A review of past and current research on short rotation coppice in Ireland and abroad

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Executive summary

Biomass is considered an important indigenous source of renewable energy with applications in both heating and power, and woody biomass is expected to be a major contributor to achieving Ireland's renewable energy targets. The Renewable Energy Directive has set a target for 16% of final energy from renewables and the White Paper on Sustainable Energy Development set ambitious targets for biomass for 2020; 12% of heat usage by renewables, 800 MWe of electricity from Combined Heat and Power (CHP) 'with emphasis on biomass', and 30% biomass co-firing in three peat burning power stations. The forecasted projections to meet this demand are in the region of 3.6 million m^3 of whole stem softwood by 2020. The forecasted projections for softwood forestry production for 2015 is 4.4 million m^3 per annum. To cover demand from all sectors a substantial increase in forestry area would be required; however, this would not make a net increase in production levels by 2020. Short rotation coppice is a fast growing woody crop which may fill the gap in this market.

This report investigates research in the area of short rotation coppice (SRC) willow and poplar. As most of the research in northern Europe has focused on SRC willow, and under the Bioenergy Scheme 500 hectares have been planted in Ireland, prominence has been given in this report to reviewing research on willow.

The main challenges lie with breeding high-yielding varieties which are disease and pest resistant, optimising nutrient levels on suitable sites to mitigate any negative environmental effects, and finding the most suitable and cost-effective harvesting, storage and drying methods. By analysing research to date and through discussions with key players in the research and commercial markets of short rotation coppice, this study has identified six primary areas of importance to the commercialisation of SRC for energy. These are summarised below along with recommendations for future research areas:

Area 1: Breeding and species selection.

Area 2: Site preparation.

Area 3: Disease and pest control.

Area 4: Nutrition and bioremediation.

Area 5: Harvesting, storing, drying and utilisation.

Area 6: Alternative species.

Area 1: Breeding and species selection

Willow varieties are currently bred to produce high-yielding, disease and pest resistant varieties that are suitable for specific environmental conditions. The main breeding programmes in Europe are located in Sweden and the United Kingdom (UK). The Swedish programme is run by Lantmännen Agroenergi. The UK breeding programme is located at Rothamsted. Four new willow varieties from the Swedish programme are in the pipeline, to be released to the commercial market in the coming years. Cross-collaboration exists between these programmes and other European countries where projects and field trials are ongoing in the countries involved and at locations across the UK.

It would be beneficial for research institutes in Ireland to link in with and build upon research that has been conducted and is ongoing in the UK and Europe. Recommendations for future research include:

- Establish a site in the Republic of Ireland where trials can be conducted on existing and new willow genotypes and develop a recommended list of suitable varieties for Irish suppliers and growers. The site should be linked to the existing UK network to facilitate information exchange.

Area 2: Site preparation

Most tillage and pastoral land in Ireland should not pose a problem for growing willow as long as fields are at a low elevation and do not exceed 15° in slope. Most concerns relating site preparation are already well researched and recommendations are available in a number of publications.

Polyclonal plots are preferred in maritime climates, as opposed to monoclonal plots, as a method to control the spread of rust but can lead to non-uniformity within a crop. Yield increases are correlated with planting density and rotation length; however, this must be balanced with greater handling and harvesting costs. Recommendations for future research include:

– Investigate the effect of enhanced growth levels on harvesting machinery in polyclonal plots.

– Examine the relationship between planting density, rotation length and harvesting costs.

Area 3: Disease and pest control

Willow plantations are expected to remain viable for up to 20 years. However, experience with older varieties has shown that resistance to yellow rust and other diseases can break down, with a substantial loss in productivity. Protecting a willow plantation from pathogen attack over a period of 20 years poses a significant challenge. This is particularly the case for rust as the warm, moist, maritime Irish climate is ideal for fungal growth. Work in Northern Ireland has proven the value of diverse genotype mixtures as a disease control strategy. Recommendations for future research in Ireland include:

– Continuously monitor commercial varieties for the emergence/severity of rust.

– Research to understand the nature of willow pathogens.

– Refine methods of disease and pest control in willow plantations.

– Monitor the performance of new commercial varieties in monoclonal and polyclonal plots.

– Consider a revision of the bioenergy guidelines to provide for the use of a wider range of genetic varieties at a national level as well as within individual plantations.

Area 4: Nutrition and bioremediation

Teagasc provides guidelines for application levels of nitrogen, phosphorus and potassium. However, with increased interest in the area of bioremediation, applications rates must be balanced with plant nutritional uptake to avoid environmental issues from runoff.

Organic wastes can be applied to SRC willow plantations as a fertiliser and to hydrate the crop. This process can also be used to remove heavy metals from the wastes. Wastes can be categorised as dilute effluents from the food industry and waste water treatment plants; sludges from sewage treatment plants; and landfill leachates. Opportunities for landspreading are tightly regulated by the Nitrates Directive and need to comply with nutrient management plans; however, there is an opportunity to provide alternative enterprises for local farmers and facilitate local authorities. Recommendations for future research include:

– Investigate the optimum strategy for the application of organic wastes/fertiliser in line with the uptake of nutrients.

– Investigate the uptake of heavy metals by willows, and on the changes in soil concentrations following multi-annual sludge applications.

– Examine the irrigation of willow plantations with waste water from treatment plants.

– Research sludge application techniques for the first and second years after harvest.

Area 5: Harvesting, storing, drying and utilisation

Willow is generally harvested by one of three methods:

1. Harvesting and chipping in one operation.
2. Harvesting and cutting into 5-20 cm billets.

   Both of these methods can be used to deliver chip directly to a large consumer where it can be burned as wet chip. Alternatively, it can be stored for a short period of time. Forced ventilation is required for longer periods of storage as build-up of fungi/bacteria and spontaneous combustion are possible. Forced ventilation may also be required when the end user market is for residential, commercial or smaller-sized industrial boilers for which wet chip is not suitable.

3. Whole-tree cutting with natural drying.

   The drying ability of the whole stems will depend on the site exposure. Moisture content at the time of chipping may affect the quality of chipped biomass. This method of drying can be suitable for smaller-sized boilers when forced drying is not an option, but does incur additional handling. It has the advantage of giving the grower greater input into the harvesting of the crop by using adaptations of conventional farming machinery

Focussed research into these methods, along with transportation requirements, is necessary to allow a more informed comparison of all methods. Recommendations for future research include:

– Streamline the costs associated handling and transport for whole-tree systems.

- Consider the cost of forced ventilation against the extra handling costs of whole-tree cutting.
- Research is needed to quantify and compare the economics, the energy balance as well as the greenhouse gas balance of each method.
- Examine the effect of stem moisture content on the harvesting performance and chip quality.
- Examine the logistics of chip supply to boilers and the optimum transport catchment area.
- To allow SRC willow to be supplied for co-firing at the peat stations in the most sustainable way, investigate the balance between concentrated planting near the power stations and any environmental issues such as visual intrusion and water demand that this might create.

Area 6: Alternative species

Poplar was identified as an alternative SRC crop to willow. Trials have shown that yields from poplar are comparable to yields from willow. However, most of the research in the area of SRC energy crops in northern Europe has focussed on SRC willow. Experience from the field has suggested that poplar is more difficult to breed and process, and has the same problems with rust susceptibility. Recommendations include:

- Research should concentrate primarily on willow in the short term and build on experience from other countries.
- The progress of poplar and potential of other species should be kept under review.
- If it is required to build and expand our woody biomass resources then poplar should be considered as a potential SRC crop and ash may be suitable as a longer rotation coppice choice for further research work.

Carbon mitigation potential

In addition to the areas assessed in this report, the carbon mitigation potential of energy crops warrants further investigation. Quantitative information on carbon mitigation by willow plantations is sparse and relatively little research has been carried out in this area. There is a need to conduct research in this area in order to quantify the potential of willow plantations to mitigate the rise in greenhouse gas concentrations.

Abbreviations

BEGIN	Biomass for Energy Genetic Improvement Network
CHP	Combined heat and power
EU	European Union
EWBP	European Willow Breeding Programme
ha	hectare
IACR	Institute of Arable Crop Research
$ha^{-1}yr^{-1}$	per hectare per year
kg ha^{-1}	kilogram per hectare
LARS	Long Ashton Research Station
MAI	mean annual increment
mg kg^{-1}	milligram per kilogram
MW_e	Mega-Watt electrical
odt	oven dry tonnes
S.I.	Statutory instrument
SIF	stem infecting form
SLU	Swedish University of Agricultural Sciences
SRC	short rotation coppice
SWBP	Swedish Willow Breeding Programme
UK	United Kingdom

1. Introduction

1.1 Background

At the time of the oil crisis in the 1970s, Ireland expanded the use of imported coal to reduce dependence on imported oil. This expansion policy was abandoned in the late 1980s in favour of imported natural gas (Eurostat 2009). In 2007, 91% of the energy consumed in Ireland was imported; 56% consisted of oil and petroleum products (Central Statistics Office 2009). Currently, indigenous energy generation in Ireland (~ 9%) is made up of peat (42%), natural gas (26%) and renewable energy (32%); biomass makes up 38% of the renewable portion and approximately 1% of total energy consumption (Central Statistics Office 2009).

Increases in oil and gas prices over the last few years have made fossil-based electricity and heat production more expensive. Higher energy prices, limitations in the rate of oil supply and rapidly increasing demand from growing economies such as China and India may reflect a new era in energy provision (Styles and Jones 2007). In addition, concerns about global warming have put increasing pressure on countries worldwide to limit the use of fossil fuels and increase the uptake of renewable energies.

Of the many national and EU legislative initiatives that have been introduced to promote renewable energy development over the past ten years, two have particular relevance at this time: the Irish Government's 2007 White Paper on Sustainable Energy Development, and the recent EU Renewable Energy Directive (Department of Communications, Marine and Natural Resources 2007; Commission of the European Communities 2008). These documents have set out targets for renewable energy development up to 2020. The White Paper aims for 12% of heat use and 10% of transport fuels to be from renewable sources by 2020, along with 800 MWe of electricity from Combined Heat and Power (CHP) 'with emphasis on biomass', and 30% biomass co-firing of the three power stations currently burning almost exclusively peat. The EU Directive sets a target for the EU to produce 20% of total final energy from renewable sources by 2020; Ireland has been given a 16% target in the Directive. The transport target has been modified to allow the achievement of the 10% target from all renewable sources, not solely biofuel. The Directive also requires Member States to submit National Action Plans in pursuit of the Directive targets; the template for these plans was been issued recently, and the plans have to be submitted by June 2010.

As a response to rising energy prices and these major policies, there is renewed interest in alternatives such as solid fuel biomass (Department of Environment, Food and Rural Affairs 2004) for power and heat generation. Traditionally, forest energy assortments have supplied the biomass market. However, as wood for energy is becoming increasingly more important, there is a foreseeable scenario of competition between the emerging renewable energy sector and the traditional uses of forest resources (Mola-Yudego and Pelkonen 2008). In Ireland, the attainment of the biomass heat and electricity targets will require provisional estimates of 3.3 million m^3 of whole softwood per annum by 2020. This makes up a substantial proportion of the forecasted forest production of nearly 5 million m^3 per annum by 2015 (Gallagher and O'Carroll 2001). To meet demand from all sectors, an increase in the conventional forested area is desirable and could provide a long-term increase in biomass production; however, it can make no additional contribution to the 2020 targets.

Perennial energy crops are now being planted as an alternative to conventional forestry to increase biomass production. High-yielding short rotation coppice plantations may help fill the gap between this new demand for biomass and the current supply levels (Mola-Yudego and Pelkonen 2008).

While a number of existing publications provide best practice guidelines for SRC willow plantations (Dawson 2007, Danfors et al. 1998), this report presents a short overview of guidelines along with a review of past and current research in the area of SRC in Ireland and abroad with the aim of identifying gaps in the current level of knowledge and to provide recommendations for future research necessary to advance the adoption of SRC willow as an energy crop in Ireland.

1.2 Objectives and scope

The overall objective is to review past and current research on SRC in Ireland and abroad and present an overview of the work that has been carried out in the area. Recommendations are made on future research work that should be carried out in Ireland.

The scope of this study includes a review of published research literature and discussions with key research and commercial participants to identify and assess the most relevant past and present research projects on short rotation coppice in Ireland and abroad in the areas of:

Area 1: Breeding and species selection.
Area 2: Site preparation.
Area 3: Disease and pest control.
Area 4: Nutrition and bioremediation.
Area 5: Harvesting, storing, drying and utilisation.
Area 6: Alternative species.

The analysis begins with an overview of SRC willow and major breeding programmes and concludes with the identification of current and future research needs in these areas.

1.3 Methodology

A review of published material from research institutes, industry and academic journals and government departments and agencies was conducted to identify the scope and findings of past and current research. In addition, a number of current projects were identified at research institutes and commercial operations in Ireland, the United Kingdom (UK) and Sweden. It was recommended in the early stages of research that emphasis is placed on research that has been conducted by the latter two countries as this is where most of the research and planting has taken place in Europe. The relevant people were contacted in relation to each project and where possible, a site visit was conducted to meet with and interview experts in the field (Table 1).

Table 1: Sites visits and contacts.

Site visit	Topic	Contacts
Agri-food & Biosciences Centre, Co Armagh	− Variety trials − Bioremediation − Drying	Alistair McCracken, Paul Moore
Rural Generation Ltd, Co Derry	− Commercial plantation − Variety trials − Forced-drying ventilation system − Bioremediation − Machinery	John Gilliland
Rothamsted Research Centre, UK	− Breeding programme − National willow collection − Discussion on rust	Angela Karp, Ian Shield, William Macalpine, Ming Pei
Small scale local supply system, Co Kilkenny	− Commercial plantation − Whole-tree harvesting with natural drying − Bioremediation	Michael Gabbett
Swedish University of Agricultural Sciences	− Bioremediation − Site visit to Enkoping − Breeding programme	Par Aronsson, Anki Wastljung
Swedish Institute of Agricultural and Environmental Engineering	− Project: Harvesting technology and logistics for better profitability from small cultivations of SRC	Maya Forsbery, Andras Baky

2. Short rotation coppice

Short rotation coppice (SRC) refers to a perennial, fast-growing, high-yielding woody crop that is harvested every two to five years and managed under a coppice system (Evans et al. 2007). The best known dedicated SRC crops grown commercially for heat and power generation belong to the plant family Salicaceae and include two genera: *Populus* (poplar) and *Salix* (willow) (Newsholme 1992).

The genus *Populus* ranges from sub-tropical to temperate and boreal regions of the northern hemisphere (Zsuffa et al. 1996, quoted by Karacic 2005). Willow can be found, through natural distribution or introduction, in most parts of the world (Newsholme 1992).

Much of the research work carried out in northern Europe, in particular Sweden and the UK, has focused on developing high-yielding willow as an energy crop. Today over 16,000 ha of willow are commercially grown in Sweden (Short Rotation Crops 2009), but very little poplar is grown commercially by comparison. Poplar is generally grown more widely as an energy crop in areas of southern Europe, where it is considered better suited to the environment than willow (Spinelli, Nati and Magagnotti 2008). An extensive UK study on *Yield Models for Energy Coppice of Poplar and Willow* found that willow was generally higher-yielding than poplar (Aylott et al. 2008). Experience in the UK with breeding poplar has suggested that it is more difficult to make crosses due to lower flowering, and takes a longer time to produce seed in comparison with willow which makes producing new clones more difficult (Ian Shield, personal communication). Rust susceptibility and harvesting of the crop have also presented issues (Dawson 2007). As such, this study focuses primarily on willow as a SRC energy crop.

2.1 Willow

The genus *Salix* originated in the mountains of Eastern Asia and spread into parts of temperate and Arctic regions of the northern hemisphere (Newsholme 1992). The trees thrive in temperate, wet conditions and produce strong, light wood. Traditionally, willows have been used in basket making and as garden plants, and more recently for energy production (Pei and McCracken 2005).

Willow cultivation can be dated back to the Roman Empire in the second century BC, where varieties of willow such as *Salix caprea, Salix alba* and others were used for the production of baskets, fences, medicine, and as framing for shields. Around the 1800s willow cultivation for basketry and furniture was widespread. However, at the end of the 1800s, demand for willow was declining due to competition from cheaper material and competition from basket production overseas (Volk et al. 2004). Around the 1920s a willow collection was started at Long Ashton in England; a breeding programme was also initiated around the same time (Karp 2007).

The genus *Salix* comprises approximately 400 species and more than 200 listed hybrids (Newsholme 1992); these are mainly deciduous trees and shrubs and all show a significant variation in growth rate and size. There are three main subgenera (Hanley et al. 2003) (Table 2). Willows used in energy production belong to the subgenera known as *Salix* or true willows (Larsson and Lindegaard 2003).

Table 2: Subgenera of the genus *Salix*.

Subgenus	Characteristics	Examples
Salix (true willow)	Upright, semi-pendulous or pendulous trees and large shrubs with narrow, serrate leaves	*S. alba, S. babylonica*, *S. fragilis, S. nigra*
Caprisalix or *Vertix* (osiers and sallows)	Shrubs and small trees with great variation in leaf form	*S. caprea, S. cinerea, S.aurita, S.viminalis*
Chamaetia (dwarf willows)	Creeping, mountain or arctic shrubs with small rounded or blunt leaves	*S. reticulata, S. herbacea, S. retusa, S. myrsinites*

Source: Hanley et al. 2003

Interest in willow as a SRC energy crop has evolved over the last 30 years. Willow for energy production has a number of inherent benefits both as a crop and in the wider environment and community, including:

- Fast-growing perennial plant with the ability to coppice after harvest.
- Particularly suited to climatic and soil conditions in Ireland (Dawson 2007).
- Greenhouse gas emission savings – the end market being developed for willow is renewable heat and power, and as a dedicated energy crop it can provide a long term, sustainable replacement for fossil fuels (Smart et al. 2005).
- Environment – low environmental impact when compared with conventional crops due to reduced chemical input (Mitchell et al. 1999).
- Potential to use organic fertiliser as a replacement for inorganic fertiliser.
- Biodiversity – potentially positive impact on biodiversity by offering shelter for birds and mammals. In the UK more insects live on willows than any other tree species (Kennedy and Southwood 1984, quoted by Hanely and Karp 2003).
- Alternative income for farmers with faster returns than those associated with conventional forestry (Dawson 1992, quoted by Hanely et al. 2003).
- Local supply chain – SRC plantations located at a short distance from industrial facilities may effectively meet the heating demands of these facilities (Karacic 2005).
- Applications – willow can also be used for a number of applications in conjugation with bioenergy which can work side by side with the energy producing aspect of the crop. These include bioremediation, phytoremediation (the use of plants to clean up contaminated soils and restore degraded sites), nutrient management, and streambank stabilization (Smart et al. 2005).
- Continuously producing new varieties through selection and adaptation of intra-specific (similar clones) and inter-specific (hybrid) crosses.

2.2 Yield

The biomass yield from a plantation is typically measured in oven dry tonnes per hectare per year (odt $ha^{-1}yr^{-1}$). The productivity of a plantation is site specific but average commercial yields of 8-10 odt $ha^{-1}yr^{-1}$ are attainable in Europe. Trials in the UK have shown that up to 15-18 odt $ha^{-1}yr^{-1}$ can be achieved under certain conditions; and through specialised breeding, targets of 25 odt $ha^{-1}yr^{-1}$ may be achievable (Karp 2009).

Yields are generally greater in the second harvest rotation compared to the first. This may be attributed to an overall increase in shoots per stool and stem diameter between harvests (Danfors et al. 1998).

2.3 Breeding

The majority of SRC willows currently grown in Europe are *Salix viminalis* and its clones. This species is favoured for SRC because it grows fast, coppices well and maintains a good growth form (Pei et al. 2008).

High yields can be achieved through breeding. However, gains associated with varieties of intra-specific crosses between *S. viminalis* and its clones may be limited due to the narrow genetic pool. In order to achieve higher productivity, hybridisation (inter-specific crosses between species and varieties) has been used in breeding programmes where desirable traits from the parents are brought over to the new variety (Lindegaard 2001). Most new varieties are fertile and can cross with other species/varieties (Hanley et al. 2003) and the relative ease with which hybridisation occurs in nature means there is extensive scope to make rapid improvements in yield productivity (Danfors et al. 1998).

Current willow breeding programmes aim to produce high-yielding, disease and insect resistant varieties (Appendix 1) that are suitable for commercial planting and harvesting machinery for the biomass energy industry (Lindegaard 2001) (Table 3).

In Europe, the main willow breeding programmes are located in Sweden and the UK. Smaller breeding programmes exist in other European countries. The geographic locations of breeding programmes influence varieties being produced; for example, in Sweden the varieties that are being bred show greater tolerance to frost (Hanely et al. 2003).

Table 3: Objectives of willow breeding programmes.

Factor	Traits
Yield	Increase dry matter yield Select tallest clones Either “few and thick” or “many and thin” stools
Disease and pest resistance	Improve resistance to rust and willow beetles Select clones less palatable to mammals
Harvesting ability	Select straight rods with few side branches
Climatic conditions	Select clones suitable to local conditions; tolerance to frost in Nordic areas and drought in southern areas of Europe

Source: Lindegarrd and Baker 1997 quoted by Hanely et al. 2003.

Swedish Willow Breeding Programme (SWBP)

The Swedish University of Agricultural Science (SLU) began research on willow breeding in the mid 1970s and set up a breeding programme in 1985. In 1987, Svalöf-Weibull commenced commercial breeding activities with field selections for growth and resistance traits. This became know as the Swedish Willow Breeding Programme (SWBP). The SWBP used plant material from Sweden and central Europe, central Russia and Siberia to broaden the genetic base. The main clones used were *S. viminalis* and *S. dasyclados* (Larsson 1998). Earlier crosses produced a number of varieties, including Orm, Rapp, Ulv, Jorr and Jorrun from the intra-specific crosses of *S. viminalis* clones (Hanely et al. 2003). Later inter-specific crosses have produced high-yielding and disease-resistant varieties such as Björn and Tora (Larsson and Pirrwitz 1998). Svalöf-Weibull has been taken over by Lantmännen Agroenergi (Agrobransle 2009).

European Willow Breeding Programme (EWBP)

In 1996, the European willow breeding programme (EWBP) was initiated at Long Ashton Research Station (LARS) in England under a partnership comprising LARS, Svalöf-Weibull and Murray Carter (UK) (Karp 2007). The EWBP may also be referred to as the UK willow breeding programme.

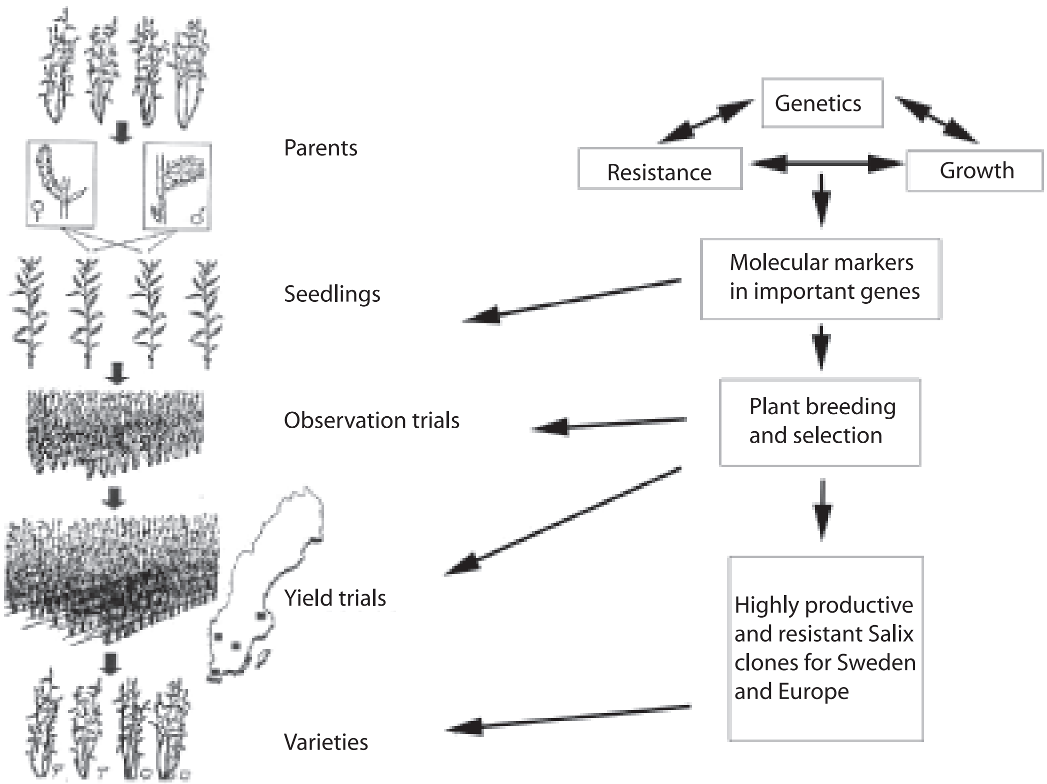
During the first five years of the programme (1996-2000), various breeding and selection strategies were employed, using over 20 different species from north and central Europe, Russia, Asia and North America (Lindegaard 2001). Species included *S.viminalis, S. caprea, S. rehderiana, S. udensis, S. schwerinii, S. discolor* and *S. aegyptiaca* (Lindegaard et al. 2001). The EWBP successfully bred eight new commercial biomass varieties (Quest, Beagle, Resolution, Discovery, Nimrod, Terra Nova, Endurance and Endeavour) and has released other varieties such as Ashton Stott and Ashton Parfitt which predate the EWBP (Karp 2007). The breeding programme was discontinued in 2002, due to the closure of the Institute of Arable Crop Research (IACR) at Long Ashton. The willow collection was moved to Rothamsted Research Centre. Breeding has since continued there, through funding from the UK Department of Environment, Food and Rural Affairs, as the Biomass for Energy Genetic Improvement Network – BEGIN (Karp 2007).

Rothamsted Research Centre houses the UK national willow collection with over 1,300 varieties and 100 from the known 300 species of the genus *Salix*, together with an extensive set of hybrids, basket and biomass clones (Department of Environment, Food and Rural Affairs 2009).

Current breeding procedures

Current breeding procedures use molecular markers (to identify specific DNA sequences) to make early selections in the breeding process of willow and will be utilised in the ongoing breeding work to increase the efficiency of the selection and breeding process. This process will help to understand the genetics behind resistance and tolerance against insects, pests and pathogens, traits affecting plant growth and in essence will make breeding more efficient (Tuskan 1998).

Both the Swedish and UK breeding programmes are involved in developing molecular maps for willow hybrids. Early detection of traits and combining individuals with several of these traits means that fewer plants need to be tested than are required with traditional breeding methods (Figure 1).



Source: SLU 2009

Figure 1: Marker-based breeding programme for willow.

The UK breeding programme has identified three major markers associated with rust resistance and six associated with biomass yield, including one associated with the yield components (maximum stem diameter, maximum stem height) and a second associated with shoot number (Karp 2007). Currently at Rothamsted, five genotypes look promising for commercial development in the near future (Shield et al. 2009).

Lantmännen Agroenergi is currently involved in commercial breeding in Sweden and every year new crosses are being made. For example, in 2008, more than 5,000 new genotypes were produced, after which selections were made for field trails. Currently, four clones are in the pipeline at the Community Plant Variety Office, a European Union agency, for variety approval (August 2009); these are Klara, Stina, Lisa and Linnéa. The date for the commercial release of these onto the market is not yet known (Inger Ahman, personal communication).

Recently, the willow genetic map was aligned with the poplar genome map (Shield et al. 2009) which is available on the Joint Genome Institute website (http://genome.jgi-psf.org). The similarly between maps has made identifying genetic markers in the willow genetic map more successful. However, work is ongoing and the challenge remains to identify all genes associated with biomass yield (Karp 2007).

3. Review of past and current research

The production of harvestable biomass from SRC energy plantations involves techniques and management required to optimise total dry matter yield. These include breeding and species selection; site preparation; control of disease and pests; provision of nutrients; harvesting, drying and storage of wood chip; and ensuring that a quality fuel is delivered in an efficient way to the end user. Research and some level of commercial activity into energy crops other than willow is also underway. The sections below provide an overview of each of these areas in terms of work that has been done to date and that is ongoing nationally and internationally, with a view to identifying gaps in knowledge and providing recommendations for future research work necessary to optimise the use of SRC energy crops in Ireland.

3.1 Breeding and species selection

Given that biomass willow breeding programmes are relatively new compared to those for more conventional food crops, it is likely that the potential for producing superior varieties is high (Hanley et al. 2003). Genetic improvement of willow is necessary to obtain locally adapted varieties which show improved growth and yield rates, improved resistance to disease and pests and therefore increase the economic attractiveness of growing willow as an energy crop (Kopp et al. 2005).

Current research projects

Rothamsted Research Centre hosts the Biomass Energy Genetic Improvement Group (BEGIN). This group is involved with Swedish and German partners in an ERA-NET bio-energy project entitled *Targeted Breeding of a European SRC Willow Crop for Diverse Environments and Future Climates*. The aim is to breed high-yielding willow varieties that perform well in drought conditions in anticipation of drier conditions in east Britain due to global warming. This project began in early 2000 when 35 crosses were made in a greenhouse setting. During the summer of 2000, about 5,000 plants were raised in a nursery. Selections for further trials were made based on plants showing traits desirable for high yields. Around 10% (~ 500) were moved to field trials the following spring; this number was limited due to the size of the area designated for the project. Varieties were planted in sandy soils to represent drought conditions. Further observation and yield trials are being conducted. A number of willow varieties are in advanced observation in yield trials located across the UK at Rothamsted, Long Ashton, Yorkshire, Lincolnshire, Loughgall (Northern Ireland) and Londonderry (Northern Ireland). It is expected that new varieties may be chosen for research and commercialisation in 2011 (Shield et al. 2009).

Lantmännen Agroenergi in association with the Swedish University of Agricultural Science (SLU) is involved in a project entitled *Salix Molecular Breeding Activities* (Samba). A set of new varieties is currently being tested at sites across Europe: three in Sweden, one in Portugal, one in Italy and one in Slovakia. These varieties have been bred for warmer climatic conditions.

In Ireland, Teagasc recently recommenced trials supported by the Department of Agriculture Stimulus Research Fund in partnership with the Carlow Kilkenny Energy Agency, Carlow Institute of Technology and a number of other partners. The variety trials are located at Oak Park in Carlow and include varieties from the EWBP - Resolution, Tera Nova and Endurance, and from the SWBP - Sven, Inger, Tordis, Tora, Doris, Torhild and Karin. Future Irish trials should be linked with projects ongoing in the UK and Europe.

Species selection

The Irish Department of Agriculture *Bioenergy Best Practice Manual for SRC Willow* states that all varieties grown in Ireland must be suited to the 'Irish climatic conditions' (Department of Agriculture, Fisheries and Food 2009). Past experience has shown varieties from Sweden which did not perform well there have performed adequately in trials in the UK (Agri-food and Biosciences Institute 2009). There is a need to monitor new commercial varieties from the Swedish and UK breeding programmes to ensure that new varieties are suitable for Irish climatic conditions. In Northern Ireland, the Department of Agriculture, Food and Rural Development is closely involved in the selection of potential new varieties.

In addition, very little independent information on varieties is available to growers and no recommended or descriptive list exists for commercial willow varieties unlike the situation in the arable crop sector (Knightley et al. 2008). New varieties must be monitored and a recommended list for Irish suppliers and growers developed.

3.2 Site preparation

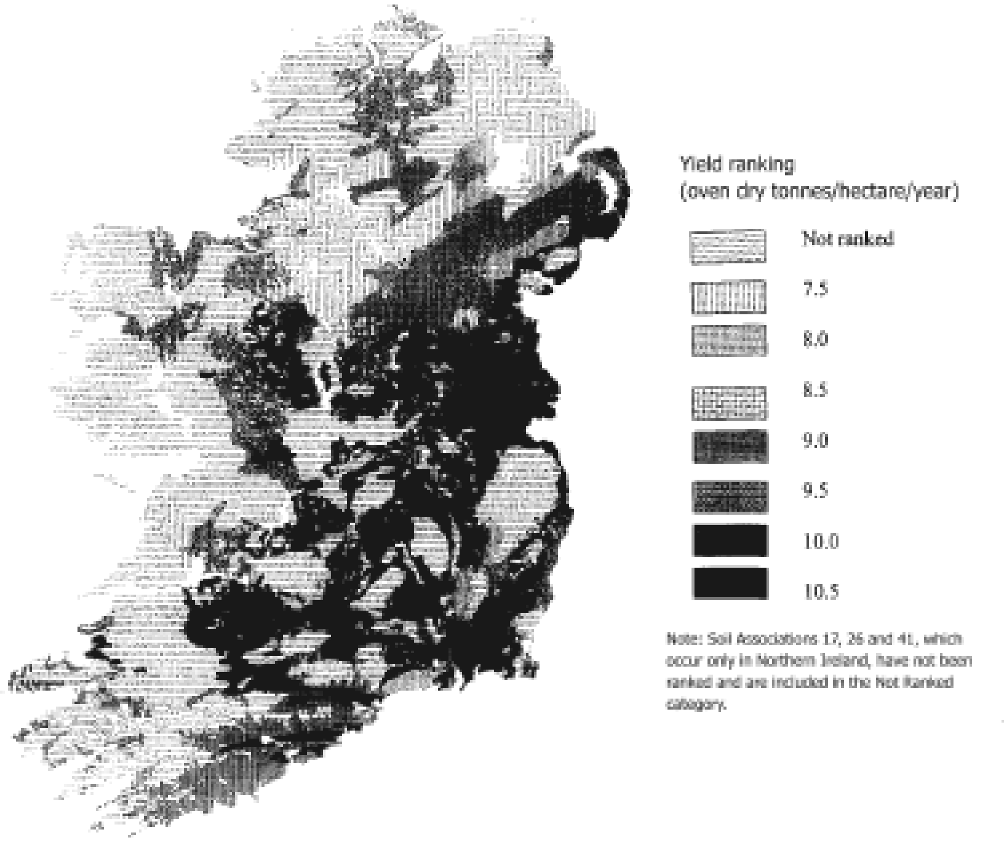
Soil types

The choice of site is particularly important for a high-yielding willow plantation. Willow is very water-dependent so sufficient moisture should be available to the crop. Annual rainfall of around 900-1,100 mm per annum is recommended. Willow grows best in soils with a pH between 5.5 and 7.5. Soils which are prone to summer frost and waterlogging should be avoided (Danfors et al. 1998).

UK willow variety trials were conducted between 1991 and 1995 at IACR-Long Ashton in Bristol, Markington in North Yorkshire, Loughgall in Armagh and North Molton in Devon. The LARS (Long Ashton Research Station) site was more productive than the others. The soil at LARS is fertile brown earth, which is one of the best soil types for SRC production. The Loughgall site in Northern Ireland contained heavy clay loams with an underlay of limestone, was exposed and for the first four years produced comparatively low average yields. In 1995, higher yields were attained from Loughgall on a more sheltered site with rich soil (Lindegaard et al. 2001).

A map illustrating the potential yield from areas in Ireland based on soil type (Figure 2) was produced in the 1990s.

More detailed maps were produced for the UK in the mid 1990s by Forest Research (FR) from a study on yield models for energy coppice of poplar and willow. Forty-nine sites were selected throughout the UK to cover the major soil types suitable for poplar and willow, over a range of climatic conditions (Forest Commission 2009). Results were used to generate regional 'opportunity maps'. Sites were classified as high, medium or low yielding. The maps are available on the Department of Environment, Food and Rural Affairs website (Figure 3). Maps similar to these may be useful for Ireland but it may be enough to deduce that there is sufficient rainfall in Ireland and that most areas are suitable if guidelines are followed according to the *Bioenergy Best Practice Manual for SRC Willow*. Generally, fertile agricultural land at low elevation with a slope not exceeding 15° is suitable. Peaty soils, dry or waterlogged soils should be avoided (Department of Agriculture, Fisheries and Food 2009). Sustainable Energy Ireland is developing a GIS-based Bioenergy Mapping System which will provide general guidance on areas suitable for planting energy crops such as SRC willow. However, each site should be individually assessed for suitability.



Source: Van den Broek et al. 1997.

Figure 2: Potential suitability map for willow short rotation coppice.

Source: Department of Environment, Food and Rural Affairs (2009).

Figure 3: SRC yield map for South West England.

Site selection and planting density

Willow plantations should be laid out to facilitate harvesting machinery. Rows should be as long as possible with headlands at least 10 m wide (Danfors et al.1998).

The planting season is from early spring to mid summer, but early planting means earlier establishment and a longer growing season (Dawson 2007). Planting is carried out by a step planter: unrooted dormant willow cuttings are planted in double-row spacing. In Ireland, the current recommendation for plant spacing is 0.6 m between cuttings within rows, 0.75 m between rows and 1.5 m between double rows (Figure 4) (Department of Agriculture, Fisheries and Food 2009).

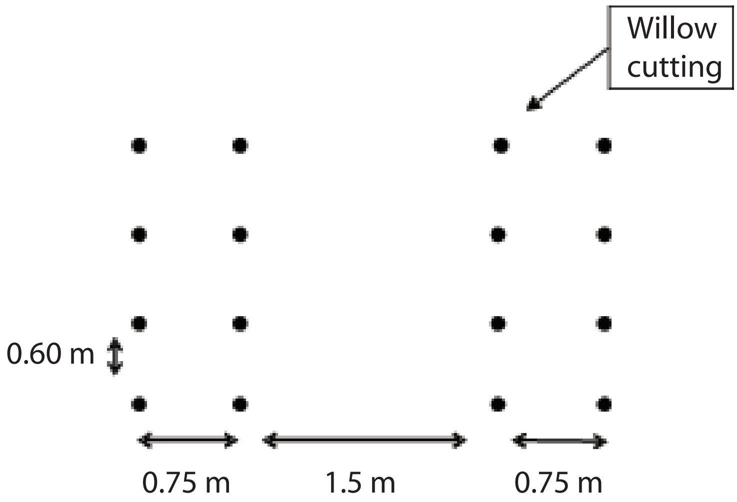


Figure 4: Recommended willow planting layout.

The planting arrangement (Figure 4) gives a planting density of approximately 15,000 cuttings per hectare. Closer spacing may be desirable for energy production resulting in higher yields (Mead 2005).

A Swedish study showed that stem biomass yield is strongly correlated with planting density, showing higher yields at denser spacing. Biomass yield reached a maximum at a spacing density of 20,000 plants per ha and did not increase significantly beyond this density. A substantial yield reduction was found at 10,000 plants per ha (Bergkvist and Ledin 1997).

A more recent study in Northern England showed that the willow variety Ashton Scott produced the highest yield at 20,000 plants per hectare with no net increase in yield beyond this density. Tora produced only a slight increase at 25,000 plants (Wilkinson et al. 2007). At higher densities (> 20,000), coppiced *S. viminalis* has been shown to self-thin (some shoots die with the remaining shoots developing an increased stem dry weight) (Verwijst 1991, quoted by Wilkinson et al. 2007). Further density increases (> 25,000) can result in stool mortality increases due to competition between stools with no significant gains observed (Willebrand and Verwijst 1992, quoted by Bergkvist et al. 1997). Overall, the economics of increased biomass offset by the cost for extra plants should be considered (Wilkinson et al. 2007).

The influence of planting design, double or single row spacing does not have a significant impact on yield at any given planting density (15,000, 20,000 etc.). This is most likely due to the ability of the plant to take advantage of available space (Bergkvist and Ledin 1997).

Monoclonal verses polyclonal plots

In drier regions, such as eastern England and Sweden, there has been a preference for monoclonal plots for a number of reasons: single variety plantations allow clearer observation of crop performance, easy access for crop replacement if a variety fails and more uniformity in harvesting (Department of Environment, Food and Rural Affairs 2007). However, in recent years, monoclonal plots have posed a major problem to willow plantations in Ireland and parts of England. Diseases such as yellow leaf rust, which thrives in moist conditions, can spread easily through monoclonal plantations. Studies have shown that a variety that is initially not prone to rust can break down after 10-12 years of exposure to the disease, particularly when grown in monoclonal plots (McCracken and Dawson 2003).

Polyclonal (mixed variety) plots can act as a control strategy to the spread of rust; varieties not susceptible to rust can act as a physical barrier to the spread of the disease. For example, in 1987, four clones (*S. viminalis* Bowles Hybrid, *S. viminalis* 683, *Salix x dasyclados* and *S. burjatica* Germany) were planted both as monoclonal and polyclonal plots in trials in Northern Ireland. The results found that yields in the first year were not significantly different between monoclonal and polyclonal plots, but by the second year the mean dry matter yield from the polyclonal plots were higher than yields from the monoclonal plots (about 37%). Differences were maintained through the third year of growth. There were no significant differences between the dry matter yields of all monoclonal crops (Dawson and McCracken 1995). The lower yield from the monoclonal plots was attributed to the onset of rust; the higher yield from the polyclonal plots was attributed to successful varieties occupying free space made available by failed varieties (Dawson et al. 1995).

However, enhanced growth of one variety relative to another in polyclonal plots may lead to non-uniformity within the crop which can pose an issue with harvesting (Department of Environment, Food and Rural Affairs 2007).

Rotation length

Stems are cut back during the winter after the first growing season to allow coppicing. A rotation length of 2-3 years is usually practised; however cycle length should coincide with when the peak mean annual biomass increment (MAI) occurs. A UK study showed that higher annual yields were attainable with higher planting densities, combined with more frequent harvesting (Bullard et al. 2002). However, shorter rotation lengths require more intensive management, and the yield benefits of harvesting every two years may be offset by harvesting costs being almost 50% higher than harvesting every three years (Wilkinson et al. 2007). In addition, less robust harvesting machinery may be used as stem sizes are narrower.

A study investigating the relationship between rotation length, planting density, yield and harvesting costs would be useful.

Other issues during establishment

Pre-planting weed control is usually one or two doses of glyphosate-based herbicide. A pre-emergence residual herbicide is then applied 3-5 days before planting (Dawson 2007). Following establishment and after cutback a further herbicide application will be necessary to keep the crop weed-free (Dawson 2007). There is, however, a restricted range of broadleaf herbicides available for use on willow. This can make weed control difficult in certain circumstances.

Grazing by deer, hares and rabbits can be a particular problem in small, isolated, newly established crops (Royle et al. 1995). Fencing should be put in place in SRC crops where there is a sufficient number of hares and rabbits present in the area. Best practice should be followed for weed control and fencing and there is no need for future research work in these areas.

3.3 Disease and pests – occurrence and prevention

At present, the major factors contributing to yield limitation in willow plantations are disease infection, most notably rust (*Melampsora* spp.), and insect infestation, particularly willow beetles, willow aphids, leaf hoppers and crane fly larvae (Department of Environment, Food and Rural Affairs 2007).

Rust

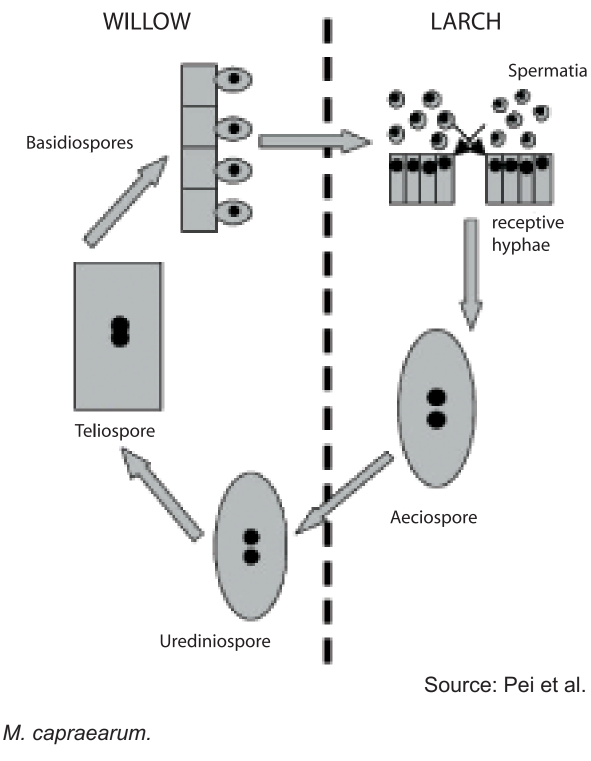
Leaf rust, caused by the *Melampsora* fungus is the most important and widespread disease affecting coppice willow in the British Isles and Sweden (Pei et al. 1999). This pathogen favours especially wetter climatic conditions (Dawson 2007) and infects willow leaves by causing them to wither prematurely and can cause defoliation with resulting yield reductions (Dafros et al. 1998).

Severe rust also predisposes plants to infections by secondary pathogens which may lead to death of the plants. In most willows, rust only affects the expanded leaves but in some species such as *S. viminalis* and *S. caprea* rust also attacks the stems and young leaves (Pei et al. 1999). Around 15 pathogens have been identified in the UK, including a stem infecting form (SIF) which thrives particularly on *S. viminalis* clones (Pei et al. 2000).

The two rust species common in willow plantations are *Melampsora epitea* and *Melampsora capraearum*. *M. epitea* is the predominant fungus and mainly affects *S. viminalis, S. burjatica* and *S. cinerea*, while *M. capraearum* mainly infects *S. caprea* and its hybrids. They both have a complex life cycle, during which five types of spores are produced (Pei and Hunter 2000) (Figure 5).

As larch serves as an alternate host of willow rust, willow plantations should be sited as far away from larch plantations as practicable to delay the onset and reduce the severity of rust (Pei et al. 1999). *M. epitea* and *M. capraearum* use European larch as a host more readily than Japanese larch (Pei et al. 2003).

The rust pathogen has the ability to quickly change through gene exchange (Pei et al. 2000). New pathotypes have arisen in the UK in response to selection pressure from long-term planting



Source: Pei et al. 1997, quoted by Hanley et al. (2003).

Figure 5: Life cycle of *M. epitea* and *M. capraearum*.

of certain clones (Royle et al. 1995). For example, in 1992 a new rust pathotype, larici-eptiea-typica-4 (LET4), developed and infected an important biomass willow (*S. mollissima* x 'Q83') which was highly resistant to rust prior to this. *S. burjatica* 'Germany', which was resistant to rust until the early 1990s, has now become one of the most susceptible clones and has gone out of commercial use. More recently there are indications that the SIF evolved with a shorter life cycle and as a single spore stage which over-winters on infected willow stems or buds, causing new infections earlier in the season (Pei et al. 2000).

Trials conducted in the UK, Sweden and Canada have shown similar patterns of occurrence of *Melampsora* species on willows varieties across the UK and Sweden. Canadian clones were not affected in the UK, and clones of European origin were not affected in Canada. However, pathotype composition of the species varied between regions of each country and between growing seasons (Pei et al. 1999). In Sweden, the severity of the attack was much less than in the UK. It was concluded that the severity of rust is affected by environmental conditions in addition to the virulence of pathotypes to clones (Royle and Ostry 1995). There is a need to monitor the nature of rust pathogens in Irish conditions.

The use of fungicides to control rust is technically very difficult in a willow plantation, and may not be environmentally or economically viable (Dawson 2007). A biological control method using a fungal hyperparasite to attack the rust fungi has shown that willow rust spore can be reduced by up to 98% (Pei et al. 1999). The most economic method of managing the spread of rust, however, is the use of mixtures as a control strategy (McCracken 1998).

A major concern related to planting mixtures with low genetic diversity is that as *M. epitea* pathogens quickly change through gene exchange during the sexual life cycle, and mixtures may favour the emergence of 'super races' that are capable of attacking all components of mixtures (Pei et al. 1999). The practice of planting genetically diverse mixtures implies high diversity of pathotypes and prevents the predominance of one specific pathotype (Begley et al. 2009). Therefore it is recommended that some of the highest yielding varieties with similar progenies - Tora, Tordis and Resolution from the SWBP - are not planted in mixtures together (Crops4Energy 2009).

Commercial practice in Northern Ireland (NI) promotes planting mixtures comprised of seven clones, with at least three coming from each of the European and Swedish breeding programmes (Begley et al. 2009). The Department of Agriculture's *Bioenergy Scheme Best Practice Manual for SRC Willow* states that each plantation must include a minimum of five varieties from either or both of the breeding programmes. The manual should be revised to follow the NI guidelines to include a mixture of both European and Swedish varieties.

In 2008, a study of rust in inoculation tests showed that the majority of the willow varieties from the Swedish and European willow breeding programmes had high levels of resistance to rust. It is not yet clear how long resistance will be sustained in these varieties (Pei et al. 2008). In addition, trials of new varieties from both the UK and Swedish breeding programmes are performed in monoclonal plots with no consideration to plant performance in mixtures (Ian Shield, personal communication). It is unknown how these varieties will perform in mixtures. Studies have shown that certain varieties performed particularly well in mixtures while others did less well (McCracken 2001). Some consideration for future research may be given to performance of new commercial varieties grown in mixtures under Irish conditions.

Pests

Leaf beetles (Coleoptera: Chrysomelidae) are the principal pest affecting willow plantations, of which *Phratora vulgatissima* L. (blue willow beetle), *Phratora vitellinae* (the brassy willow beetle) and *Galerucella lineola* (the brown willow beetle) are most abundant (Hanley et al. 2003).

These beetles have been shown to have feeding preferences for certain clones (Royle et al. 1995); for example, *P. vitellinae* prefers to feed on different clones to *P. vulgatissima* and *G. lineola*, which have been shown to have similar feeding preferences in some studies (Hanely et al. 2003). In particular, the leaf beetle *P. vulgatissima* can be found on several species of willow but is most abundant on *S. viminalis*. Severe defoliation of willow plants can occur, which can lead to substantial plant growth reductions (Bjorkman et al. 2000, quoted by Dalin 2004).

The use of insecticides is not an option because of technical and economic issues. Therefore, increased knowledge regarding other factors that may prevent leaf beetle outbreaks is required. Adults often hibernate off-site and this can provide a cost-effective opportunity for the control of beetle spread. In early spring, the borders of the plantation can be sprayed with a once-off application of insecticide before the beetles re-colonise the plantation; routine spraying is not recommended for economic and ecological reasons (Dawson 2007). This method can also be used to control crane fly larve which have been reported as a problem in some plantations.

Currently, Teagasc and the National University of Ireland, Maynooth, are co-operating on a project to examine the impact of leaf beetle (*Phratora vulgatissima*) on coppice production and the role of temperature in determining beetle outbreaks and damage. The project will determine the mechanism of resistance of willow beetle and examine the geographical patterns of resistance as associated with ambient temperatures and likelihood of insect attack. The expected completion date is 2011.

Other threats

Other pest problems encountered in the UK include the terminalis midge and leaf curling midge at Long Ashton, where they were most prevalent on the Swedish *S. viminalis* clones. Elsewhere, leaf curling midge, leaf miners and aphids were recorded. The giant willow aphid *Tuberolachus salignus* and the black willow aphid *Pterocomma salicis* have reduced above and below biomass growth (Dawson 2007). Since rust is the most important threat in Ireland, preference should be given to researching this.

3.4 Nutrition and bioremediation

Nutrient requirement

The current Teagasc guidelines for nutrient application to willows are given in Table 4 (Finnan et al. 2009). Soil index refers to the amount of nutrients available in the soil with soil index 1 being very low but responsive to nutrient applications. The recommended rates reduce rapidly at higher soil fertility indices. No phosphorus application is recommended for index 3 soils or higher. For index 2 soils, an application rate of 24 kg ha^{-1} of phosphorus is recommended.

The nutritional needs of willow are not fully understood. It has been observed that fertilisation requirements depend on soil nutrient status, frequency and time of harvest, and degree of plant utilisation (Ledin 1986, quoted by Adegbidi et al. 2000).

Table 4: Recommended nutrient application rates (kg ha^{-1}) for SRC willow.

Soil Index	Nitrogen (N)	Phosphorus (P)	Potassium (K)
1	130	34	155
2	100	24	135
3	75	0	120
4	40	0	0

Source: Finnan, Caslin and Plunkett (2009).

A number of studies have indicated different application rates. In Finland, fertilization rates of 100-200, 20-40 and 100-200 kg ha^{-1} yr^{-1} of N, P and K respectively have been recommended. In Sweden, an application of 60 kg ha^{-1} of N in the planting year and in subsequent years 80-120, 30 and 80 kg ha^{-1} of N, P and K, respectively are recommended (Adegbidi et al. 2000). Research is needed to identify the optimum fertilisation strategy over a 2-3 year rotation.

There is growing interest in using bioenergy crops for the bioremediation of organic wastes. On most sites, the major factors limiting the amount of organic waste that can safely be applied to willows are the phosphorus content and its availability to growing plants. Availability levels are typically from 20 to 60% depending on the treatment method (Fehily Timoney and Company 2007). Matching fertilisation to the nutritional requirements of willow is critical to avoid environmental problems caused by runoff and leaching.

Bioremediation

Disposal of the organic fraction of municipal and industrial waste is becoming an increasing problem. Following the ban on dumping at sea, and with the Landfill Directive curtailing its placement in landfill, alternative disposal methods are urgently needed (Commission of the European Communities 1999). Recycling to land would have many advantages. It would help to maintain soil organic matter levels, and it would partially supply crop fertiliser needs and reduce agriculture's dependence on energy-intensive and price-volatile mineral fertiliser. But land spreading, in particular on food and feed crops, does introduce a number of potential problems relating to food safety and animal health. The other option is to spread the material on perennial energy crops.

The wastes in question can be divided into two categories:

- Dilute effluents from the food industry, in particular from brewing; these have a high Biological Oxygen Demand (BOD) but a low nutrient content, and can be handled as liquids.
- Sludges from sewage treatment plants; these have a higher dry matter and nutrient content, and are typically handled as solids.

Land application of food industry effluents to willows generally presents few problems as long as it is carried out in compliance with the Nitrates Directive. Effluents can be applied in large volumes through conventional irrigation systems (as on M. Gabbet's farm, Appendix 2). Water volume as well as nutrient concentration may have beneficial effects on crop yield. Experimental field trials at four locations in Europe (Sweden, Northern Ireland, Greece and France) investigating irrigation of willow plantations with waste water (Ahman et al. 2008) found higher growth levels after a 3-year period when compared with non-irrigated and pure water irrigated plantations. Similar results have been reported from commercial willow plantations in Sweden (Larsson et al. 2003). The irrigation of willow plantations with waste water from treatment plants may need further investigation.

Land application of sludges to willows would alleviate food safety concerns, but compliance with the Nitrates Directive on nutrient applications and with the Waste Management (Use of Sewage Sludge in Agricultural) Regulations, S.I. 148 and the Foot and Mouth Disease Amendment, S.I. 267 in relation to heavy metal levels will still be essential. These materials would either have to be injected after a harvest (as on J. Gilliland's farm, Appendix 2) or broadcast with solid manure spreading equipment. Some consideration needs to be given to sludge application techniques.

The production of municipal sewage sludge reached 86,400 dry tonnes in 2007 (Environment Protection Agency 2009). It has been estimated that the area required for all the municipal sludge currently produced would be about 30,000 ha of land with a soil index not exceeding 2.

Heavy metals

Maintenance of trace elements within the limits in S.I. 148 and 267 is more complex, since the pre-planting soil levels and the concentrations in sludges from various treatment plants are likely to vary widely. The concentration of these in the soil must be checked before planting to establish the scope for sludge application. For most typical sludges, the maximum permissible trace element application rates are high enough to allow substantial tonnages of sludge to be applied, but low enough to ensure that their effect on soil concentrations is small (Table 5).

Studies have shown the ability of willow to remove heavy metals (Cu, Zn and Pb) from the soil (Larsson et al. 2003). The removal rate depends on the metal concerned, soil properties, the plant species/variety grown and the amount of biomass produced. Relatively little has been published specifically looking at metal uptake, but some work has indicated that there is a net increase in the accumulation of metal concentration in soils after the application of organic wastes on willow plantations (Britt et al. 2002). Further research is needed in this area, in addition to the long tem effects of metal accumulation in soils.

Heavy metals can be stored in the roots, stem or leaves in different amounts, with more accumulation in the roots and stems (Ericsson 1994, quoted by Adegbidi et al. 2000). When biomass is burned, heavy metals will remain in the ash. It is technically relatively easy to remove heavy metals from ash (Dimitriou and Aronsson 2005), but this is not done in Ireland at present. Further investigation is needed to address the issues surrounding the disposal of ash.

Table 5: Maximum permissible soil concentrations of heavy metals and annual application rates as per S.I. 148 and S.I. 267.

Metal	Max soil values (mg kg^{-1})	Max annual application (kg ha^{-1})
Cadmium	1	0.05
Copper	50	7.50
Nickel	30	3.00
Zinc	150	7.50
Mercury	1	0.10
Chromium		3.50

Source: Department of Environment and Local Government (1998, 2001).

3.5 Harvesting, storage, drying and utilisation

Harvesting

Willow should be harvested during the period between leaf fall and emergence: otherwise leaves will cause difficulties during storage, drying and combustion. During this period, the moisture content of the wood is about 55%. Three distinct harvesting systems have been identified and used in practice to varying degrees:

1. *Harvesting and chipping in one operation, using adapted forage harvesters, followed by immediate transport to the end user or forced-ventilation drying facility.* This has been the most widely used system to date in Ireland. There have been few reported studies of the harvesting operation, but several reports on systems of drying the chips (e.g. Rice et al. 1990, Kristensen and Kofman 2000). In Sweden, this method is practised with high moisture chip (~ 50%) being delivered to the end user as it is the lowest-cost option (Spinelli 2008).
2. *Cut into 5-20 cm billets or chunks, followed by transport to storage/drying facility or end user*. This system has not yet been used in Ireland. Some work on the drying of billets has been reported (e.g. Baadsgaard-Jensen 1998, Gigler et al. 2000, Gigler et al. 2004).
3. *Whole-tree cutting and windrowing with specialist harvesting machinery, followed by transport of biomass to a drying area, followed by chipping and transport to end user after drying*. Considerable effort was put into the development of this type of system at Loughry

College in Northern Ireland in the 1980s, without a successful outcome (McCain 1984), as funding ceased. In the past two years a similar system based on a Danish machine has been used. Again, the only relevant studies have been on the progress of drying and dry matter loss in piles of whole Short Rotation Forestry (SRF) trees (Rice et al. 1990). This method has an advantage of giving the grower greater input into transport of the crop by using conventional farm machinery such as tractors.

A study will soon be completed at the Swedish Institute of Agricultural and Environmental Engineering comparing the cost-effectiveness of these three systems for willow harvesting. Pari et al. (2008) compared the three systems for poplar in Italy. While these studies provide a useful guide on the methodology of such a study, they do not remove the need to carry out a similar exercise under Irish conditions, where the climate at harvest and the market requirements differ greatly from Italy and Sweden. Harvesting represents one of the major costs in willow chip production, and for low-cost production it must be carried out efficiently.

Where the product can be delivered immediately in an undried condition to an end user, e.g. a large power station burning a proportion of biomass, the direct harvest-chip system may be cheaper. Where dried chips are required for a winter heating market, the cost of forced-ventilation drying in the direct-chip system has to be balanced against the extra handling costs in the whole-tree system.

Drying and storage – willow chip

Where freshly harvested willow chips are stored in unventilated piles, the rapid temperature rise generated initially by respiration of viable wood cells and later by the growth of fungi and bacteria has been well documented (e.g. Feist et al. 1971, 1973). If such chips are stored for extended periods in large unventilated piles, the risks of high dry matter loss, allergy-inducing spore production and even spontaneous combustion are high. Nevertheless, the low cost associated with such a system may still make it acceptable for short-term storage prior to delivery to an all-year combustion unit that can cope with high-moisture fuel.

To achieve the desired temperature control and moisture removal, chips must be kept at close to ambient temperatures. To meet the requirements of small boilers for residential, commercial or industrial use, chips must be eventually brought to a moisture content between 25 and 35%. Some level of forced ventilation is required.

Several studies of the drying and cooling of wood chips by forced air ventilation have been reported. To establish basic ventilation data, Kristensen and Kofman (2000) measured a resistance to air-flow of 39 Pa m^{-1} depth in chips with a cut length of 28 mm, ventilated at an air speed of 0.1 m s^{-1}. Rice et al. (1990) measured a very similar pressure drop (3 mm H_2O/m) at the same air speed. This is substantially lower than in most other ventilated materials such as cereals. It illustrates the opportunity to ventilate willow chips at low energy cost, but also the need to select a fan that can operate efficiently at very low back pressures.

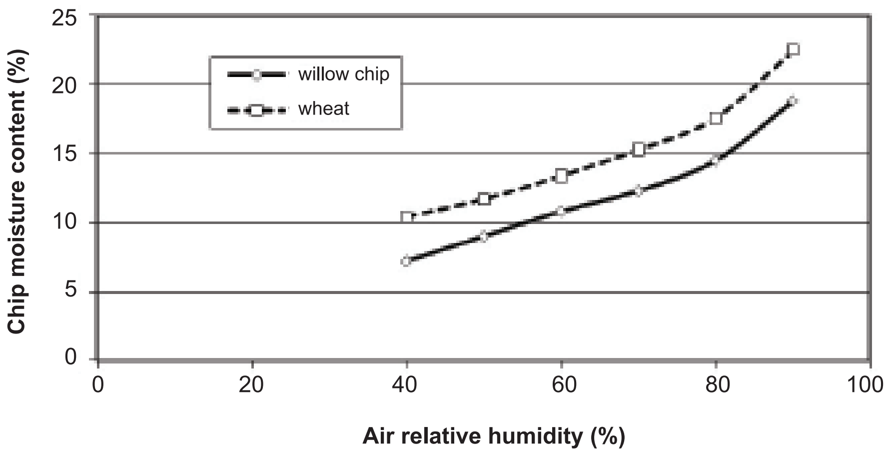
To provide an assessment of the extent of drying achievable with ambient or near-ambient air, the equilibrium moisture content of willow chips in air has been studied (e.g. Pakowski et al. 2007, Gigler et al. 2000). Corresponding literature values for wheat are considerably higher. This shows that willow chips could be dried more easily than wheat, and that moistures well below 20% can be achieved with unheated ambient air (Figure 6).

In practice, a wide range of willow chip drying rates can be achieved by varying the ventilation rate. Figure 7 gives a summary of ventilation trials carried out at Oak Park in summer weather in 1987-9 (Rice et al. 1990). The drying period is defined as the time required for the removal of 20% moisture. Figure 7 shows that the drying rate increased in proportion to the ventilation rate up to about 1,500 m^3 hr^{-1} per dry tonne. Above that, the diffusion of moisture to the surface of the chip became limiting, and little further increase in drying rate could be achieved.

In practice, two approaches could be taken to the forced-ventilation drying of willow chips:

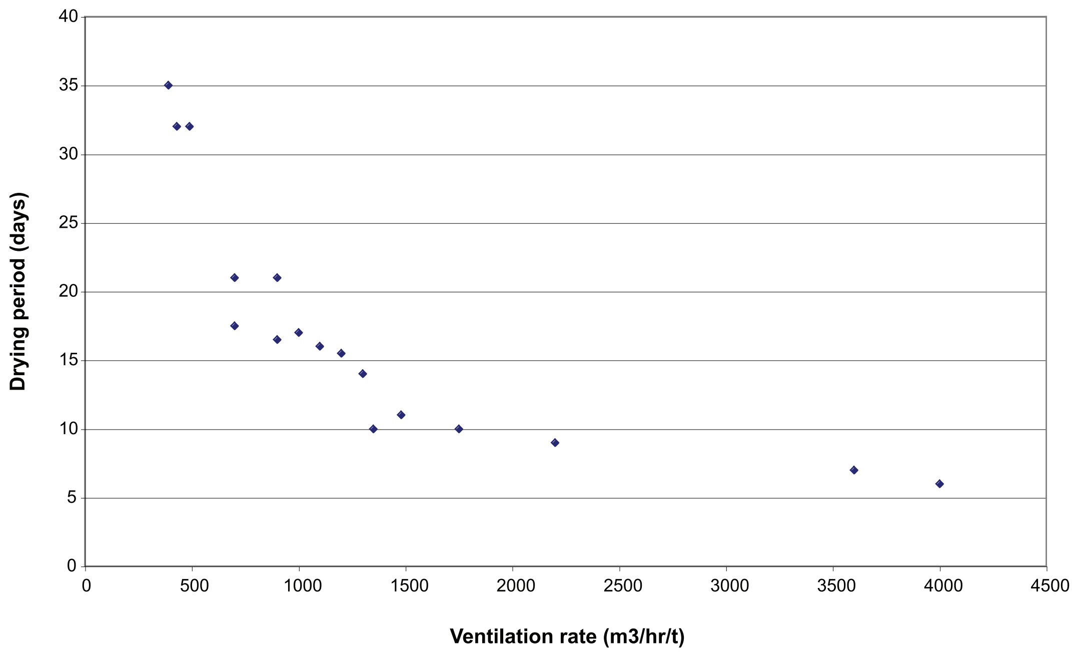
1. They could be dried quickly using a high ventilation rate and then stored prior to delivery, with the drying facility used to dry several lots per season. With this approach, a more expensive drying installation with bigger, more powerful fans and ducting is required. A separate covered storage area for the dried chips is also needed. However, a high annual throughput of chips at any desired moisture content can be achieved.

2. The chips could be dried slowly over the summer period using a low ventilation rate, with only one batch dried per season. A low-cost outdoor system along these lines has been constructed and tested over three years in Oak Park (Finnan 2009). Ventilation rates were from 200 to 300 m^3 hr^{-1} t^{-1} of dry chips for 12 hours from 8.00 am to 8.00 pm each day. Drying commenced immediately after harvest in April, and by August the chip moisture was reduced to below 20%. These results are in broad agreement with the earlier trial results presented in Figure 7. The chip temperature was maintained close to ambient air



Source: Miscellaneous trials conducted by Teagasc, 1985-1990

Figure 6: A comparison of published equilibrium moisture curves for willow chips and wheat.



Source: Rice et al. (1990)

Figure 7: Approximate drying periods (20% moisture removal) achieved in Oak Park willow chip ventilation trials, 1987-9.

temperature, and no mould growth was visible at the end of the storage period. Dry matter losses of samples placed in the piles were very variable, ranging from 1% to 3% per month. Electricity consumption was from 100 to 120 kWh per dry tonne, but there is scope to further reduce electricity use by increasing duct sizes and apertures. Significant cost reductions could also be achieved by maximising night rate electricity usage.

Drying and storage - whole-tree

Some willow whole-tree drying trials were carried out at Oak Park between 1987 and 1989 (Rice et al. 1990). The results, illustrated in Figures 8 and 9, showed that trees cut and bundled in March reached 30-35% moisture in the first summer, but the moisture content increased

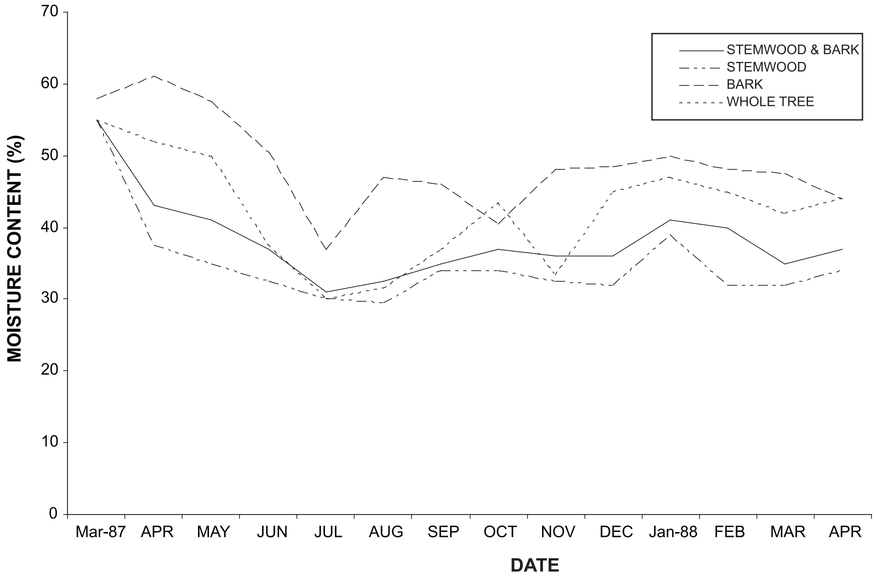
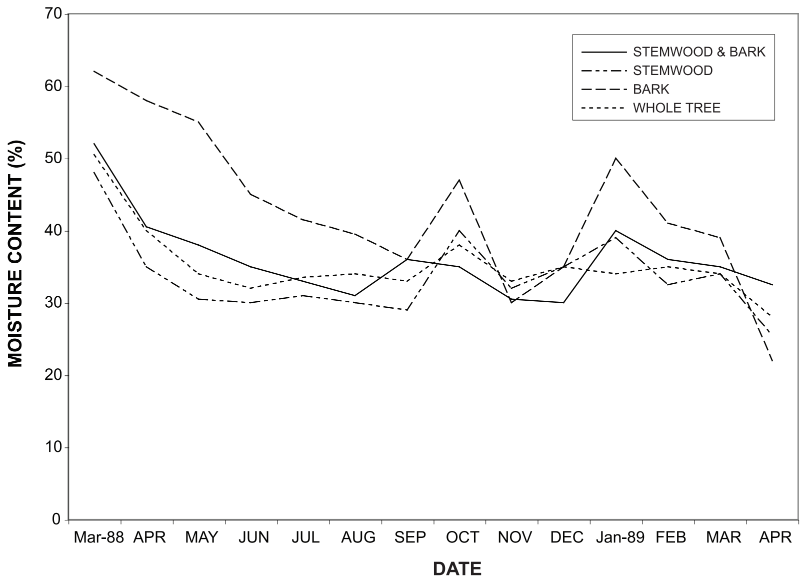


Figure 8: Drying rates of whole-tree bundles cut in March 1987.



Source: Rice et al. (1990)

Figure 9: Drying rates of whole-tree bundles cut in March 1988.

somewhat in the following winter. Dry matter losses were about 1.6% per month for the first six months of storage.

The results of this type of natural drying may be expected to be somewhat site-specific, depending on wind exposure and method of placement of the stems on the ground. Nevertheless, these results suggest that whole-tree bundles could be safely chipped in late summer and stored for the winter heating market. A study is needed to examine the effect of stem moisture on the quality of the chips produced by various chipping machine designs, and on the chipper power requirement and wear and tear. Systems of handling the stems from the harvest site to the storage area also need to be optimised and costed.

Drying and storage - billet

Billet research has focussed mainly on drying in storage without fan ventilation. Kristensen and Kofman (2000) measured very low air-flow resistance (2 Pa m^{-1} height at an air flow rate of 0.1 m s^{-1}) in a pile of 200 mm billets. Baadsgaard-Jensen (1988) stored 75-200 mm billets under a permeable tarpaulin: very little drying was achieved, but dry matter losses were 0.3% per month, compared with 2.9% per month for chips stored in the same conditions. No noticeable difference was found between billet sizes.

It is to be expected that the drying rate achieved will be affected by the site climate, the shape, size and orientation of the pile, and to a lesser extent by the billet size. In an experiment of part-covered piles of billets with natural wind drying, moisture content of around 10% was achieved after 5 months. The average pile moisture content decreased fast due to the combined effect of relatively low air humidity and relatively high wood moisture content (Gigler et al. 2004). In comparison with whole-tree piles, billet piles have an increased particle surface area but also an increased air-flow resistance, so drying rates similar to those for whole-tree piles can be expected.

Combustion of willow chips

There are some minor differences between the fuel properties of willow chips and forest thinnings, none of which are likely to have a significant effect on combustion (Kaltschmitt and Hartmann 2001). Tables 6 and 7 illustrate typical results from various fuel tests carried out by Teagasc over the last number of years. Calorific values, volatiles and carbon (C) and hydrogen (H) contents are similar. The ash content of the SRC willow is considerably higher, which may be a slight deterrent in some applications. Higher potassium (K) and sulphur (S) contents of

Table 6: Fuel properties of willow SRC.

Material	Calorific value (MJ kg^{-1})		Ash content (%)	Volatiles (%)
	Gross	Net @ 30% MC		
Willow SRC	18.4	11.2	2.0	80.3
Spruce + bark	18.8	11.5	0.6	82.9

Source: Miscellaneous fuel tests conducted by Teagasc.

Table 7: Fuel minerals of willow SRC.

Element	C	H	N	K	S	Cl
			Weight %			
Willow SRC	47.1	6.1	0.54	0.26	0.045	0.004
Spruce + bark	47.9	6.2	0.22	0.15	0.015	0.006

Source: Miscellaneous fuel tests conducted by Teagasc.

willow chips may slightly increase corrosivity on heat transfer surfaces, though chlorine (Cl) content is low. Overall, any wood-burning appliance should have little difficulty coping with willow chips.

Markets for willow chip

Two primary energy markets for willow chips are envisaged in Ireland: commercial heating boilers (typically from 100 kW to 1 MW), and co-firing in the three midland peat-burning stations. The boiler market requires chip drying and storage, but is well dispersed and could be supplied from locally-grown willows. A network of wood chip suppliers is already becoming established. The optimum scale of these operations, and the transport distance beyond which they become unviable, needs to be examined.

The co-firing market is located at only three centres; while it could be supplied directly from the field with undried chips, several environmental and logistical issues may arise. To keep transport distances to a minimum, plantings should be as close as possible to the power station. However, concentrated planting in one area of a tall energy crop with a high water requirement could have some environmental repercussions, e.g. visual intrusion and lowered water tables. The balance between these considerations and transport costs would need to be examined at an early stage to allow this development to proceed in an optimal manner.

3.6 Review of alternative species for energy production

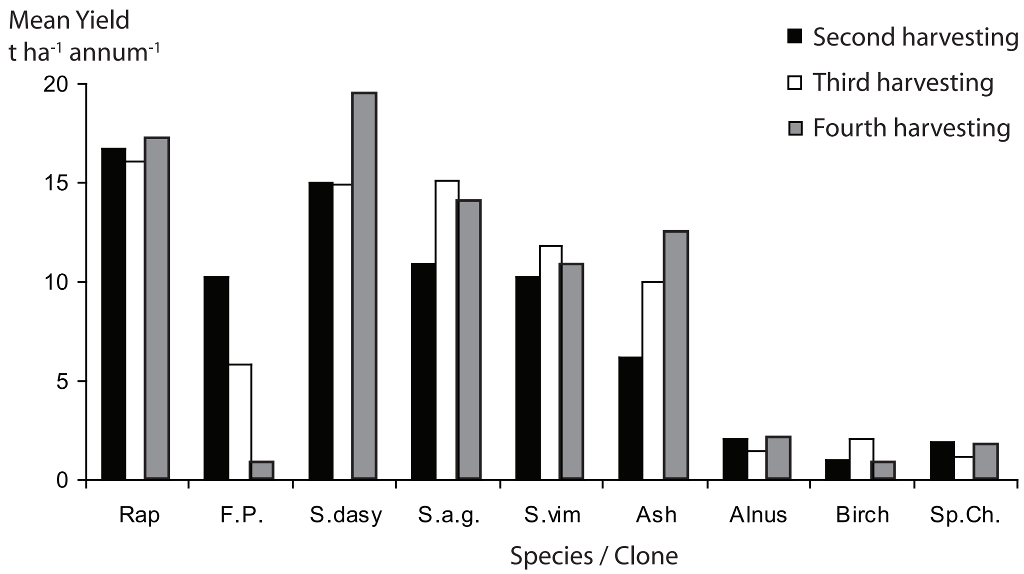
Short rotation coppice

Short rotation coppice *Salix* (willow) was reviewed in this report. An alternative species is *Poplus* (poplar). Poplar hybrids, like willow hybrids, are currently being developed for the biomass energy market (Rae et al. 2004).

Poplar has long been cultivated for timber and pulp production, shelter and amenity purposes (Pei et al. 2004). Poplar can be planted as unrooted cuttings and harvested on a 3-5 year rotation, similar to willow. However, the wood is generally lighter and more brittle than willow wood and generates fewer and larger spouts when coppiced. This can have a significant impact on harvesting performance (Spinelli et al. 2007).

Mean annual yields from poplar can vary in response to the soil quality, climatic conditions and disease and insect infestation (Aylott et al. 2008). Trials in Canada assessing the field performance of willow and poplar varieties recorded yields of up to 18.05 odt $ha^{-1}yr^{-1}$ for poplar and between 8.96 and 16.8 odt $ha^{-1}yr^{-1}$ for willow (Labrecque and Teodorescu 2005); willow beetles were observed frequently on the lower yielding willow variety (Labrecque et al. 2005). A UK study of four poplar genotypes recorded yields as high as 23.7 odt $ha^{-1}yr^{-1}$ (Rae et al. 2000) and a study in Belgium showed mean annual yields of between 2 and 10.4 odt $ha^{-1}yr^{-1}$ (Laureysens et al. 2005).

Poplar can be high-yielding and is suitable as an option for short rotation coppicing. However, current research in northern Europe has been limited and experience in breeding with poplar has suggested that it is more difficult to produce new varieties (Ian Shield, personal communication). The availability of the poplar genome should allow for the quick identification of genes that are associated with high biomass yields (Aylott et al. 2008) and advances have already been made in this area. ‘Popyomics’ is a poplar breeding programme which was initiated in 2002 by a number of European partners (UK, Sweden, France, Belgium and Italy). The project uses the latest techniques in molecular genetic mapping of poplar to define traits that determine yield and disease resistance and to develop poplar for the bioenergy industry across Europe (University of Southampton 2009). Progress in poplar should be monitored.



Source: Neenan (1989).

Figure 10: Results from silvicultural trials in Ireland in the late 1970s.

Longer rotation coppice

In 1978 the Forest and Wildlife Service in Ireland conducted silvicultural trials which measured yields from a number of short rotation crops (Figure 10). The range of species included *Salix*, *Populus, Alnus* (alder), *Betula pubescens* (birch), *Castanea sativa* (Spanish chestnut) and *Fraxinus excelsior* (ash). The latter four species have longer rotation periods.

These trials showed that *P. rap* and *S. dasyclados* maintained a consistent yield over the second, third and fourth harvestings. *S. aquatica gigantea* was initially promising but failed badly due to rust disease from 1984 onwards. Ash improved with yield, and at the end of the period of last harvesting yields were around 12 t $ha^{-1}yr^{-1}$ and had a dry matter yield content much higher than *Populus* and *Salix*. Other trials on the coppicing ability of species showed that willow is the best species to coppice, with poplar and ash also being satisfactory. Testing was not comprehensive and some of the species were grown in only one trial or at a single location (Neenan 1989) which may indicate a need for more research in this area.

4. Conclusions and recommendations

Based on assessment of work to date and on the advice of participants and experts in the field, the following conclusion have been deduced along with a list of recommendations for future research initiatives necessary to advance the adoption of SRC willow as an energy crop in Ireland.

Breeding and species selection

Modern genotypes, bred for high biomass yield and disease resistance are available from the Swedish and UK breeding programmes. These genotypes are being tested at a range of sites throughout the UK and Northern Ireland, and field trials are ongoing across Europe. Recommendations for future research include:

- *Establish a site in the Republic of Ireland where trials can be conducted on existing and new willow genotypes and develop a recommended list of suitable varieties for Irish suppliers and growers. The site should be linked to the existing UK network to facilitate information exchange.*

Site preparation

Site preparation is particularly important to the success of a willow plantation. Site preparation has been well researched, with potentially higher yields attainable from higher planting density and shorter cycle lengths, but with an impact on harvesting costs. Recommendations for future research include:

- *Review the relationship between planting density, rotation length and harvesting costs.*

Planting mixtures with genetic diversity can act as a cost-effective suppressant to rust but can lead to non-uniformity within the crop. Recommendations for future research in Ireland include:

- *Determine the effect of enhanced growth levels in mixtures on harvesting machinery.*

Disease and pest control

Melampsora, yellow leaf rust, poses the biggest threat to willow plantations in terms of disease and pest control, and hampering the spread of the disease is the biggest challenge to the success of willow plantations. Research has shown that varieties initially not prone to rust have, over time, become susceptible.

Rust is especially a problem in Ireland as climatic conditions here favour its growth. Rust can adapt quickly to new genotypes and it is not known how long currently used high-yielding commercial varieties will remain resistant. Planting genetically diverse willow species in mixtures can be an economical way to stop the spread of rust and other diseases. New varieties from the SWBP and EWBP have not been tested in monoclonal plots; this may pose an issue for future performance. Recommendations for future research include:

- *Continuously monitor commercial varieties for the emergence/severity of rust.*
- *Research to understand the nature of willow pathogens.*
- *Refine methods of disease and pest control in willow plantations.*
- *Monitor the performance of new commercial varieties in monoclonal and polyclonal plots.*

Nutrition and bioremediation

Understanding the nutritional needs of willow is particularly important considering the growing interest in using bioenergy crops for the bioremediation of organic wastes. Sewage sludge production is increasing, but opportunities for its disposal are reducing. Application to perennial energy crops such as short rotation willows in accordance with the requirements of the Nitrates Directive and Waste Management Regulations would facilitate local authorities and provide alternative enterprises for local farmers. To facilitate the development on the use of safe sewage sludge on energy crop sites, more information is needed in the following areas:

- *Better data on the effects of sludge treatment on the availability and uptake of nutrients applied as sludges would help in the determination of application rates.*
- *There is insufficient information available on the uptake of heavy metals by willows, and on the changes in soil concentrations following multi-annual sludge applications.*
- *The irrigation of willow plantation with waste water from treatment plants may need further investigation.*
- *Sludge application techniques for years one and two after harvest need to be researched.*

Harvesting, storing, drying and utilisation

The three common methods for harvesting willow plantations are the direct chip, billet and the whole-tree harvesting methods. Little information exists on the relative advantages of each method and research is needed to determine:

- *For the whole-tree system, handling and transport systems need to be streamlined and costed.*
- *Research is needed to quantify and compare the economics, the energy balance as well as the greenhouse gas balance associated with each method.*
- *The effect of stem moisture content on the harvesting performance and chip quality.*
- *The logistics of chip supply to boilers and the optimum transport catchment area.*
- *To allow SRC willow to be supplied for co-firing at the three peat stations in the most sustainable way, the balance between concentrated planting near the power stations and any environmental issues that this might create needs to be investigated.*

Alternative species

Willow (*Salix*) is the predominant species used for SRC in Europe. Approximately 500 ha have been established in Ireland over the past few years. Studies have shown that poplar may be a promising crop in terms of yield. However, much of the research in northern Europe is being dedicated to developing and breeding willow as a SRC wood energy crop and therefore research should concentrate primarily on willow in the short term and build on experience from other countries. However, the following should be considered;

- *The progress of poplar and potential of other species should be kept under review.*
- *If an increase in our woody biomass resources is required, poplar should be considered as a potential SRC crop and ash may be suitable as a longer rotation coppice choice.*

Carbon mitigation potential

In addition to the areas assessed in this report, the carbon mitigation potential of energy crops warrants further investigation. Quantitative information on climate change mitigation by willow plantations is sparse and relatively little research has been carried out in this area. There is a need to conduct research to quantify the potential of willow plantations to mitigate the rise in greenhouse gas concentrations.

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Appendix 1 – Willow varieties

Table 8: Commercial willow varieties

Swedish varieties	UK varieties
• Tordis	• Endurance
• Sven	• Beagle
• Tora	• Ashton Scott
• Olof	• Resoultion
• Sherwood	• Quest
• Gudrun	• Discovery
• Torhild	• Endeavour
• Loden	• Ashton Parfitt
• Jorr	• Terra Nova
• Jorun	
• Doris	
• Inger	

Species: *S.viminalis*

Name	Variety number
Eva	811110
Lisa	811208
Hanna	821624
Chistina	821629
Marie	832501
Anki	832502
Gustaf	832803
Orm	SW870082
Rapp	SW870083
Ulv	SW870148
Jorr	SW870013
Jorunn	SW870201
Astrid	SW870435
Bowles Hybrid	115/34
Gigantea	115/15
Beagle	LA960326

Species: *S.viminalis x S.schwerinii*

Name	Variety number
Bjorn	SW910006
Tora	SW910007
Olof	SW930387
Torhild	SW930769
Sven	SW930824
Asgerd	SW930935
Tordis	SW960299
Sheerwod	SW930504
Quest	SW930231

Species: *S. dasyclados*

Name	Variety number
Aud	SW
Loden	SW890129
Gudrun	SW040598

Species: *S.viminalis x S.burjatica*

Name	Variety number
Stott 1	034/01
Stott 2	034/02
Stott 3	034/03
Stott 4	034/04
Stott 7	034/07
Stott 8	034/08
Ashton Stott	034/10
Ashton Parfitt	034/11

Appendix 2 – Site visits

Site visits and interviews conducted during this project are outlined below.

1. Local supply chain

Contact: Michael Gabbett

Michael Gabbett is a farmer in Co Kilkenny. In 2000 he planted 6 ha with willow under a Forest Service pilot scheme initiated by Clearpower Ltd and Purser Tarleton Russell Ltd. Current operations involve taking waste from a local brewery to irrigate and fertilise the willow plantation. Located close to the plantation is a container (Figure 11) to store the waste, and a moveable irrigation system (Figure 12) is used to irrigate the crop. A gate fee is received for the disposal of the waste material.

A whole-tree harvesting method is used. Stems are left to dry naturally over a summer before chipping; harvesting is carried out by a company from Northern Ireland. Wood chip from this

Figure 11: Effluent bag container at Gabbett farm.

Figure 12: Irrigation system at Gabbett farm.

plantation is used to fuel a wood chip boiler installed at Mr Gabbett's house and is also supplied to a nearby mini-district heating system. This can be considered an integrated solution for water and nutrient management, organic waste handling and SRC for energy provision at the community level (Mirck, Isebrands, Verwijst and Ledin 2005).

The type, operation and performance of a chipping machine can have an effect on the quality of wood chip being produced (Figure 13).

Screening is required to remove large irregular pieces of wood chip (Figures 14 and 15).

Figure 13: Well graded willow chip.

Figure 14: Screening system for willow chip.

Figure 15: Residue from screening.

2. Willow variety trials at Teagasc, Oakpark

Contact: John Finnan

Teagasc has recently recommenced willow variety trials at Oak Park in Carlow. The trials are located on 0.5 ha and include varieties from the EWBP - Resolution, Tera Nova and Endurance, and from the SWBP - Sven, Inger, Tordis, Tora, Doris, Torhild and Karin (Figure 16).

Figure 16: Willow trials at Oakpark.

3. The Agri-food and Biosciences Institute (AFBI), Northern Ireland

Contact: Alistair McCraken

Research and development work in SRC as an alternative and renewable energy source using *Salix* began in Northern Ireland in the mid 1970s (McCracken and Dawson 1992) and still continues at the Agri-Food and Biosciences Institute (AFBI). AFBI is a provider of scientific research and services to government, non-governmental and commercial organisations in Northern Ireland. AFBI has seven locations throughout Northern Ireland with particular attention being paid to short rotation coppice at the Loughgall and Hillsborough sites. A number of projects are now ongoing, including:

- The influence of insects and pests on willow established in mixed species plantations and grown for bioremediation;
- Interactions of new and improved willow genotypes grown in mixtures;
- Testing of new and improved willow genotypes for their suitability to climatic conditions in Northern Ireland. Species from other breeding programmes such as the New York willow breeding programme are being tested;
- Bioremediation of farm waste water and landfill leachate to develop optimum nutrients application levels (Figure 17).

A Renewable Energy Centre has been built at Hillsborough where research is being conducted by AFBI on aspects of bioenergy including wood chip drying, storage and biomass heating systems (Figure 18).

Figure 17: Willow plantation using bioremediation of farm waste water.

Figure 18: Willow wood chip drying facilities at Hillsborough.

4. Rothamsted Research Centre, Hertfordshire, UK

Contact: Angela Karp

Rothamsted Research Centre is involved in a variety of activities aimed at the sustainable production of biomass from energy crops for heat and power. These include the Biomass Energy Genetic Improvement Group (BEGIN), which is targeted at breeding high-yielding, rust and pest resistant varieties of SRC willow that will thrive in UK environmental conditions. The UK national willow collection is maintained at Rothamsted (Figure 19).

Figure 19: Part of the UK national willow collection at Rothamsted.

Under the BEGIN project seedlings are raised in nurseries (Figure 20) for further for observation and yield trials (Figure 21).

Figure 20: Willow nursery at Rothamsted.

Figure 21: Observational trials.

5. Rural Generation Ltd., Northern Ireland

Contact: John Gilliland

Rural Generation specialises in the production of wood energy, organic waste recycling and wood-fired boiler provision, installation and commissioning. The company is based at Brook Hall estate on the outskirts of Derry City. Rural Generation grows willow plantations for the provision of renewable energy (wood chip) and currently has approximately 160 ha planted near the estate. Most of this is for commercial use but there are also variety trials being carried out on the estate, in association with AFBI. To date, around 30,000 t of municipal waste from Northern Ireland Water and Donegal County Council, as well as dairy sludge, have been applied on-site using an organic sludge injector (Figure 22).

In addition, Rural Generation specialises in machinery design and is involved in developing new designs for harvesting machines (John Gilliland, personal communication). Willow on the estate is harvested using the ‘direct chip and dry’ method (Figure 23). A forced-drying ventilation system is used to dry wet willow chip using heat supplied by a wood chip boiler.

Figure 22: Organic sludge injector used at Brook Hall Estate.

Figure 23: Willow harvester at Brook Hall Estate.

6. Enkoping waste water treatment facility

Contact: Par Aronsson, SLU

In Enkoping (population 20,000), in the eastern part of Sweden, heating is provided to large businesses in the area through a district heating, wood chip fired combined heat and power plant (Figure 24). The plant is primarily owned by an energy company, and is fired by biomass all year round with a mixture of forest residues, sawdust, wood chips and about 20% willow. Electricity generated is supplied back to the grid.

Wet wood chip is delivered to the power station where it is off-loaded into an auger feed system (Figure 25).

Effluent from the local waste water treatment plant (Figure 26) is used to irrigate and fertilise the willow plantation. Treated sludge is mixed with residual ash from the power plant and the mixture is delivered to local farmers in the area to fertilise SRC willow plantations.

Figure 24: Power station at Enkoping with willow plantation to the left.

Figure 25: Off-loading system for wet wood chip at Enkoping.

Figure 26: Waste water treatment plant located beside the power station.