9	37.3	8.1	22.6	33.9
Wales (40 site/variety combinations)	min	1.2	4.6	5.2	0.8	1.8	2.4
	mean	3.9	13.6	21.3	4.8	10.6	17.1
	max	6.7	22.7	38.7	9.7	25.9	42.3
N. Ireland (22 site/variety combinations)	min	2.9	8.8	10.5	0.7	0.9	0.9
	mean	5.0	13.3	18.1	4.4	7.5	9.7
	max	7.1	15.7	20.6	7.9	12.7	17.6
England (139 site/variety combinations)	min	0.3	0.0	0.0	0.0	0.0	0.0
	mean	4.0	11.7	20.1	5.0	11.8	18.2
	max	12.5	25.3	44.5	11.6	27.4	42.2

3.7. Yield maps of willow and poplar varieties

In order to present the yield data from 49 sites in an easy-to-interpret manner colour coded maps of the UK were generated using standing biomass estimates for the three willow and three poplar varieties planted at all 49 trial sites. 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. Standing biomass estimates were assigned different colours according to their magnitude or ‘yield class’. Five yield classes were used:

Very poor	=	< 3 odtha^{-1}
Poor	=	3 - < 6 odtha^{-1}
Moderate	=	6 - < 9 odtha^{-1}
Good	=	9 – 12 odtha^{-1}
Very Good	=	> 12odtha^{-1}

The upper and lower limits of these classes were multiplied by the age of the coppice shoots i.e. a ‘Good’ coppice crop in the second growing season of either the first or the second cutting cycle would be standing at 18 - <24 odtha^{-1}. These yield classes were fixed at the levels described after provisional analysis of the standing biomass estimates, expectations of commercial growers and field experience had been taken into account. One map was produced for each site, variety and age combination. Data from sites established in phase 1 and phase 2 were pooled in order to provide sufficient points for reasonable coverage of the UK. Although the relatively small number of sites limits the resolution of the maps, sufficient data is available to pick up general trends in variations in yield amongst varieties, geographic location and crop ages. These maps are presented in Figures 3.1 to 3.9. In the first cutting cycle all three poplar varieties were generally more productive in the western half of the UK. This trend is most pronounced for Ghoy in the second year of the cutting cycle (Figure 3.8) and for

Trichobel in the third year (Figure 3.9). As the crop becomes more established and enters the second cutting cycle the east/west division remains but yield is higher in the east than the west. This is possibly as a result of *Melampsora* spp. rust infection becoming more prevalent in the west of the country and limiting yield (see rust distribution maps figures 4.5 to 4.16). By the end of the second cutting cycle it is clear that over most of the UK the varieties Beaupré and Ghoy are unlikely to provide an economically sustainable source of woodfuel when managed as short rotation coppice because of low yields and high disease loads.

Data shown in the maps generated for the three extensive willow varieties suggests that in the first year of the first cutting cycle productivity was generally poor in the north east of England. Productivity was higher in a band running through the central belt of Scotland and a second band running through north to mid Wales and extending into the east midlands and the south east England. Productivity in South West England was generally poor to moderate. In most areas Jorunn generally out performed the other varieties.

In the first year of the second cutting cycle Jorunn produced high levels of biomass throughout the UK and continued to produce good to moderate levels of biomass for the remainder of the cutting cycle. The performance of Germany was patchy in the second cutting cycle, at many sites this variety suffered some plant deaths and poor regrowth in the first year following harvest. Although achieving only moderate yield in the first cutting cycle, Q83 performed well in the second with good or very good yield recorded in the extreme South West, the Midlands, Northern England and large parts of Scotland.

Figure 3.1 Standing biomass yield maps of three willow clones, cutting cycle 1, shoot age 1

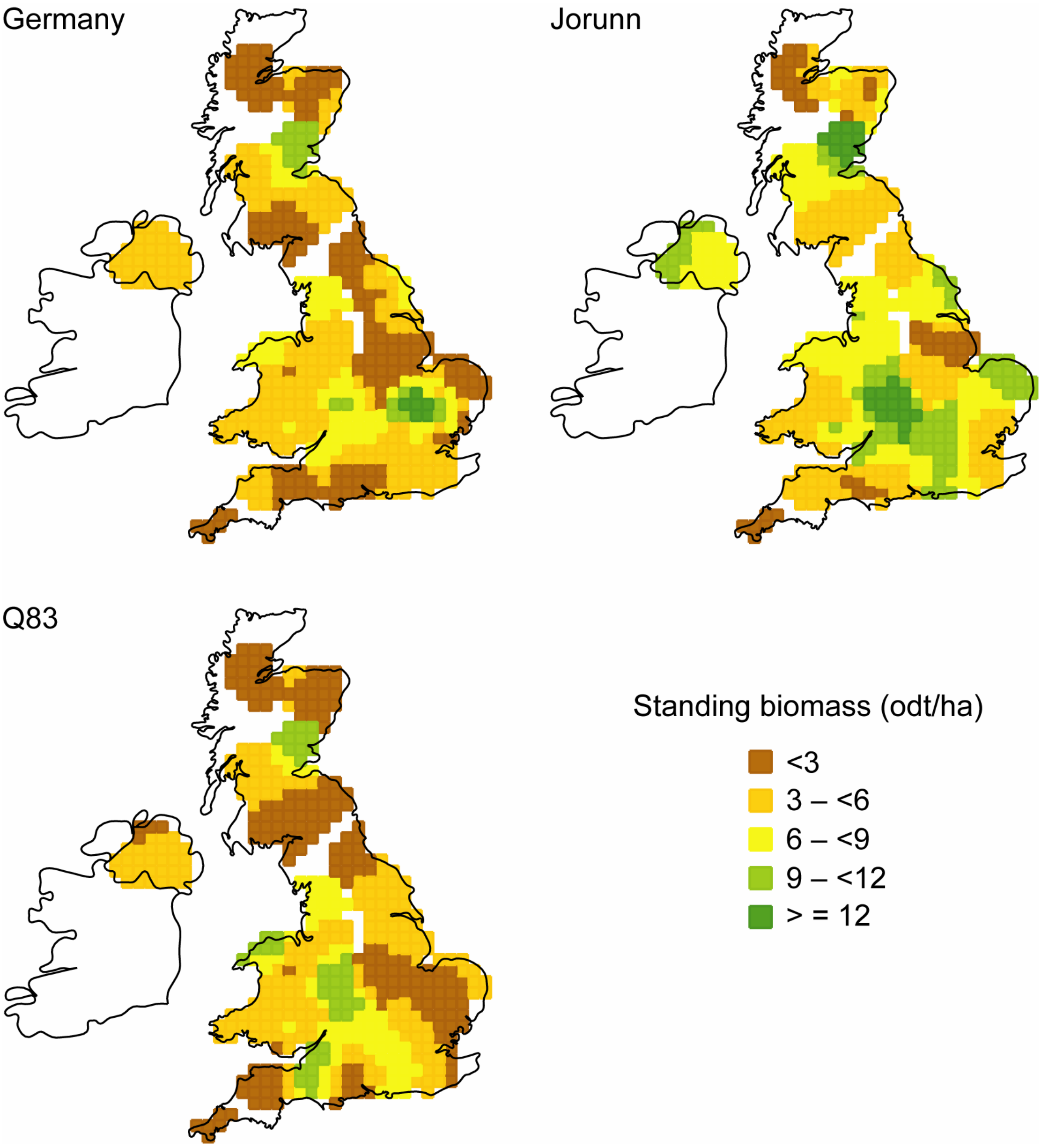


Figure 3.2 Standing biomass yield maps of three willow clones, cutting cycle 1, shoot age 2

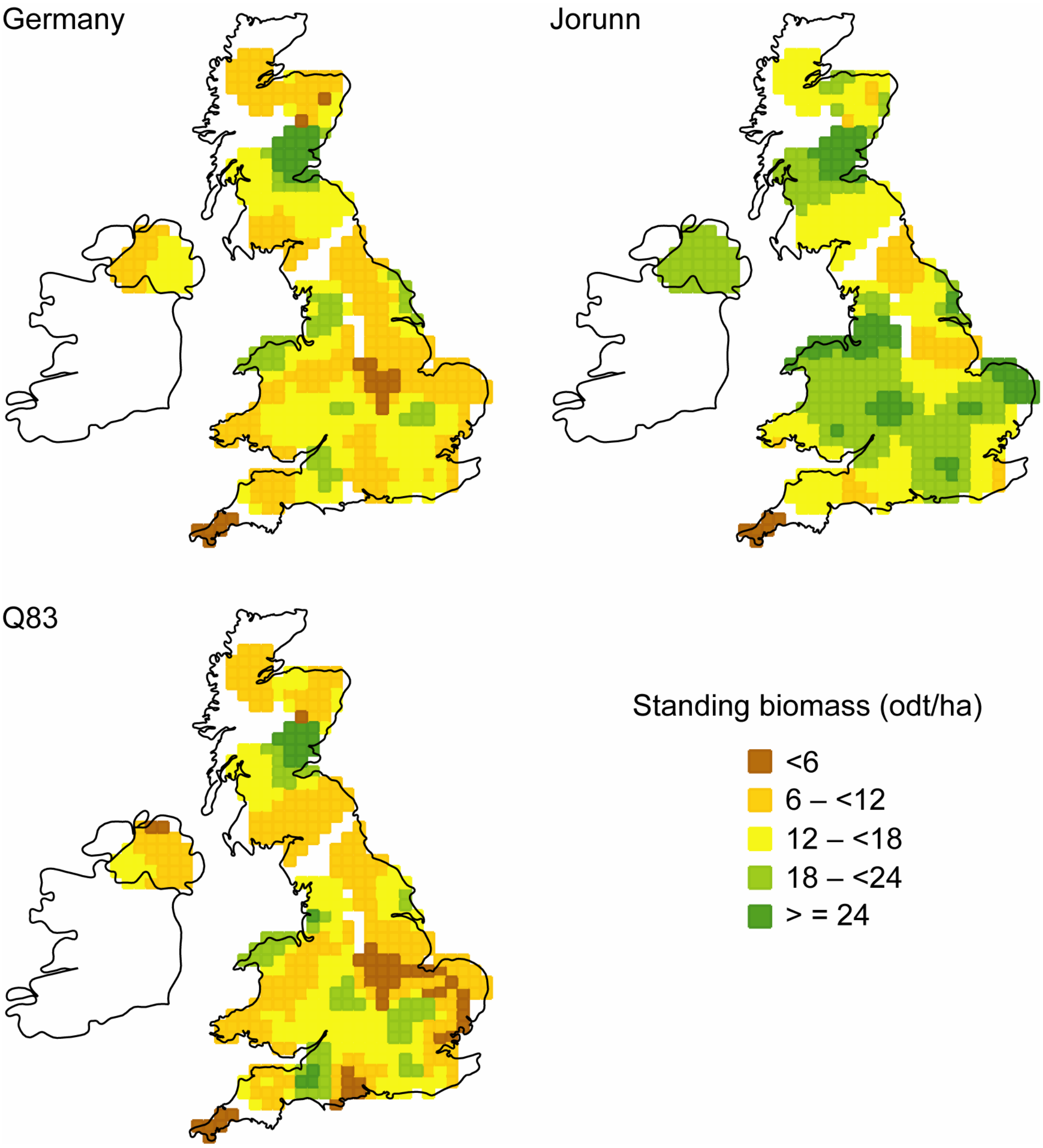


Figure 3.3 Standing biomass yield maps of three willow clones, cutting cycle 1, shoot age 3

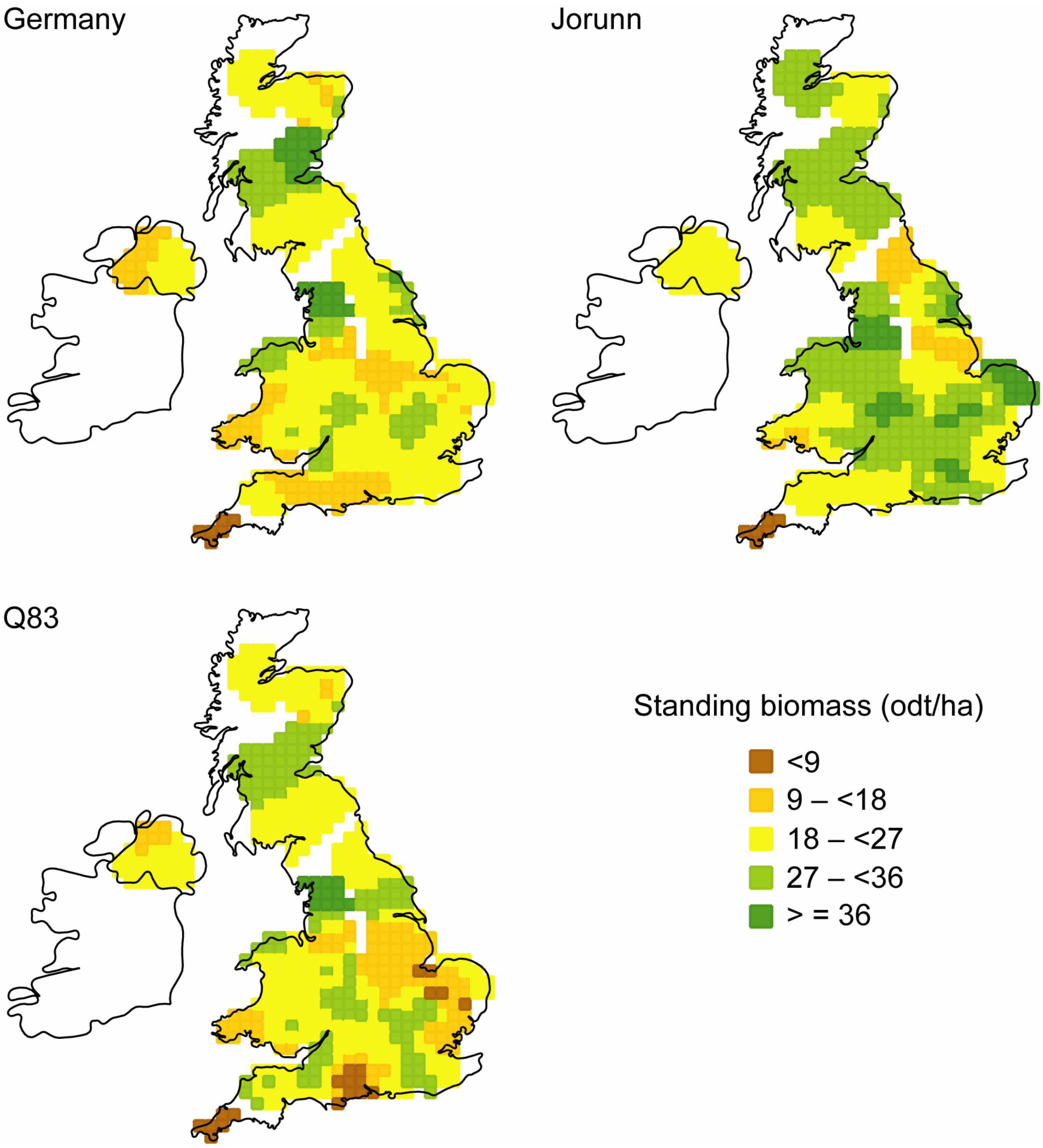


Figure 3.4 Standing biomass yield maps of three willow clones, cutting cycle 2, shoot age 1

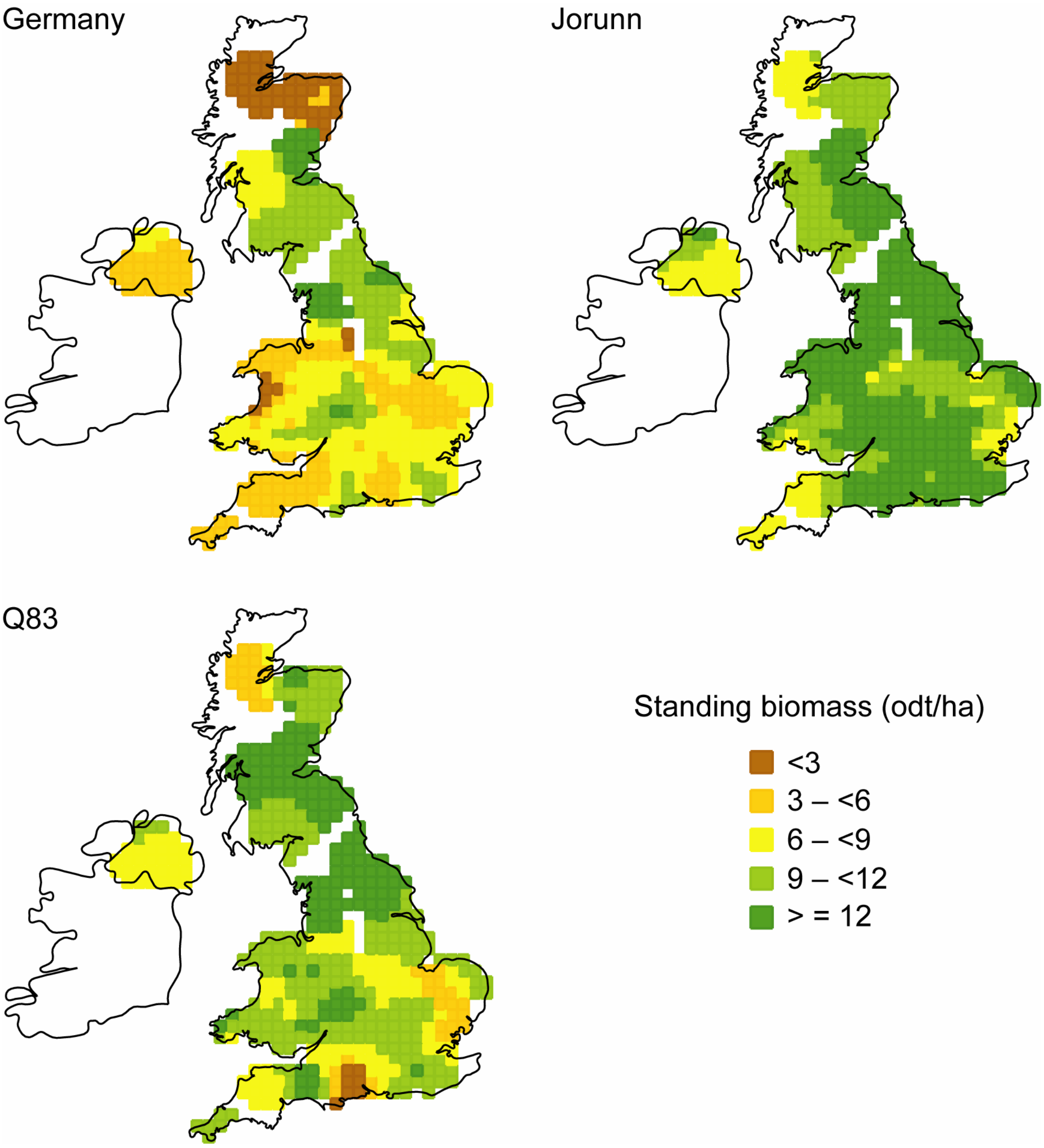


Figure 3.5 Standing biomass yield maps of three willow clones, cutting cycle 2, shoot age 2

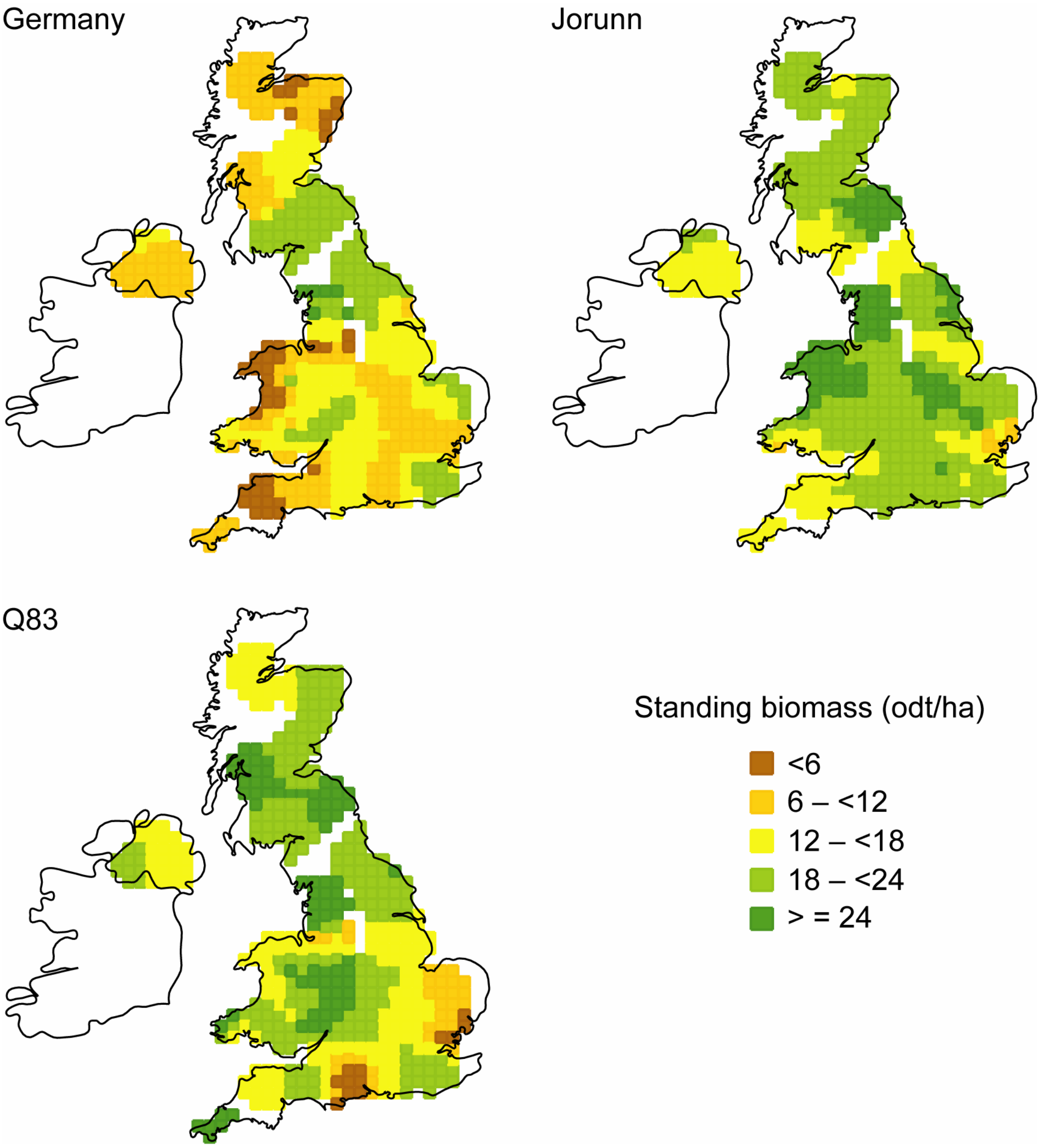


Figure 3.6 Standing biomass yield maps of three willow clones, cutting cycle 2, shoot age 3

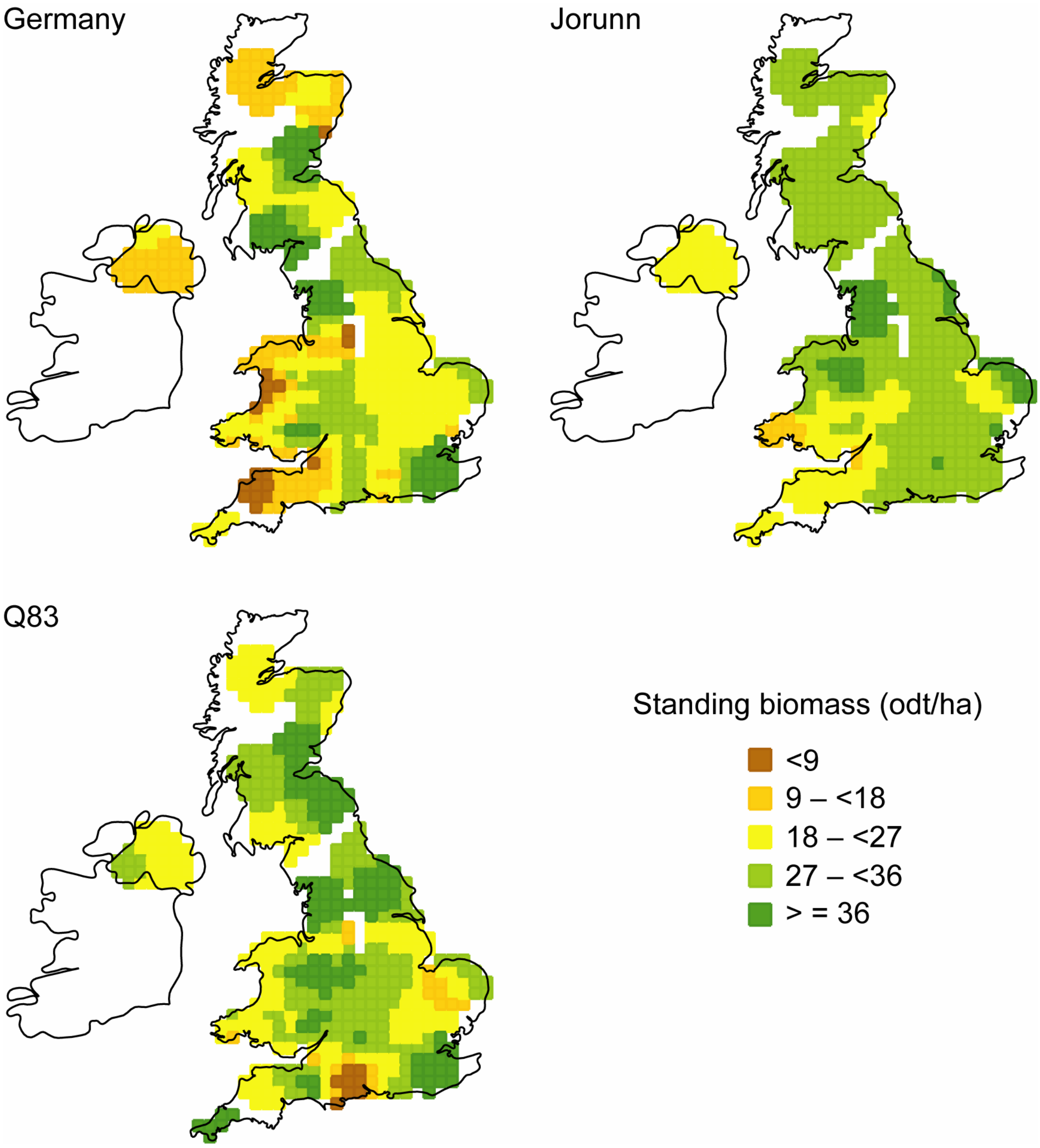


Figure 3.7 Standing biomass yield maps of three poplar clones, cutting cycle 1, shoot age 1

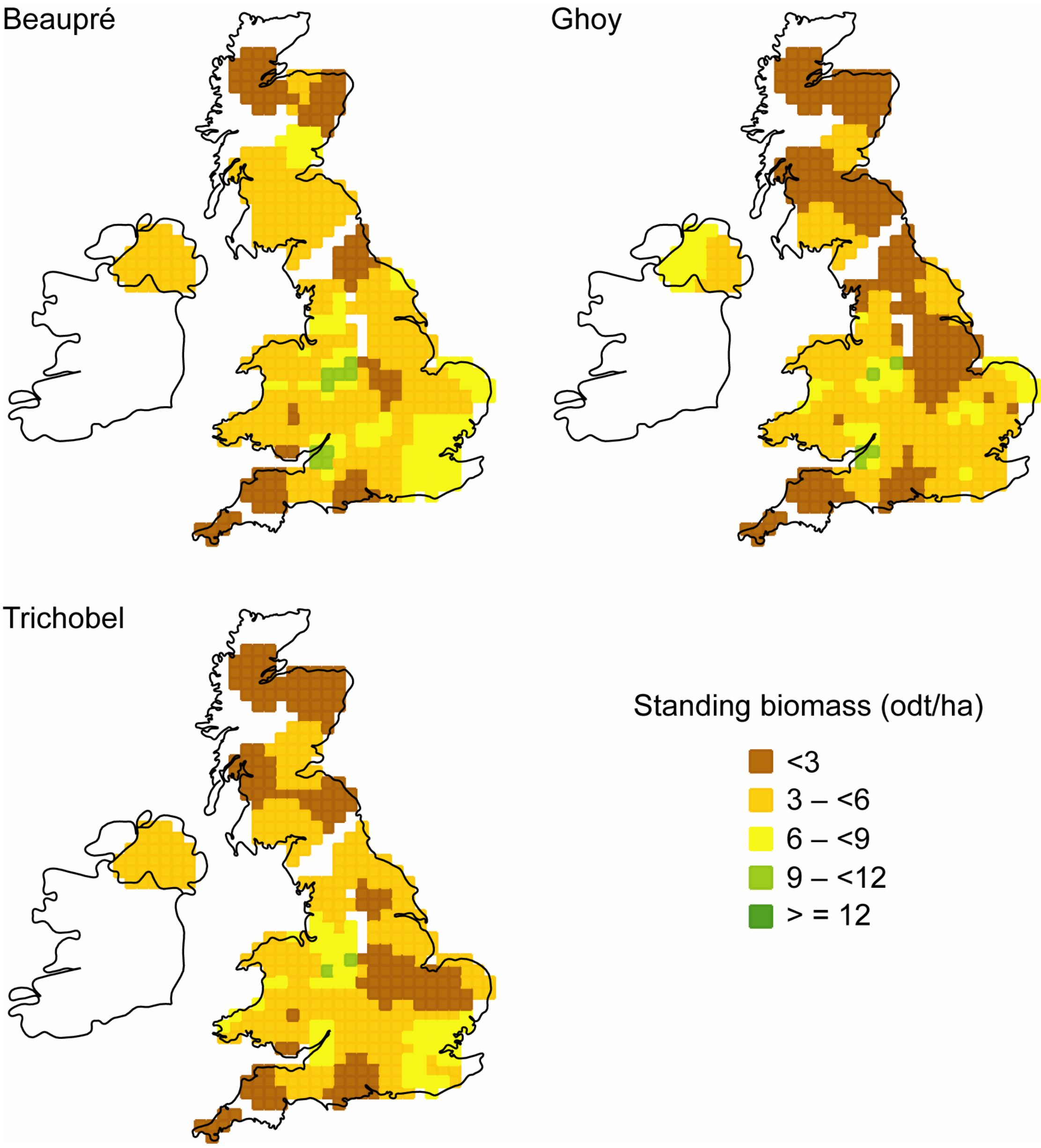


Figure 3.8 Standing biomass yield maps of three poplar clones, cutting cycle 1, shoot age 2

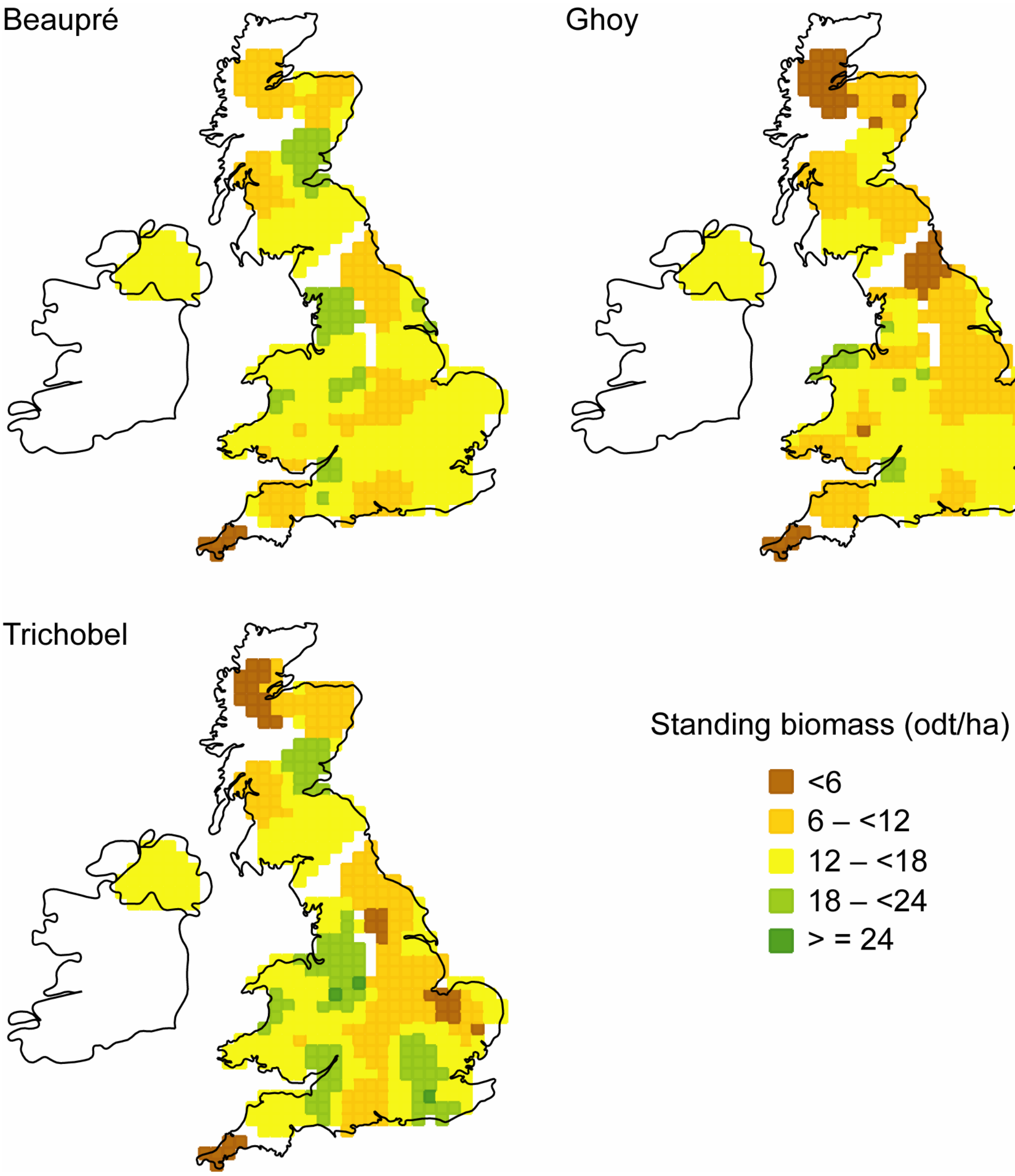


Figure 3.9 Standing biomass yield maps of three poplar clones, cutting cycle 1, shoot age 3

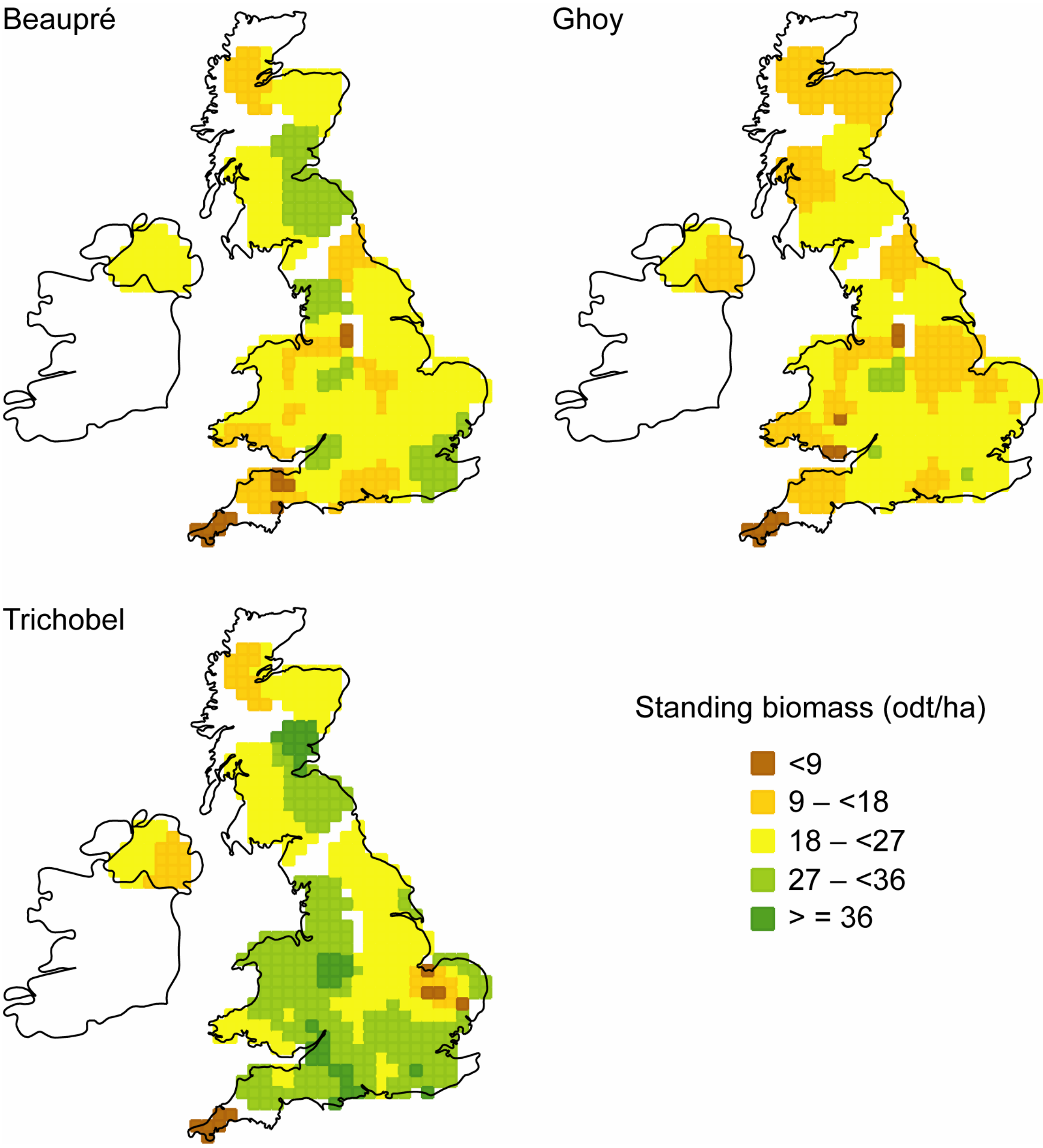


Figure 3.10 Standing biomass yield maps of three poplar clones, cutting cycle 2, shoot age 1

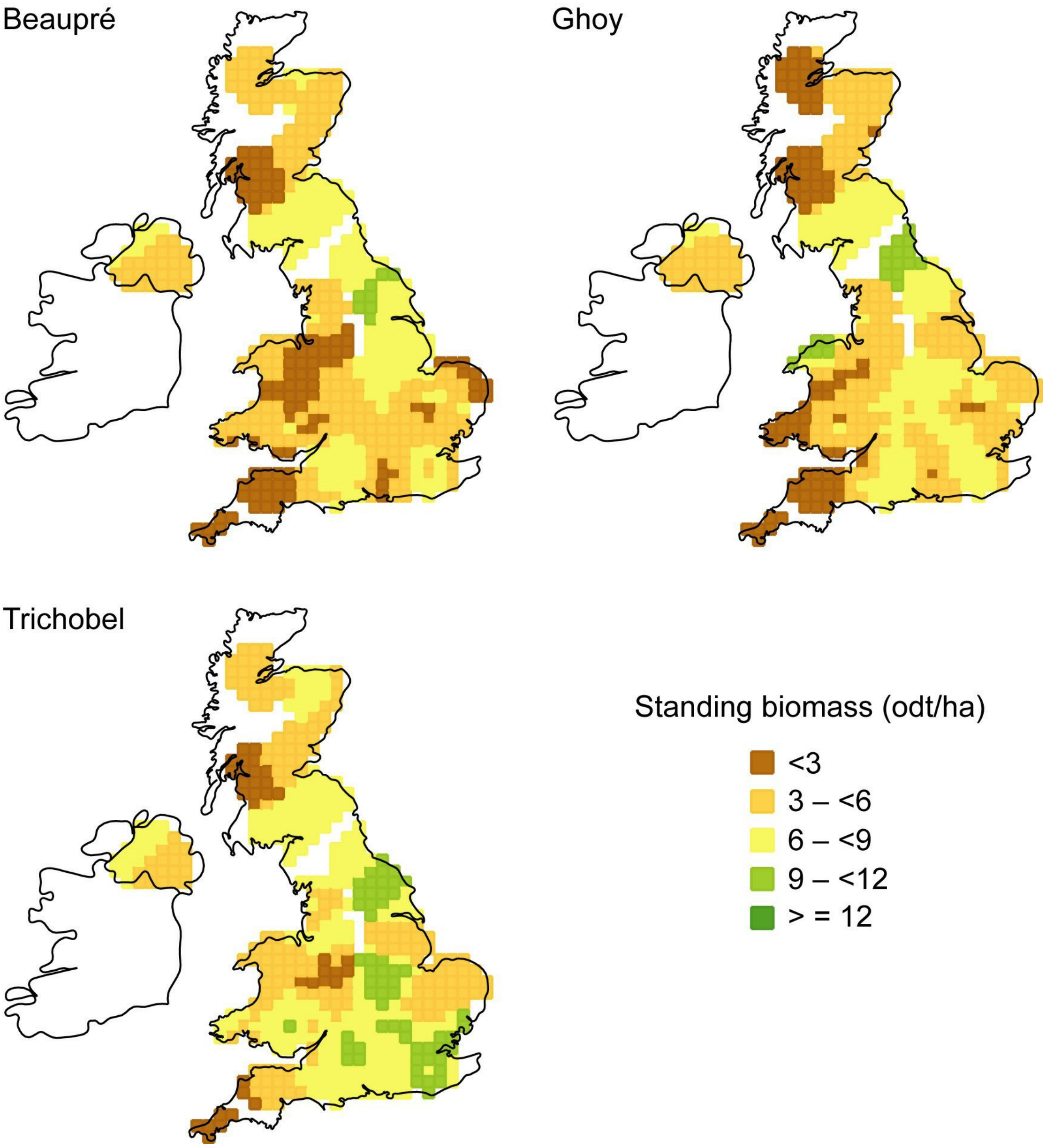


Figure 3.11 Standing biomass yield maps of three poplar clones, cutting cycle 2, shoot age 2

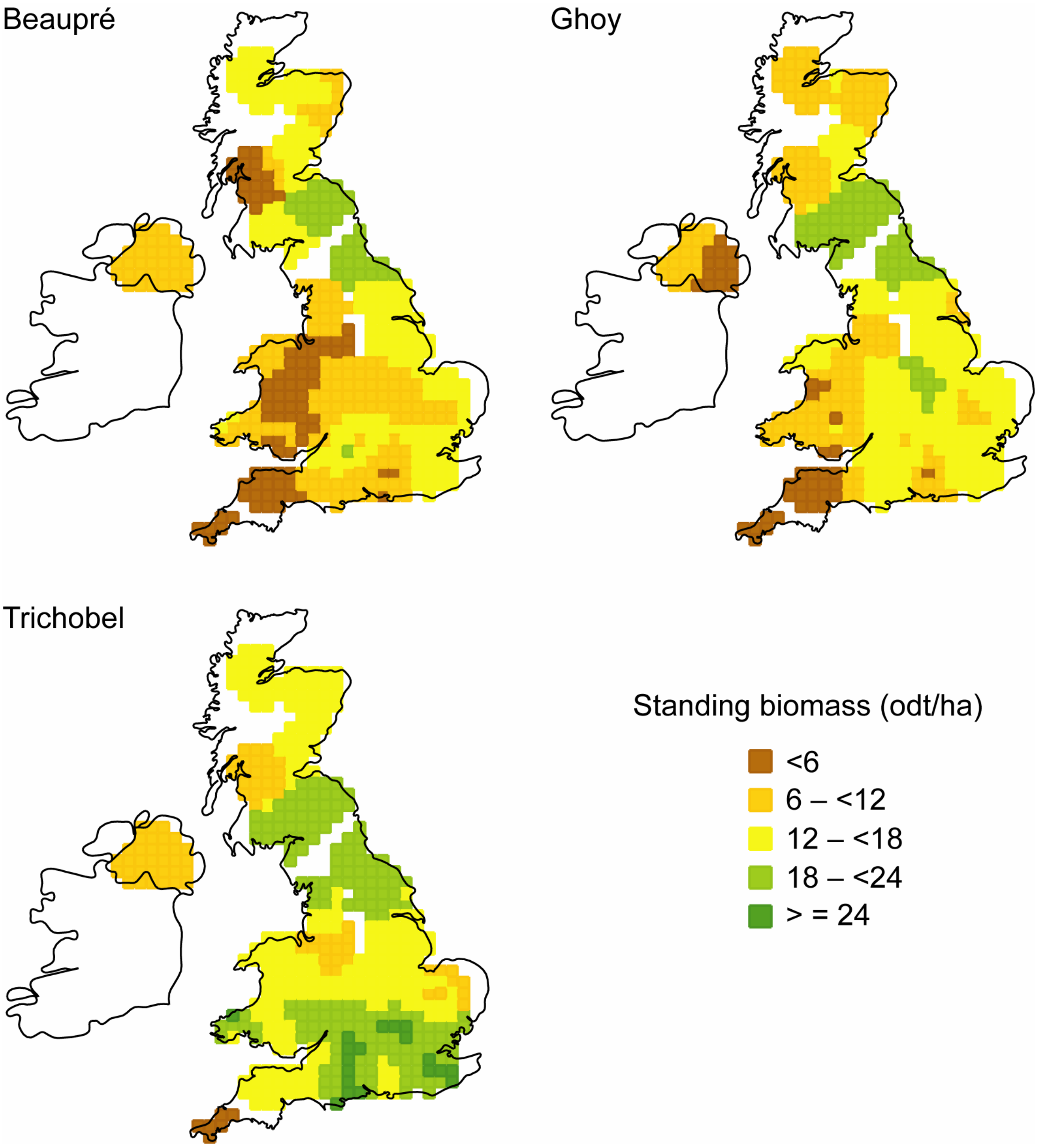
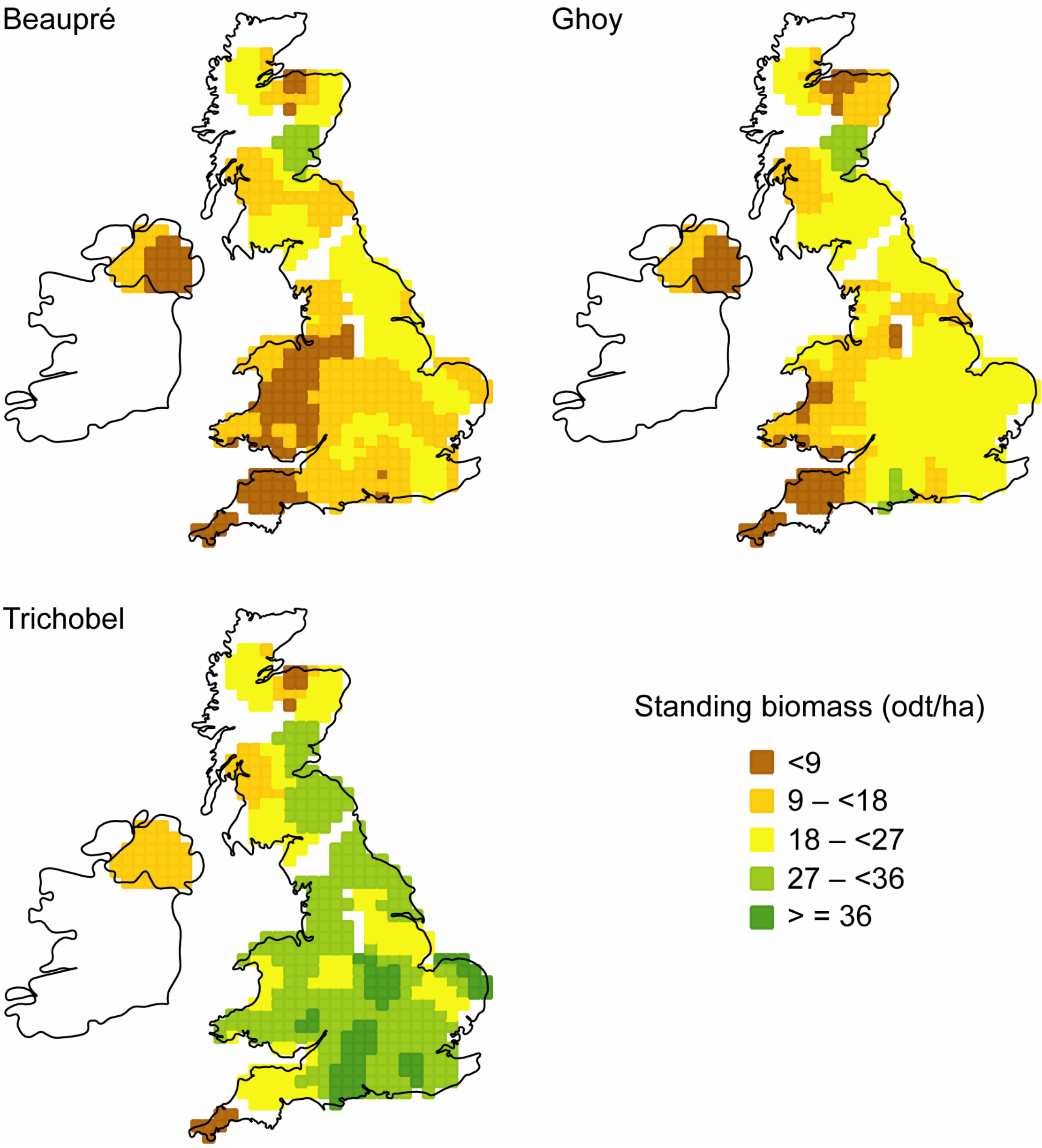


Figure 3.12 Standing biomass yield maps of three poplar clones, cutting cycle 2, shoot age 3



3.8 The effect of row mixtures on coppice growth

Commercial SRC plantations have been established using a mixture of varieties planted together in the same block. In research plots this planting design has been shown to give some protection against pest and disease. However, as different varieties exhibit different growth characteristics such as date of bud burst and shoot length, some components of these mixtures may become suppressed by other components in the mixture. This may have a negative impact on yield.

REML (GenStat®, 2005) analysis was used to compare plant growth (D100 and number of shoots per stool) on monoclonal and row mixture plots.

For the willow varieties (Jorunn, Germany and Q83) little difference was observed in the D100 values of monoclonal and mixture plots. However, there was some evidence that Jorunn produced larger shoots in mixture plots than in monoclonal plots in the second and third years of the cutting cycles. Conversely, there was some evidence of larger shoots in monoclonal plots of Q83 at these same ages. The number of shoots per stool for all three varieties was significantly higher on monoclonal plots than on mixture plots, this difference was most obvious for Q83 in the second crop rotation.

The results for willow suggest that planting these three varieties in row mixture plots leads to suppression in the production of shoots for all three varieties, but supression of shoot growth (D100) is limited to Q83. Comparing standing biomass estimates for willow mixture and monoclonal plots (Appendicies K and M) shows that mixture plots were always less productive than the most productive variety grown as a monoculture in the third year of both cutting cycles.

For poplar variety Beaupré no significant difference in the size (D100) or number of shoots was observed between monoclonal and mixture plots. For Ghoy and Trichobel, monoclonal plots showed significantly higher numbers of shoots and D100 values than mixture plots. This effect was most obvious in the second crop rotation.

The results for poplar suggest that planting these three varieties in row mixture plots leads to suppression in the production and growth of shoots for Ghoy and Trichobel but causes no significant effect on Beaupré. Mixture plots were nearly always (30 out of 32 occasions) less productive than the most productive variety present in the monoclonal plots at the same site.

4. Summary of pest and disease survey data

4.1. General trends in pest and disease data

A large amount of data on the incidence and severity of insect pests and fungal and bacterial pathogens were collected at the trial sites. Each experiment plot was assessed for 23 categories of pest, disease and damage caused by abiotic factors twice each year, once in early summer and again in late summer. Data collection protocols are described in Appendix A. Only data collected in surveys conducted in the late summer are presented here as the effect of pest and disease is most easily seen in this data subset. Data in Tables 4.1 - 4.4 show that most categories of pest and disease quantified during the assessments did not cause significant damage despite being very widespread. For example ‘Leaf Chewers’ affected at least 95% of plots planted with either Beaupré, Ghoy or Trichobel but overall mean plots scores show that only around 5% of leaf area was lost to this form of damage by late summer. Levels of pest and disease were very similar between sites established in Phase 1 and those established in Phase 2. There was a tendency for both the number of plots effected by any given pest and the severity of infestation or damage caused to increase through the cutting cycle (see overall mean plot scores and % plots affected for Rust (leaves) in Tables 4.1 and 4.3). Levels of damage tended to be higher in the second cutting cycle than the first (see % plots affected in tables 4.1 and 4.2). These observations suggest that a resident pest and disease population takes time to become established within new coppice plantations.

Table 4.1 Overall plot mean scores for each damage category for 'Beaupré', 'Ghoy', 'Trichobel' at Phase 1 sites, 1st cutting cycle

	September 1996			September 1997			September 1998		
Incidence scores (0-5 scale)	Overall mean plot score	Maximum plot score	% plots affected	Overall mean plot score	Maximum plot score	% plots affected	Overall mean plot score	Maximum plot score	% plots affected
Aphids - 2 year stem	0.00	0.33	1	0.00	0.00	0	0.00	0.11	1
Aphids – 1 year stem	0.00	0.00	0	0.00	0.22	1	0.00	0.05	1
Aphids on leaves	0.01	0.40	7	0.01	0.25	16	0.02	0.37	25
Frost Damage	0.00	0.00	0	0.00	0.00	0	0.01	1.11	2
Hail damage	0.00	0.03	3	0.02	0.59	9	0.08	1.29	21
Leaf and Petiole Galls	0.03	0.59	16	0.00	0.18	10	0.03	0.62	22
Leafhopper damage	0.08	1.55	22	0.04	0.98	23	0.07	1.79	27
Rust (leaves)	0.14	3.68	18	1.09	5.00	71	1.52	5	74
Shoot Dieback	0.01	0.94	2	0.04	1.83	4	0.14	5	17
Spittle Bugs	0.00	0.05	0	0.00	0.05	0	0.00	0	0
Stem Borers/ Woody Galls	0.00	0.11	5	0.00	0.11	5	0.00	0.5	2
Stem Lesions	0.03	0.38	27	0.06	0.94	28	0.29	3.05	27
Incidence scores (0-3 scale)									
Leaf chlorosis	0.15	1.07	57	0.34	2.79	75	0.20	1.4	55
Leaf distortion	0.24	1.77	55	0.38	2.81	57	0.39	2.74	64
Rust (Whole Stool)	0.14	3.00	12	0.93	3.00	62	1.05	3	65
Incidence scores (0-1 scale)									
Aphids in Terminal Shoots	0.00	0.00	0	0.00	0.00	0	0.00	0.05	0
Caterpillars in Terminal Shoots	0.00	0.11	2	0.00	0.05	0	0.00	0	0
Terminal bud Galls - death	0.01	0.44	7	0.01	0.72	8	0.01	0.27	6
% leaf area lost									
Blotch leaf miners	0.17	5.00	22	0.22	8.47	20	0.40	28.05	18
Disease spots and blotches	3.48	13.93	52	5.53	44.02	59	10.67	76.38	84
Leaf Chewers	4.18	13.51	94	5.70	23.75	96	5.60	26.11	97
Linear leaf miners	0.18	3.33	31	0.30	4.02	31	0.27	4.16	23
Skeletonising	3.75	33.14	58	3.67	16.01	67	4.18	12.73	80
Taphrina leaf Galls	0.09	6.11	8	0.04	2.77	5	0.74	11.94	29

Table 4.2 Overall plot mean scores for each damage category for 'Beaupré', 'Ghoy', 'Trichobel' at Phase 1 sites, 2nd cutting cycle

	September 1999			September 2000			September 2001		
Incidence scores (0-5 scale)	Overall mean plot score	Maximum plot score	% plots affected	Overall mean plot score	Maximum plot score	% plots affected	Overall mean plot score	Maximum plot score	% plots affected
Aphids - 2 year stem	0.00	0	0	0.01	0.66	3	0.00	0.00	0
Aphids – 1 year stem	0.00	0.72	2	0.00	0	0	0.00	0.00	0
Aphids on leaves	0.00	0.12	10	0.02	0.46	22	0.00	0.09	5
Frost Damage	0.00	0	0	0.01	0.72	4	0.00	0.00	0
Hail damage	0.02	0.83	12	0.04	0.68	23	0.01	0.44	11
Leaf and Petiole Galls	0.00	0.11	8	0.03	0.40	21	0.02	1.35	8
Leafhopper damage	0.06	1.96	21	0.03	0.42	19	0.00	0.05	3
Rust (leaves)	0.96	4.77	81	1.90	5.00	82	2.01	5.00	82
Shoot Dieback	0.00	0.22	1	0.11	1.77	21	0.14	4.00	19
Spittle Bugs	0.00	0	0	0.00	0.00	0	0.00	0.00	0
Stem Borers/ Woody Galls	0.00	0.05	1	0.00	0.27	5	0.01	0.16	8
Stem Lesions	0.14	2.35	23	0.12	1.77	22	0.13	1.16	30
Incidence scores (0-3 scale									
Leaf chlorosis	0.17	3	49	0.16	1.37	55	0.09	1.00	46
Leaf distortion	0.19	1.55	46	0.20	2.50	55	0.17	2.37	42
Rust (Whole Stool)	0.97	3	77	1.42	3.00	78	1.57	3.00	78
Incidence scores (0-1 scale									
Aphids in Terminal Shoots	0.00	0.05	1	0.00	0.05	0	0.00	0.00	0
Caterpillars in Terminal Shoots	0.00	0	0	0.00	0.05	0	0.00	0.00	0
Terminal bud Galls - death	0.00	0.17	5	0.01	0.16	9	0.00	0.11	6
% leaf area lost									
Blotch leaf miners	0.14	2.63	14	0.18	5.13	14	0.42	10.83	13
Disease spots and blotches	6.82	40.55	85	10.71	82.50	84	12.59	68.88	77
Leaf Chewers	4.79	12.17	98	5.57	12.36	99	6.71	32.77	96
Linear leaf miners	0.09	1.52	19	0.19	2.77	28	0.23	4.86	19
Skeletonising	3.75	18.05	70	5.92	31.94	82	7.03	34.86	71
Taphrina leaf Galls	0.03	1.94	3	0.20	8.47	18	0.13	1.94	19

Table 4.3 Overall plot mean scores for each damage category for 'Jorunn', 'Germany' and 'Q83' at Phase 1 sites, 1st cutting cycle

	September 1996			September 1997			September 1998		
Incidence scores (0-5 scale)	Overall mean plot score	Maximum plot score	% plots affected	Overall mean plot score	Maximum plot score	% plots affected	Overall mean plot score	Maximum plot score	% plots affected
Aphids - 2 year stem	0.01	0.55	5	0.01	0.61	2	0.39	4.00	30
Aphids – 1 year stem	0.00	0.05	0	0.06	1.50	10	0.06	2.83	2
Aphids on leaves	0.00	0.09	6	0.00	0.12	9	0.12	1.24	28
Frost Damage	0.00	0.00	0	0.00	0.00	0	0.00	0.16	0
Hail damage	0.00	0.07	5	0.01	0.50	6	0.01	0.25	5
Leaf and Petiole Galls	0.01	0.40	11	0.02	0.83	9	0.04	1.31	10
Leafhopper damage	0.04	0.96	14	0.06	1.00	17	0.13	2.75	18
Rust (leaves)	0.31	5.00	21	0.97	5.00	69	1.30	5.00	53
Shoot Dieback	0.03	1.66	6	0.02	0.88	5	0.06	1.83	9
Spittle Bugs	0.00	0.00	0	0.00	0.16	1	0.00	0.00	0
Stem Borers/ Woody Galls	0.00	0.33	0	0.00	0.00	0	0.00	0.11	1
Stem Lesions	0.04	0.44	24	0.09	1.38	37	0.26	3.00	27
Incidence scores (0-3 scale									
Leaf chlorosis	0.12	3.00	45	0.33	1.92	68	0.16	1.29	35
Leaf distortion	0.26	3.00	55	0.44	3.00	64	0.38	2.59	61
Rust (Whole Stool)	0.30	3.00	16	0.94	3.00	57	1.04	3.00	47
Incidence scores (0-1 scale									
Aphids in Terminal Shoots	0.00	0.00	0	0.00	0.00	0	0.01	0.66	1
Caterpillars in Terminal Shoots	0.00	0.05	1	0.00	0.11	1	0.00	0.00	0
Terminal bud Galls - death	0.09	1.00	28	0.05	0.88	17	0.04	0.83	6
% leaf area lost									
Blotch leaf miners	0.05	3.47	9	0.11	7.22	11	0.24	5.97	11
Disease spots and blotches	3.11	42.63	39	4.49	26.80	45	7.91	57.12	60
Leaf Chewers	5.06	22.36	89	6.43	22.50	96	6.58	25.69	87
Linear leaf miners	0.01	0.97	2	0.04	1.11	11	0.14	4.30	9
Skeletonising	4.46	54.67	60	3.38	16.34	58	4.04	35.55	64
Taphrina leaf Galls	0.00	0.27	0	0.00	0.00	0	0.00	0.00	0

Table 4.4 Overall plot mean scores for each damage category for ‘Jorunn, Germany and Q83 at Phase 1 sites, 2nd cutting cycle

	September 1999			September 2000			September 2001		
Incidence scores (0-5 scale)	Overall mean plot score	Maximum plot score	% plots affected	Overall mean plot score	Maximum plot score	% plots affected	Overall mean plot score	Maximum plot score	% plots affected
Aphids - 2 year stem	0.00	0.11	1	0.19	2.16	22	0.11	1.72	14
Aphids – 1 year stem	0.18	4.44	15	0.23	5.00	15	0.00	0.11	1
Aphids on leaves	0.02	0.90	17	0.03	0.35	34	0.00	0.16	13
Frost Damage	0.00	0.00	0	0.00	0.16	4	0.00	0.00	0
Hail damage	0.01	0.44	8	0.00	0.05	2	0.00	0.07	1
Leaf and Petiole Galls	0.03	1.09	11	0.05	0.74	24	0.06	1.62	17
Leafhopper damage	0.03	1.09	11	0.04	3.53	18	0.02	0.40	16
Rust (leaves)	1.51	5.00	77	1.47	5.00	74	1.46	5.00	72
Shoot Dieback	0.01	0.77	4	0.12	2.44	29	0.13	2.33	32
Spittle Bugs	0.00	0.00	0	0.00	0.00	0	0.00	0.00	0
Stem Borers/ Woody Galls	0.00	0.11	1	0.01	0.22	9	0.01	0.44	5
Stem Lesions	0.06	1.05	24	0.07	0.66	36	0.10	1.94	34
Incidence scores (0-3 scale									
Leaf chlorosis	0.34	2.87	54	0.23	1.46	72	0.30	2.38	71
Leaf distortion	0.30	2.88	63	0.35	2.59	70	0.20	1.44	53
Rust (Whole Stool)	1.33	3.00	73	1.20	3.00	70	1.21	3.00	68
Incidence scores (0-1 scale									
Aphids in Terminal Shoots	0.00	0.00	0	0.00	0.16	2	0.00	0.00	0
Caterpillars in Terminal Shoots	0.00	0.05	1	0.00	0.05	2	0.00	0.00	0
Terminal bud Galls - death	0.04	0.88	18	0.03	1.00	16	0.16	1.00	28
% leaf area lost									
Blotch leaf miners	0.24	13.88	12	0.09	3.88	14	0.05	1.66	11
Disease spots and blotches	6.11	39.02	70	6.82	47.36	74	5.98	25.41	74
Leaf Chewers	6.04	22.59	97	7.47	19.72	99	8.87	60.00	94
Linear leaf miners	0.02	1.80	3	0.05	0.69	22	0.03	0.97	11
Skeletonising	3.23	10.00	64	4.24	25.78	73	6.98	74.72	67
Taphrina leaf Galls	0.00	0.00	0	0.01	1.11	1	0.01	1.80	1

4.2 Rust fungus on SRC grown in monoclonal plots

The rust fungus *Melampsora epitea* has the potential to adversely effect the productivity of willow SRC whilst *Melampsora larici-populina* is a commonly found pathogen of poplar which can cause serious damage or even kill susceptible varieties. These pathogens can infect large areas of leaf surface, reducing levels of photosynthesis and hence yield. Early defoliation and an increased susceptibility to frost damage can also occur if the host plant becomes heavily infected. Five damage categories were used to assess infection levels in the field, these were:

Rust score category	incidence of pest/disease	% leaf area lost
1	very light	0 – 10%
2	light	10 – 20 %
3	moderate	20 – 40 %
4	severe	40 – 65 %
5	very severe	65 – 100 %

Variations in the severity of rust infection occur amongst varieties, sites and years. This section explores and summarises this variation.

4.2.1 Varieties planted at extensive experiment sites

When data from all sites are pooled according to variety and age, variations in rust infection amongst willow varieties are clearly shown. Figures 4.1 and 4.2 show that rust levels remained low on the willow variety Jorunn throughout both cutting cycles. The level of rust found on Germany and Q83 increased through the first cutting cycle. These varieties were more severely infected by rust than Jorunn in all years studied.

Figure 4.1 Rust infection levels on three willow varieties in the first cutting cycle

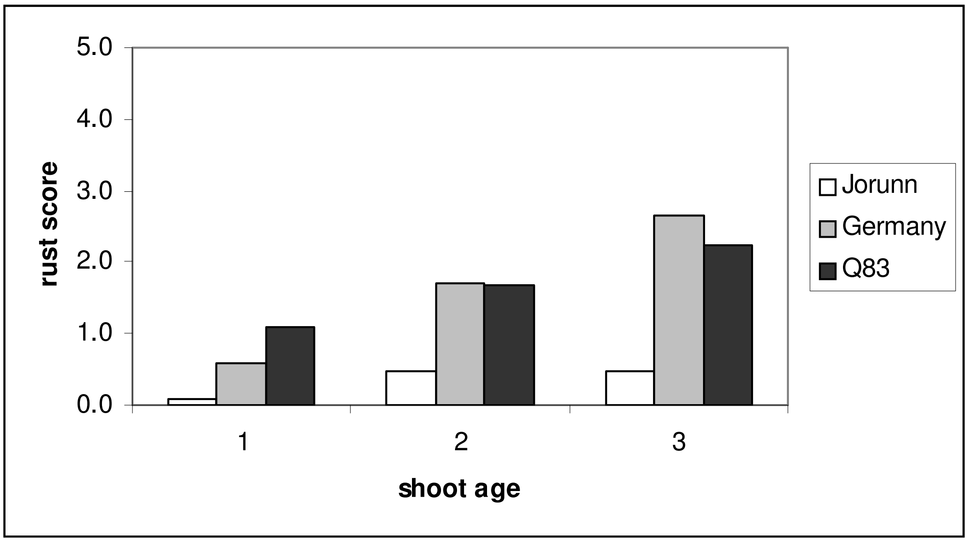
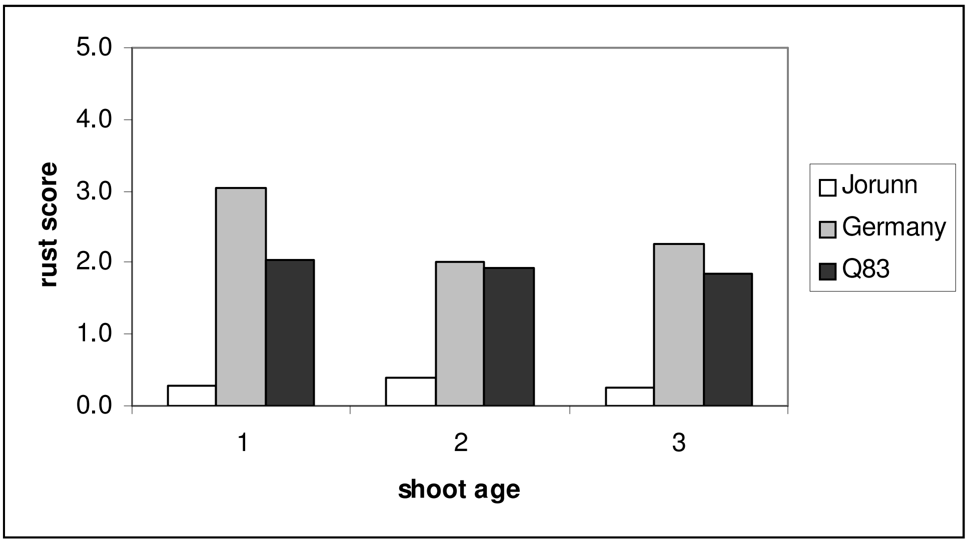


Figure 4.2 Rust infection levels on three willow varieties in the second cutting cycle



Differences in rust levels amongst poplar varieties were also observed, as shown in figures x and y. Beaupre was more severely infected than Ghoy in all years studied whilst Ghoy was more severely infected than Trichobel. Again, the severity of infection increased during the first cutting cycle. Severity of infection dipped slightly in the first year of the second cutting cycle but increased in the second year. Infection levels were similar on all varieties in the second and third year of the second rotation.

Figure 4.3 Rust infection levels on three poplar varieties in the first cutting cycle

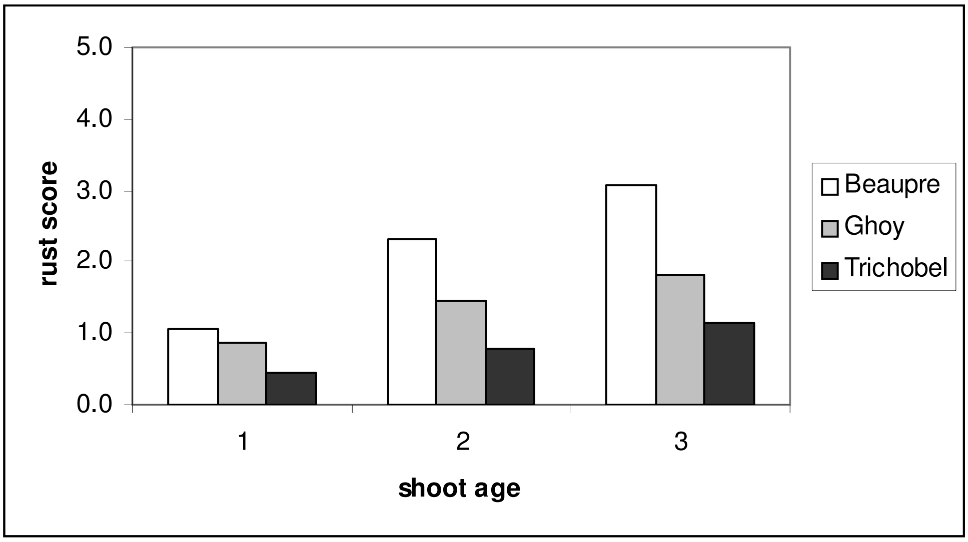
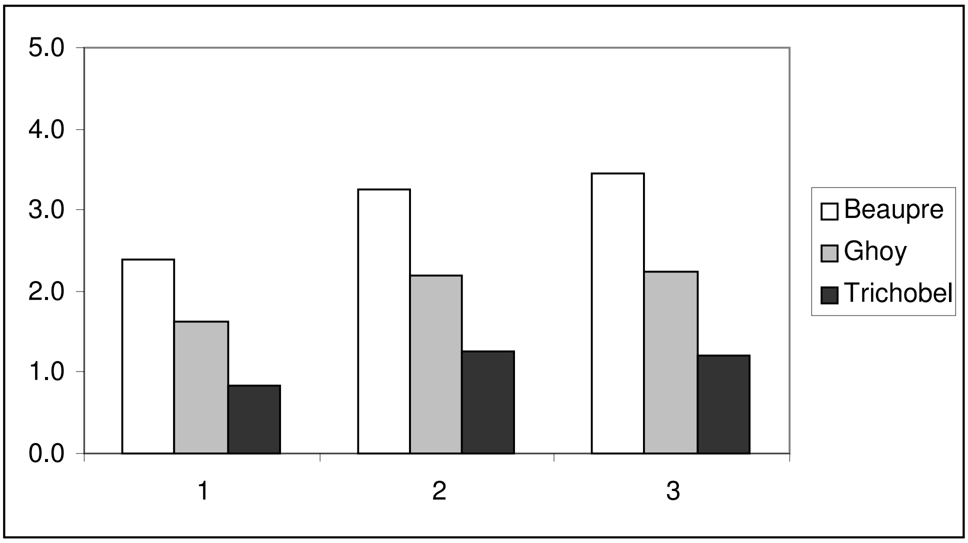


Figure 4.4 Rust infection levels on three poplar varieties in the second cutting cycle



4.2.2 Distribution and severity of rust fungus on short rotation coppice

In order to gain an improved understanding of how levels of rust infection varied not only amongst varieties and growing season but also between sites, maps were generated based on site, variety and shoot age mean plot scores.

The rust score categories used in this exercise were:

Rust score category	incidence of pest/disease	% leaf area lost
<1	very light	0 – 10%
1 - <2	light	10 – 20 %
2 - <3	moderate	20 – 40 %
3 - 4	severe	40 – 65 %
> = 4	very severe	65 – 100 %

The maps generated are shown in Figures 4.5 to 4.16. These show that Beaupré became extremely susceptible to rust diseases and that the incidence of infection became more widespread and more severe over time. Infection by *Melampsora* spp. was linked to stool deaths in Beaupré and other *Populus trichocarpa x Populus deltoides* varieties, especially in Southern England. Ghoy was less serious affected by rust infection and Trichobel remained disease free over large parts of the UK. Were infection was present on this variety severity was generally either light or moderate.

The distribution of rust infection was less clear when data for willow varieties is examined. Jorunn suffered severe or very severe infection at a limited number of sites in South West England in two years. Elsewhere this variety was largely free from rust infection. Germany was the most susceptible willow variety, infection was generally most severe in the west of England and Northern Ireland although initial growth in the second cutting cycle at sites in North Scotland also suffered high levels of the disease. Very severe rust infection on Q83 was generally limited to Northern Ireland and Southern England although patches of severe and moderate infection occurred else where.

Figure 4.5 Maps of the incidence and severity of *Melampsora* spp. rust infection on the willow variety Germany in the first cutting cycle (rotation)

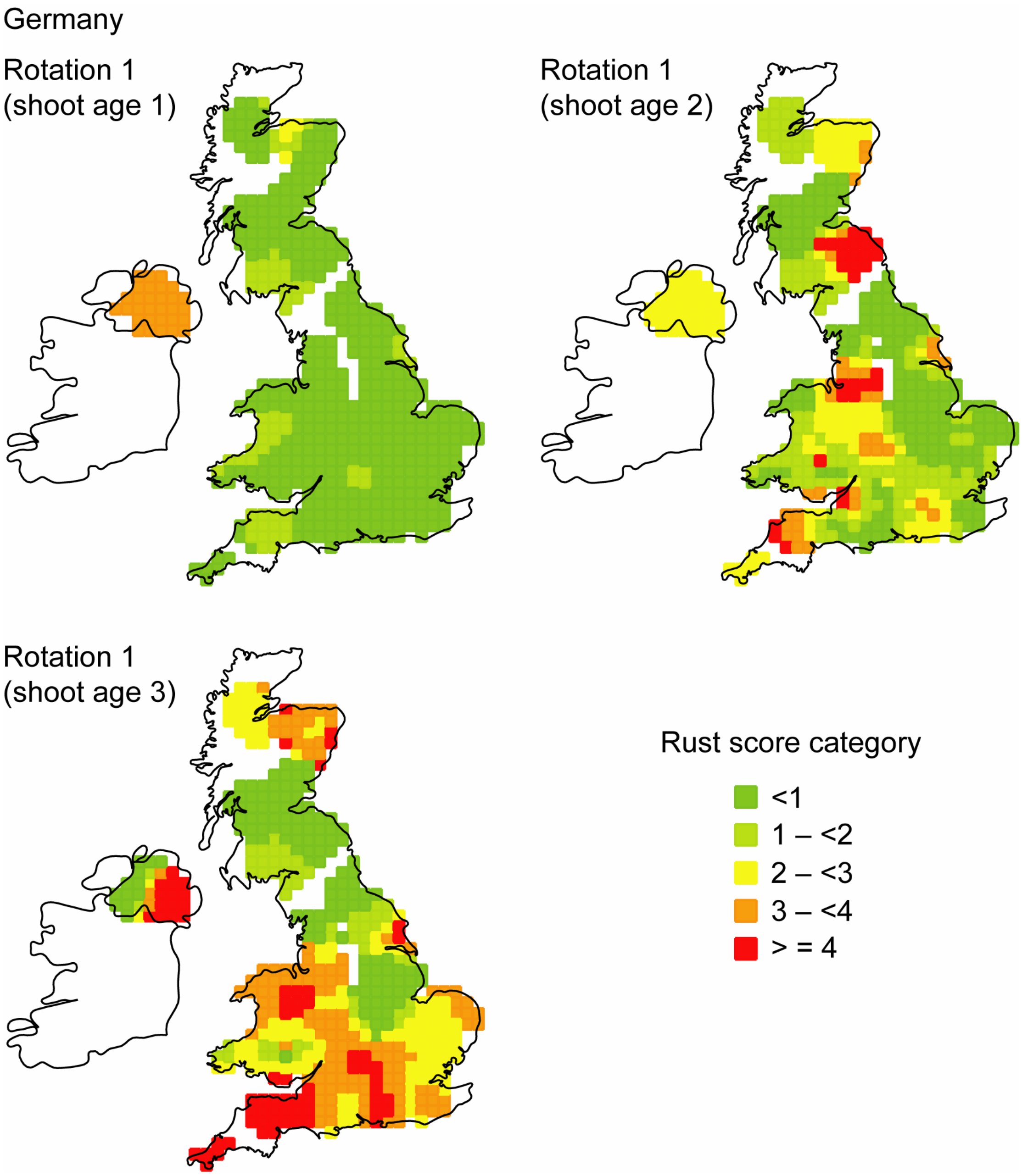


Figure 4.6 Maps of the incidence and severity of *Melampsora* spp. rust infection on the willow variety Germany in the second cutting cycle (rotation)

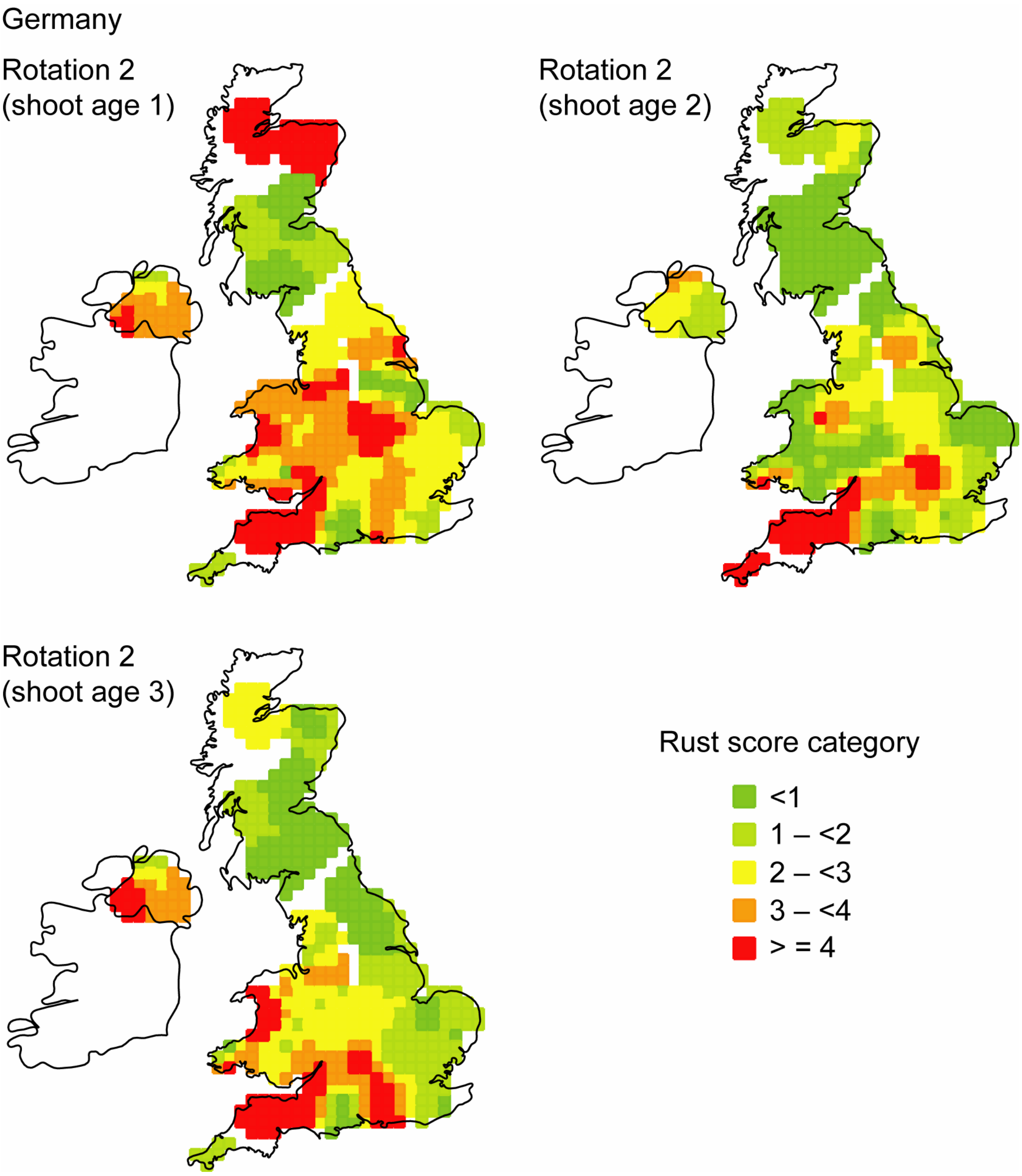


Figure 4.7 Maps of the incidence and severity of *Melampsora* spp. rust infection on the willow variety Jorunn in the first cutting cycle (rotation)

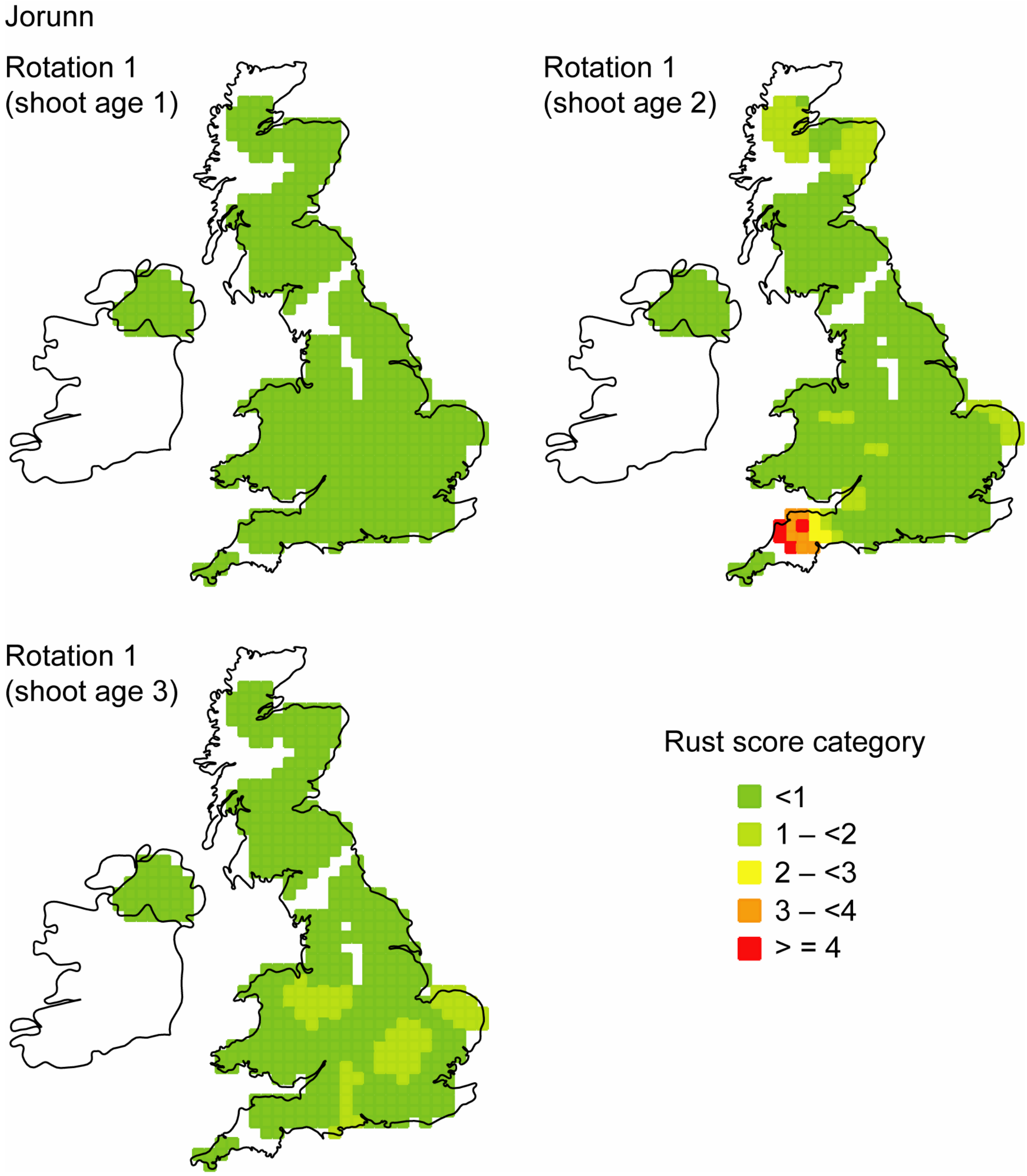


Figure 4.8 Maps of the incidence and severity of *Melampsora* spp. rust infection on the willow variety Jorunn in the second cutting cycle (rotation)

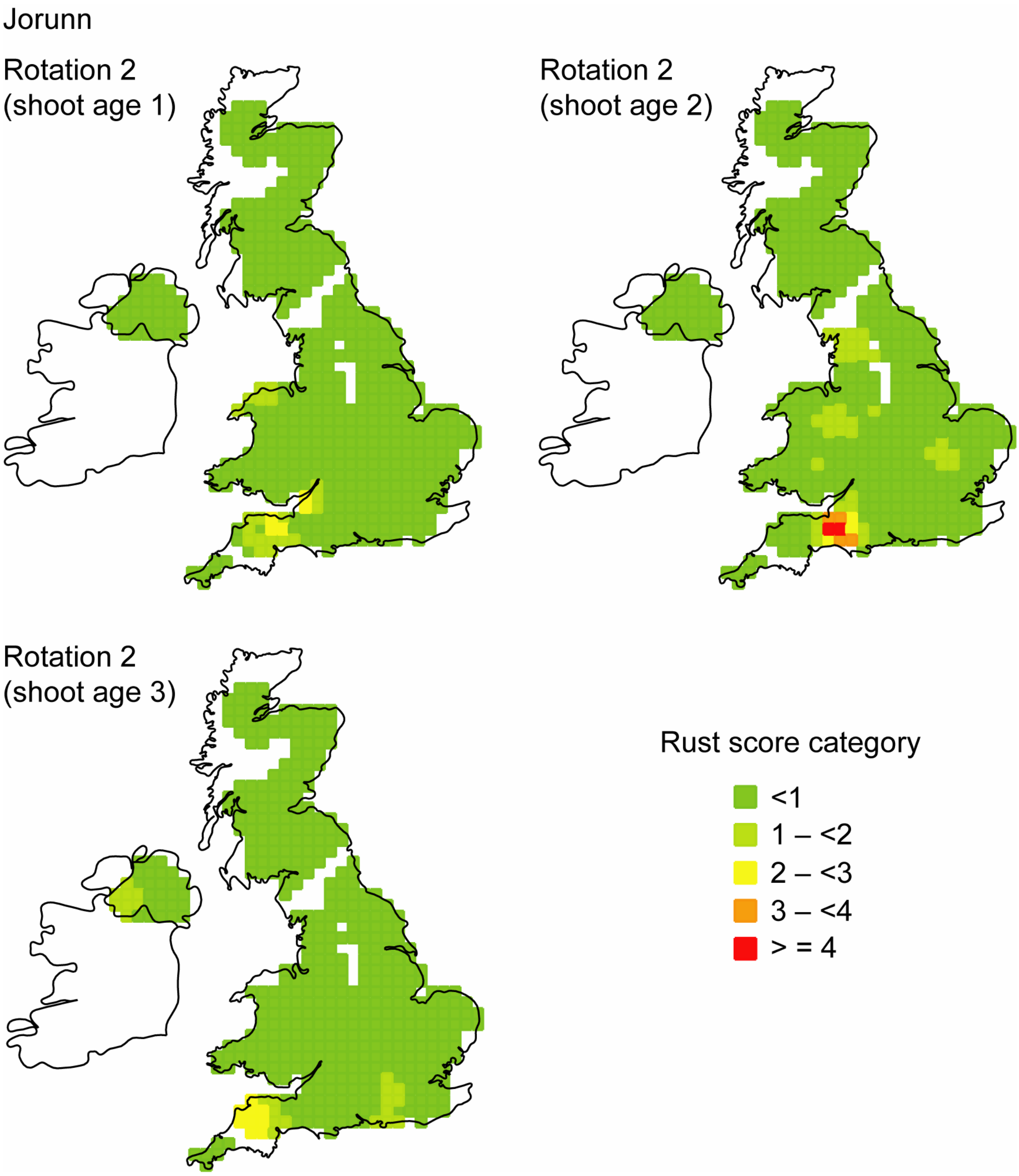


Figure 4.9 Maps of the incidence and severity of *Melampsora* spp. rust infection on the willow variety Q83 in the first cutting cycle (rotation)

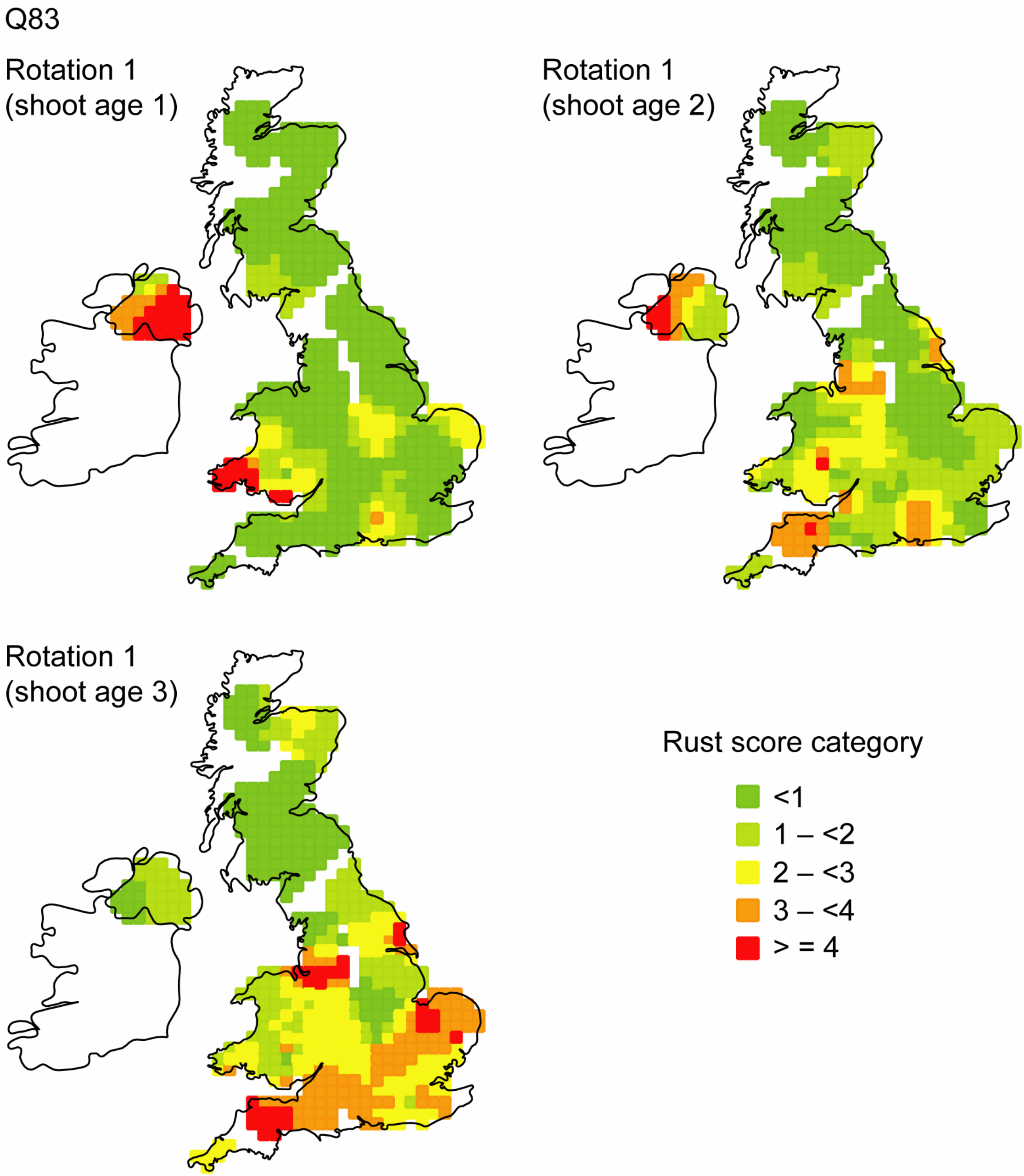


Figure 4.10 Maps of the incidence and severity of *Melampsora* spp. rust infection on the willow variety Q83 in the second cutting cycle (rotation)

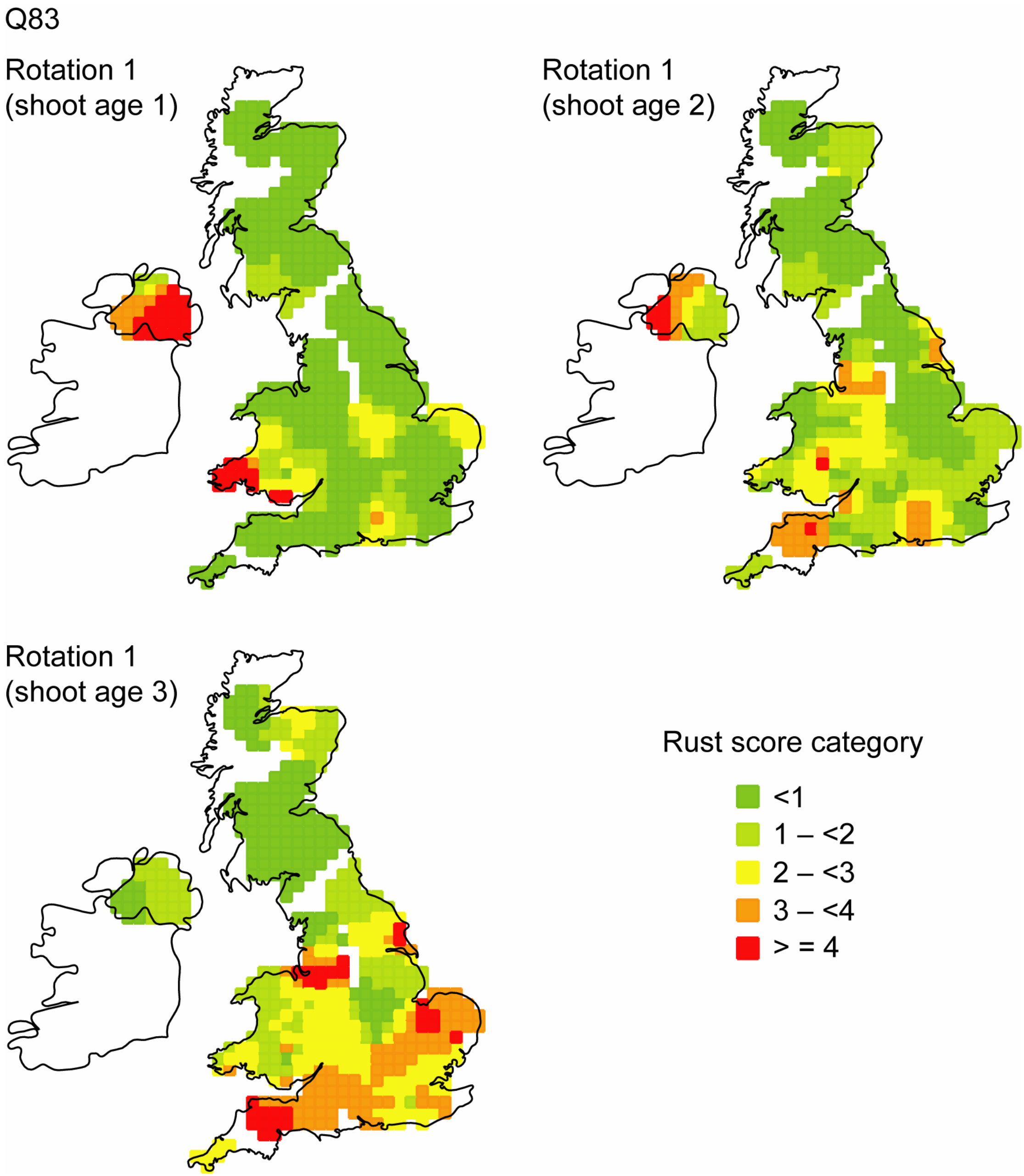


Figure 4.11 Maps of the incidence and severity of *Melampsora* spp. rust infection on the poplar variety Beaupré in the first cutting cycle (rotation)

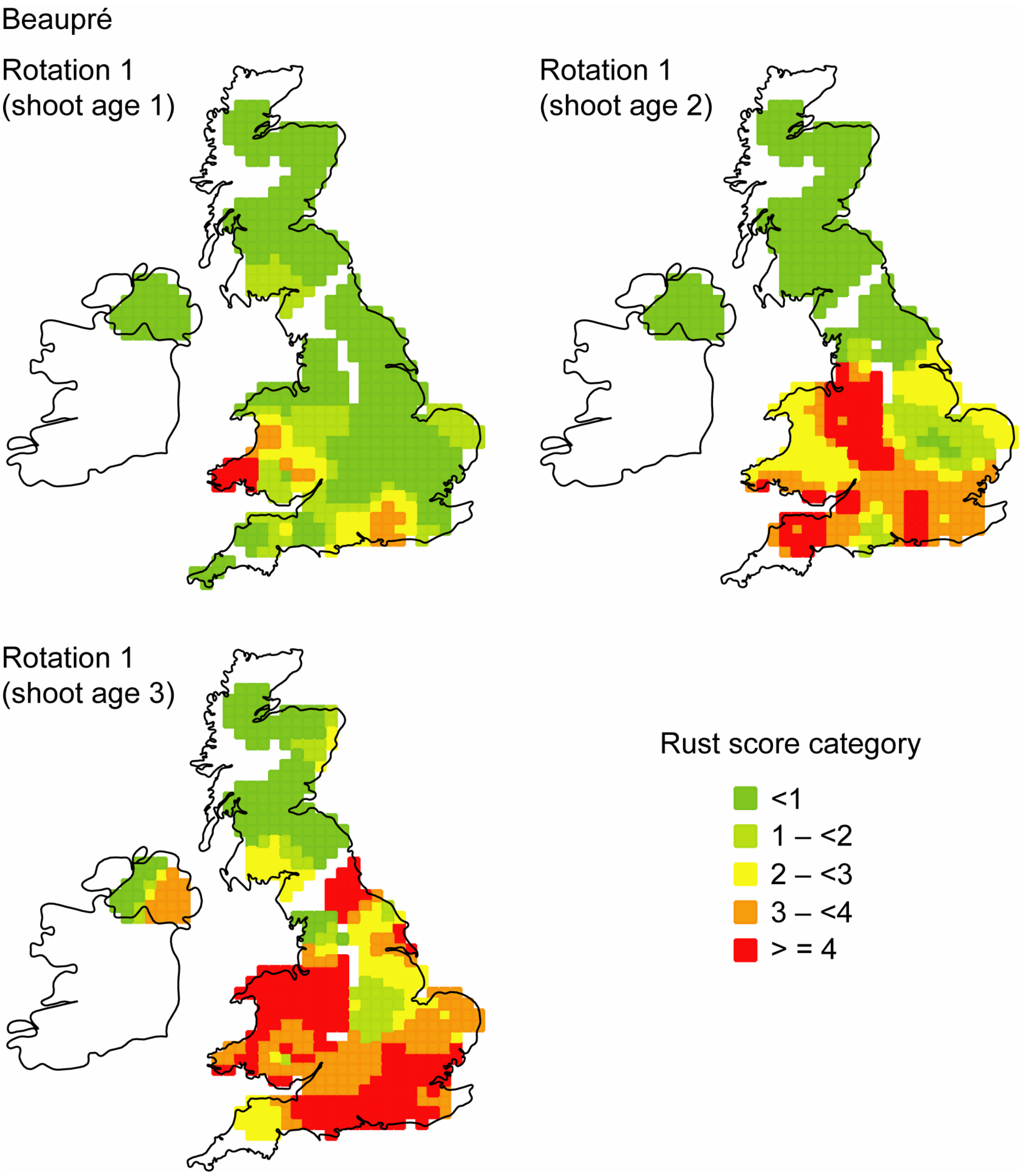


Figure 4.12 Maps of the incidence and severity of *Melampsora* spp. rust infection on the poplar variety Beaupré in the second cutting cycle (rotation)

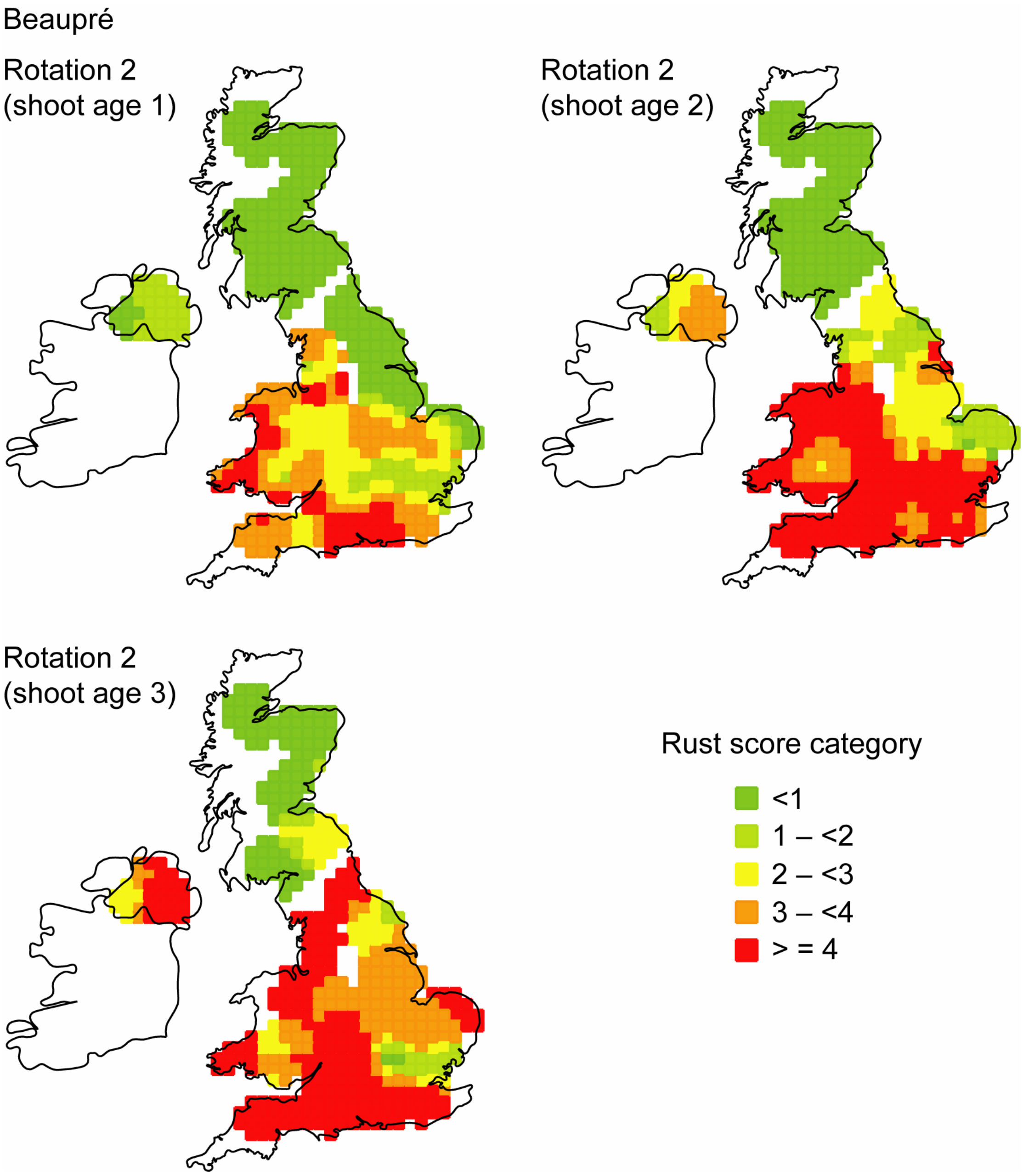


Figure 4.13 Maps of the incidence and severity of *Melampsora* spp. rust infection on the poplar variety Ghoy in the second cutting cycle (rotation)

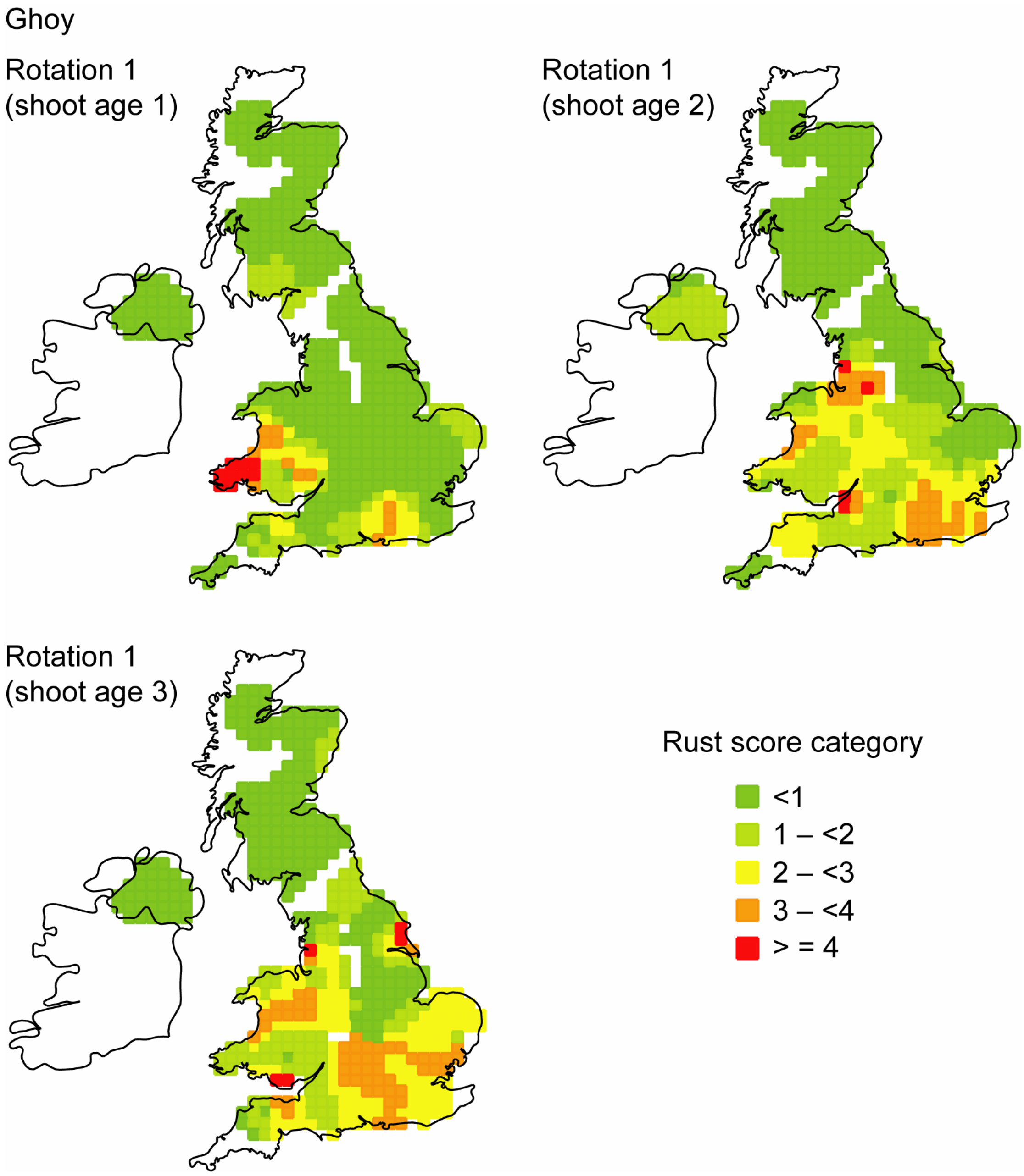


Figure 4.14 Maps of the incidence and severity of *Melampsora* spp. rust infection on the poplar variety Ghoy in the second cutting cycle (rotation)

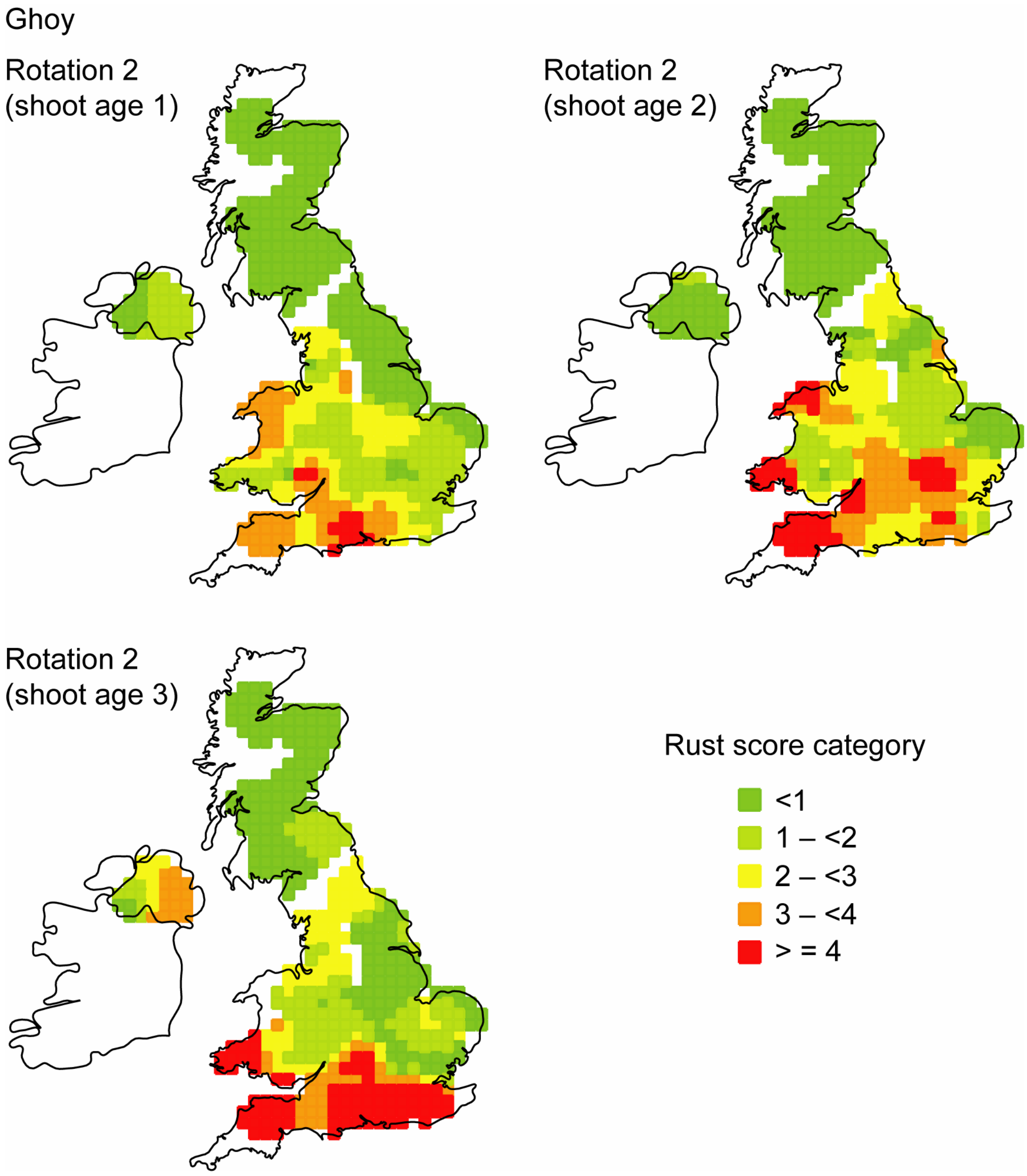


Figure 4.15 Maps of the incidence and severity of *Melampsora* spp. rust infection on the poplar variety Trichobel in the first cutting cycle (rotation)

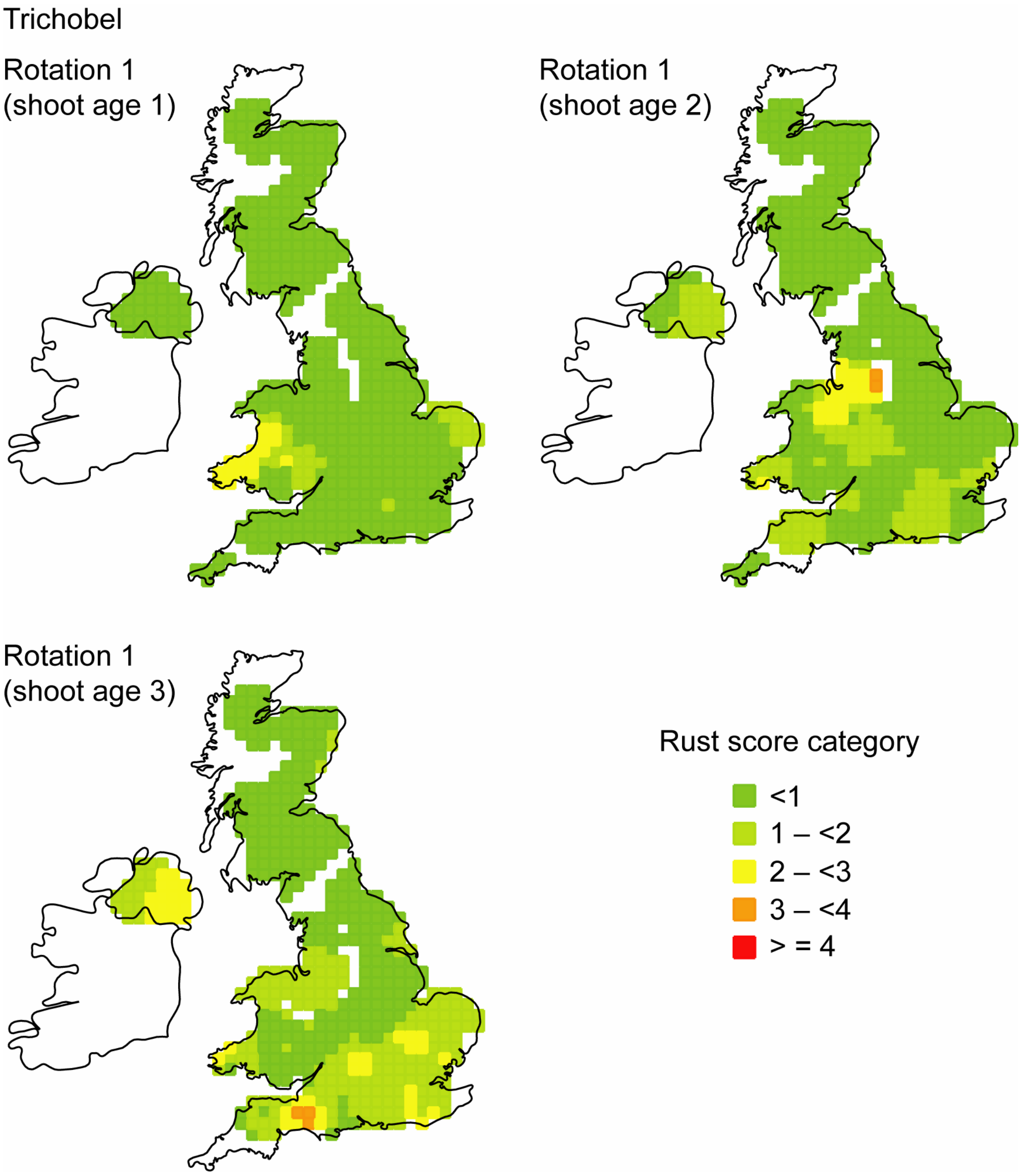
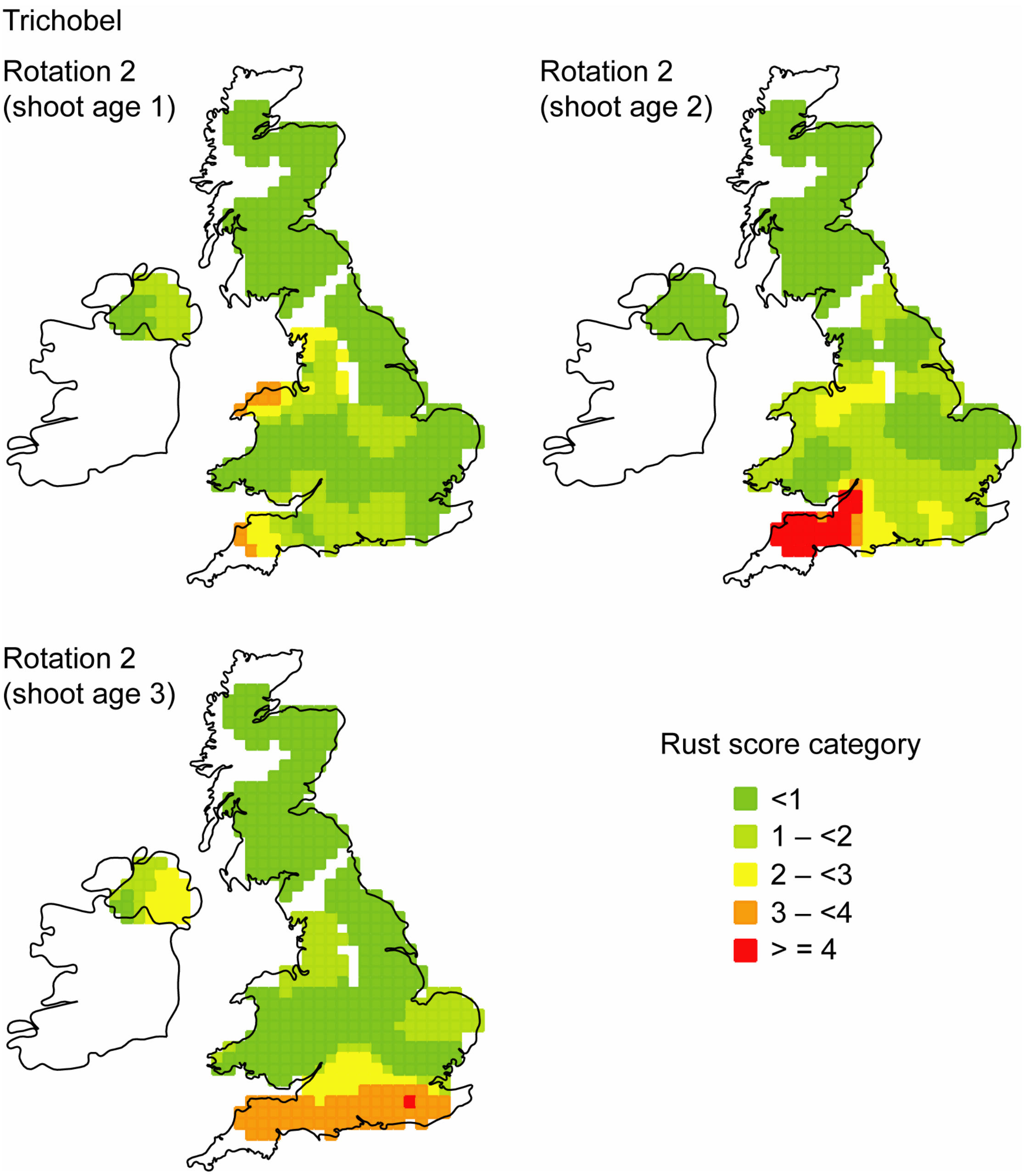


Figure 4.16 Maps of the incidence and severity of *Melampsora* spp. rust infection on the poplar variety Trichobel in the second cutting cycle (rotation)



4.2.3 Varieties planted at 'intensive' experiment sites

Insufficient data existed to generate nationwide maps showing changes in rust infection levels amongst varieties planted at the seven intensive sites. Instead data was tabulated to show variations amongst varieties and years (Table 4.5 and 4.7) and sites and years (Tables 4.6 and 4.8). As for varieties grown at the extensive sites, rust infection was scored on a 1 – 5 scale.

The willow varieties Bjorn, Tora, Bebbiana, Ulv, Delamere, Dasyclados and Jorunn suffered only minor levels (rust score <1) of rust infection during the study period. Stott 10 and Stott 11 became more heavily infected over time. It is interesting to note that the varieties Germany and Q83, planted at all 49 sites, were amongst the most most heavily infected varieties at the intensive sites

Table 4.5 Variations in willow rust infection amongst varieties over time (infection scores range between 0 -5).

Variety	Cutting Cycle 1, age 1	Cutting Cycle 1, age 2	Cutting Cycle 1, age 3	Cutting Cycle 2, age 1	Cutting Cycle 2, age 2	Cutting Cycle 2, age 3
Jorunn	0.22	0.50	0.42	0.70	0.40	0.22
Germany	0.82	0.84	2.40	2.75	1.63	2.36
Q83	1.10	1.90	1.95	2.32	1.91	2.38
Spaethii	0.39	0.74	1.61	1.54	1.56	1.89
Dasyclado s	0.34	0.23	0.42	0.50	0.32	0.61
ST/2481/55	1.15	1.50	1.54	1.98	1.65	2.23
Delamere	0.38	0.35	0.27	0.66	0.58	0.60
Bebbiana	0.00	0.00	0.00	0.00	0.00	0.00
v789	0.39	0.60	1.04	0.60	0.87	1.10
Stott 10	0.58	1.21	1.94	1.82	1.06	2.21
Stott 11	0.60	1.01	1.70	1.57	1.40	1.71
Jorr	0.25	0.65	0.95	0.64	1.10	0.97
Bjorn	0.01	0.05	0.10	0.35	0.08	0.00
Tora	0.01	0.00	0.04	0.13	0.03	0.01
Orm	0.71	0.59	0.86	0.94	0.93	1.30
Ulv	0.20	0.18	0.51	0.49	0.67	0.68

Rust infection on willows was most severe at site 6 (Northern Ireland) in the first cutting cycle and site 2 (south west England) in the second. Willow varieties at site 7 in southern England suffered relatively high levels of infection too. The least severely infected sites were site 1 in Fife, site 3 in south Wales and site 5 in north east England.

Table 4.6 Variation in willow rust infection amongst sites over time (infection scores range between 0 -5).

Site	Cutting Cycle 1, age 1	Cutting Cycle 1, age 2	Cutting Cycle 1, age 3	Cutting Cycle 2, age 1	Cutting Cycle 2, age 2	Cutting Cycle 2, age 3
1	0.04	0.07	0.07	0.12	0.01	0.04
2	0.73	1.59	1.51	3.06	2.58	2.91
3	0.01	0.26	0.00	0.52	0.17	0.66
4	0.04	0.41	1.53		1.65	0.69
5	0.01	0.04	0.72	0.53	0.73	0.26
6	1.67	1.21	1.54	1.03	0.63	1.92
7	0.69	1.04	1.53	1.11	0.44	1.58

Many poplar varieties planted at the seven intensives sites suffered from severe rust infection during the study period. The *P. trichocarpa* x *P. deltoides* varieties Beaupré, Boelare, Unal and Raspalje and the *P. deltoides x P. trichocarpa* varieties 710091, 710151 and 710092 were particularly susceptible to rust. At more southerly sites some plots of these varieties suffered highly levels of plant death, thought to be caused by rust fungus. 690386 and 690394, also *P. trichocarpa* x *P. deltoides* varieties were initially resistant to the *Melampsora larici populina* but the emergence of a new pathotype (E5) in 1998 saw this resistance collapse and serious infection set in at sites in south west and southern England. Although the P. Deltoides x P. Nigra varieties Ghoy, Gaver and Gibecq became more heavily infected with rust fungus over time, no plants were lost to the disease. The same pattern was observed in the pure *P. trichocarpa* varietes Trichobel, Fritzi Pauley and Columbia River as well as the *P. trichocarpa* x *P. balsamifera* variety TT32.

Table 4.7 Variations in poplar rust infection amongst varieties over time (infection scores range between 0 -5).

	Cutting Cycle 1, age 1	Cutting Cycle 1, age 2	Cutting Cycle 1, age 3	Cutting Cycle 2, age 1	Cutting Cycle 2, age 2	Cutting Cycle 2, age 3
Beaupre	0.92	1.83	3.54	3.16	3.12	3.67
Ghoy	0.88	1.24	1.96	2.01	2.23	2.95
Trichobel	0.34	0.70	1.50	0.91	1.29	1.64
Boelare	1.26	2.17	3.38	3.22	3.63	3.52
Unal	0.77	1.80	2.92	2.93	3.18	3.07
Raspalje	0.48	1.50	3.09	1.96	3.52	3.18
Gaver	0.34	0.90	1.53	0.91	1.86	2.30
Gibecq	0.47	1.25	1.90	1.67	2.07	2.68
690386 (Hoogvorst)	0.04	0.04	1.16	1.66	1.89	1.59
690394 (Hazendans)	0.04	0.06	0.93	1.69	1.66	1.70
710091	1.46	1.85	3.80	3.93	3.96	4.27
710151	0.87	1.64	2.81	3.10	3.24	3.90
710092	0.78	1.64	3.06	3.04	3.60	3.66
Columbia R.	0.58	1.28	2.62	1.24	1.87	2.11
TT32/Balsam Spire	0.65	1.87	2.37	1.63	1.97	2.53
Fritzi Pauley	0.34	0.55	1.27	0.90	1.47	1.67

Poplar varieties suffered from severe rust infection in both cutting cycles at site 2 in South West England. Many coppice stools in plots planted with Beaupré, Boelare and other *P. trichocarpa* x *P. deltoides* and *P. deltoides x P. trichocarpa* varieties died at this site. Similar problems were also observed at site 7 in southern England and site 4 in East Anglia. Site 1 in Fife remained almost disease free during both cutting cycles.

Table 4.8 Variation in poplar rust infection amongst sites over time (infection scores range between 0 -5).

Site	Cutting Cycle 1, age 1	Cutting Cycle 1, age 2	Cutting Cycle 1, age 3	Cutting Cycle 2, age 1	Cutting Cycle 2, age 2	Cutting Cycle 2, age 3
1	0.00	0.04	0.23	0.00	0.00	0.12
2	2.08	2.49	4.08	3.46	4.94	4.84
3	0.03	0.91	0.91	2.64	1.55	2.01
4	0.01	0.05	2.69	5.00	3.51	2.21
5	0.00	0.27	2.70	0.40	2.32	2.11
6	0.37	1.52	2.28	1.40	1.88	3.39
7	1.76	3.40	3.29	3.87	3.22	4.43

4.3 Rust fungus on short rotation coppice grown in plots containing a mixture of varieties

A large body of work exists suggesting that mixtures of varieties planted together in the same block or plantation benefit from lower levels of disease than with monoclonal plots. Data collected from the 16 experiment sites planted with both monoclonal plots and plots containing mixtures of varieties arranged in alternating rows suggests that this benefit was not generally applicable to the varieties and planting design tested here.

Generalised linear regression (GenStat®, 2005) analysis, using specific t-tests for comparisons, was carried out to compare rust fungus levels on monoclonal and mixture plots.

Data collected from plots containing willow varieties show that disease loads were generally similar on both monoclonal and mixture plots for all three varieties. However, there was some evidence (borderline significant) to suggest that levels of rust fungus on monoclonal plots of Q83 were higher than on mixture plots (see Table 4.9).

Table 4.9 Variations in the severity of rust infection in three willow varieties grown in monoclonal and mixed plots

Variety	Plot type	Cutting Cycle 1, age 1	Cutting Cycle 1, age 2	Cutting Cycle 1, age 3	Cutting Cycle 2, age 1	Cutting Cycle 2, age 2	Cutting Cycle 2, age 3
Jorunn	Monoclonal	0.08	0.81	0.56	0.38	0.43	0.58
	Mixed	0.20	0.72	0.62	0.28	0.50	0.33
Germany	Monoclonal	0.84	2.45	3.05	3.34	2.35	2.72
	Mixed	0.92	2.32	3.08	3.28	2.34	2.34
Q83	Monoclonal	1.18	2.21	2.36	2.23	2.21	1.99
	Mixed	0.91	1.96	2.49	1.82	2.24	1.75

Similar analysis for the three poplar varieties showed clearer differences between plot types. Levels of rust on Ghoy and Trichobel were significantly higher on the mixture plots for shoots aged two and three years in both cutting cycles. No clear difference between rust levels on monoclonal and mixture plots was observed for Beaupré (see Table 4.10).

Table 4.10 Variations in the severity of rust infection in three poplar varieties grown in monoclonal and mixed plots

Variety	Plot type	Cutting Cycle 1, age 1	Cutting Cycle 1, age 2	Cutting Cycle 1, age 3	Cutting Cycle 2, age 1	Cutting Cycle 2, age 2	Cutting Cycle 2, age 3
Beaupré	Monoclonal	1.17	2.71	3.12	2.42	3.72	4.06
	Mixed	1.13	2.78	3.37	2.32	3.83	4.19
Ghoy	Monoclonal	0.97	2.17	2.14	1.71	2.42	2.52
	Mixed	0.95	2.24	2.79	1.74	3.05	2.67
Trichobel	Monoclonal	0.67	1.08	1.23	1.01	1.65	1.39
	Mixed	0.85	1.78	1.84	1.23	2.03	1.95

4.4 Damage caused by leaf skeletonising insects

Phratora spp. willow beetles are generally regarded as the most damaging insect pests of SRC. Using data collected from the field trials, maps were generated (using techniques similar to those outlined in section 4.2.2) to show variations in damage amongst years and varieties. Most of these maps showed a uniformly low level of damage and have not been included in this report. However, some combinations of site, willow variety and year did sustain higher levels of damage, as shown in Figure 4.13. The beetle infestations that caused this damage were transient and did not necessarily occur in years after the initial attack. It is possible that larger areas of SRC could sustain larger beetle populations from year to year.

When data from monoclonal and mixed plots are compared, it can be seen that planting the willow and poplar varieties tested here in row mixtures provides no advantage in terms of protection against skeletonising insects (Tables 4.11 and 4.12).

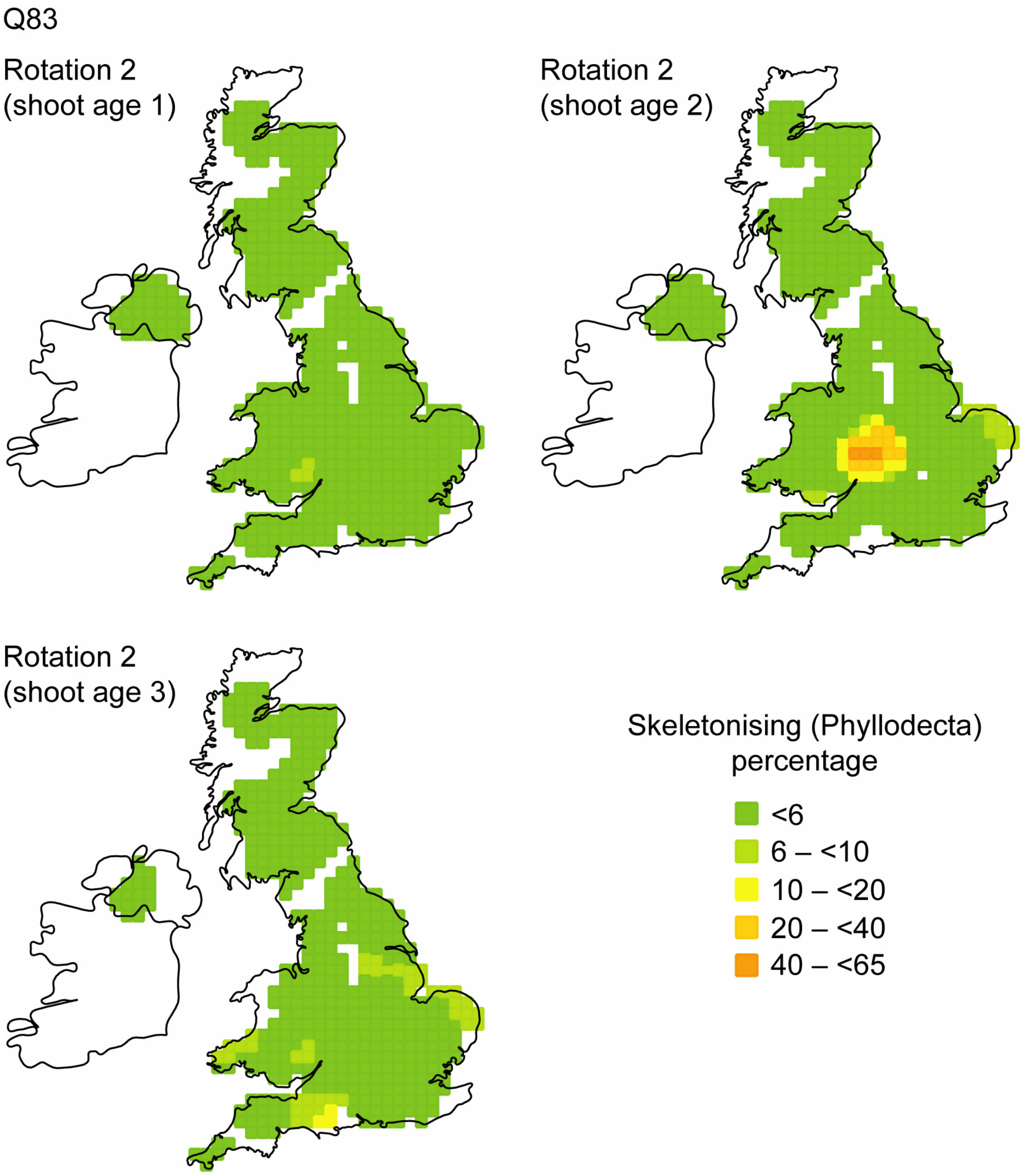
Table 4.11 Summary of damage caused by skeletonising insects to willow varieties grown in monoclonal and mixture plots (scores are % leaf area lost).

	Plot type	Cutting Cycle 1, age 1	Cutting Cycle 1, age 2	Cutting Cycle 1, age 3	Cutting Cycle 2, age 1	Cutting Cycle 2, age 2	Cutting Cycle 2, age 3
Jorunn	Monoclonal	3.09	3.67	4.82	4.64	5.56	7.21
	Mixed	2.82	3.92	6.11	4.73	6.08	7.08
Germany	Monoclonal	3.12	3.28	4.04	3.03	4.21	5.78
	Mixed	3.05	3.34	4.08	2.95	5.03	7.09
Q83	Monoclonal	3.33	3.13	3.26	3.00	3.92	4.05
	Mixed	3.51	3.50	3.78	2.92	4.75	5.93

Table 4.12 Summary of damage caused by skeletonising insects to poplar varieties grown in monoclonal and mixture plots (scores are % leaf area lost).

	Plot type	Cutting Cycle 1, age 1	Cutting Cycle 1, age 2	Cutting Cycle 1, age 3	Cutting Cycle 2, age 1	Cutting Cycle 2, age 2	Cutting Cycle 2, age 3
Beaupre	Monoclonal	2.54	3.44	5.28	4.26	3.74	6.36
	Mixed	2.43	3.74	6.54	4.02	4.79	7.69
Ghoy	Monoclonal	2.52	3.46	4.87	3.68	7.98	7.10
	Mixed	2.37	4.41	4.87	4.04	8.09	7.61
Trichobel	Monoclonal	2.51	3.20	3.62	3.88	5.46	5.40
	Mixed	2.50	4.02	4.05	3.38	5.09	5.27

Figure 4.13 Maps of the incidence and severity of leaf skeletonising damage rust infection on the willow variety Q83 in the second cutting cycle (rotation)



5. Conclusions and deliverables

- A network of 49 trial sites across the UK was successfully established and managed for two, three year cutting cycles.
- A database containing information on site specific environmental variables, insect and disease loads and plot level biomass estimates was constructed.
- The number of environmental variables that significantly effect SRC yield is large but no single variable is able to explain a large proportion (>5%) of the variation in yield observed amongst varieties, sites and years.
- Models able to account for 68.9% of the variation in shoot diameter observed amongst willow varieties, sites and years and 70.3% of the variation in shoot diameter observed amongst poplar varieties, sites and years were constructed.
- 'User friendly' software able to predict the yield of 16 willow and 13 poplar varieties managed as SRC was constructed.
- Very limited validation using data from commercial plantations suggests that yield estimates generated by this software are within 1 to 6.5 odt.$ha^{-1}yr^{-1}$ of observed yield figures.
- 'Yield maps' of willow and poplar SRC have been produced which show variations in yield amongst varieties, location and crop age.
- The incidence of pest and disease in SRC on a country scale changes significantly and rapidly over time.
- SRC pest and disease levels are currently low in Scotland.
- Varieties that are currently resistant or tolerant to disease may not remain so.
- Willow and poplar varieties that perform well in the first cutting cycle may not continue to do so in subsequent cutting cycles.
- The poplar varieties tested are unlikley to provide economically viable yields at sites in Northern Ireland.
- The standing biomass estimation software produced during the course of this project may be of commercial use to SRC growers.

6. Critical review

The network of field trials established across the UK during the initial phases of this research programme were essential to the development of empirical yield models. However, 49 sites can provide only minimal coverage of the variation in soil types and climate found in the UK. As a result maps showing variations in yield and disease levels are relatively crude and have low resolution. Likewise, the accuracy of the predictive model will be limited by the relatively low number of sites used. An increased number of sites would have added considerably to the cost of the project. Ideally all sites would have been planted with the full compliment of 16 willow and 16 poplar varieties used at the intensive sites. Again this would have added to the cost of the project.

Due to the frequency with which plant breeding companies release new varieties many of the varieties used in this project have been superseded. Little could be done to avoid this happening, indeed when the sites were established, some varieties were included prior to their commercial release (ie. Stott 10 and Stott11).

One of the main limitations with the datasets used for model development was the low number of destructive samples taken to related shoot diameter to shoot dry weight. If the number of samples had been increased, more resources would have been required to chip and oven dry the samples.

Only limited validation of the standing biomass estimates and output from the predictive model has 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.

Carrying out limited soil surveys at the end of each growing season may have provided some useful data on how coppice affected soil nutrient status, especially N,P,K levels. This may have helped inform growers on fertiliser requirements, especially if the field trials were managed for further cutting cycles.

Even when these limitations are taken into account, data from the field trials have provided perhaps the most comprehensive set of yield estimates and pest and disease information available in the UK. The yield model software also 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.

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