PURPOSE-GROWN WOODY BIOMASS CROPS

State of knowledge (FDF # 200723)

Prepared by

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SilviConsult Woody Crops Technology Inc. (SilviConsult Inc.) is a company founded and incorporated in British Columbia in 1998. The aims of SilviConsult Inc. are to promote the establishment, management and utilization of short-rotation-intensive-culture SRIC) woody crops as a farm crops in Canada and in the US-PNW.

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1 Summary

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This report is a review of the state of knowledge of purpose-grown woody biomass crops from the perspective of species preference, crop density, crop cycle and yield. This review only considers willow (*Salix* spp.) and poplar (*Populus* spp.), as these are the two woody species of greatest potential for Canada and in particular for the Prairie Region.

Sweden, the UK, the US and Italy have been actively developing purpose-grown woody biomass crop systems, using poplars and willows grown at high crop densities (10,000 - 15,000 stems per hectare) and short crop cycles (2-5 years). These systems are based on a coppice[i] approach, where these crops are harvested in the dormant season, allowing the live stumps to re-sprout new shoots for the next crop cycle. This crop approach is very suitable to Canadian conditions. Although Canada has also been actively involved in research and development of these crops, there appeared to be little appetite to commercialize the concept; that is now rapidly changing as a result of the high oil prices and the need to limit production of greenhouse gasses (mainly CO_2) from fossil sources.

Sweden and the UK have been concentrating on willows as the focus species due to their adaptability to their respective climates and the absence of suitable poplar clones. The US focuses on both poplar (the Mid-West and PNW States) and willow (the North-eastern US). Italy's focus has primarily been on poplar. All four countries have active and long-running breeding programs. Breeding programs form the basis for a sustainable crop system; e.g. yield increases of 10-20% per generation have been reported as realistic in willow and that applies equally to poplar. Main threats to these crops will be diseases and insects and a well-founded breeding program is required to deal with these on a long term basis.

Existing crop layouts used in the various countries growing poplars and willows for biomass are suitable for Canadian conditions as well. They are based on a harvest system using modified silage harvesters with specially designed harvesting units to cut, chip and deliver chips to a chip van, much like existing silage and forage systems in use in traditional agriculture. A systematic crop layout allows efficient harvesting and crop tending activities without undue damage to cut stumps and their root systems, on which the next crops depend. The efficiency of the silage harvester depends on the range of stem diameters at stump height. This can be managed through choice of clone, crop density and crop cycle, which are all interrelated. Generally the higher crop densities are associated with shorter crop cycles, resulting in the smaller cutting diameters. Various crop density-crop cycle combinations can be used without incurring an appreciable drop in total yield.

[i] Coppicing is a method of managing woody crops, by which young tree stems are cut down to a low level. When this is done in the winter, many new shoots re-sprout and grow up.

2 Introduction

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Purpose-grown woody crops planted at high crop densities evolved from the 'silage sycamore' concept in the south-eastern United States in the sixties [14], where the American sycamore (*Platanus occidentalis*) proved very suitable for the production of 'silage' crops. The OPEC oil embargo in 1973 gave impetus to the concept of SRIC woody crops for energy in North America and Europe. SRIC[i] is the acronym for 'short-rotation-intensive-culture' and refers to woody crops grown as agronomic crops on farmland on a short crop cycle[ii], using intensive cultural practices; these are multi-year farm crops. The length of the crop cycle depends on the end product; when these crops are grown for biomass feedstock, the crop cycle usually varies from 2 to 6 years, depending on climate and species.

Following the 1973 OPEC oil embargo several countries embarked on national programs to research and develop systems of energy production from biomass, including forest biomass.

- Canada developed its ENFOR[iii] project, which included purpose-grown woody crops of poplar or willows on short crop cycles.
- Starting in 1978 the US developed its Biofuels Feedstock Development Program (BFDP) of the Department of Energy (DOE), which included a woody crops component [60].
- Sweden developed its own National Energy Forestry Program, the Swedish equivalent of Canada's ENFOR program. The country developed SRIC willow as a purpose-grown woody biomass crop system.
- Other developed countries, such as the UK, New Zealand, several of the Baltic countries and Italy followed suit.

Internationally the International Energy Agency (IEA) was set up in 1974 to serve as "*energy policy advisor to 27 member countries in their effort to ensure reliable, affordable and clean energy for their citizens*" [www.iea.org]. Initially its role was "*to co-ordinate measures in times of oil supply emergencies*"; however, its mandate has since evolved to include energy security, economic development and environmental protection.

IEA Bioenergy [www.ieabioenergy.com] was set up in 1978 by the IEA. One of its objectives is "*to accelerate the use of environmentally sound and cost competitive bioenergy on a sustainable basis*". IEA Bioenergy research integrates a) biomass resources, b) supply systems, c) conversion and d) end products. The work of IEA Bioenergy is carried out through a series of Tasks, each having a defined work program. Task 30 is Short Rotation Crops for Bioenergy Systems. Task 30 involves 'Short

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[i] SRIC has several variants used around the world. In the US the term SRWC is also used; it stands for short-rotation-woody-crops. In Sweden the practice is known as SRF or short-rotation-forestry.
[ii] Throughout this report crop cycle refers to harvest cycle, cutting cycle or rotation. These terms can be used interchangeably.
[iii] ENFOR = **EN**ergy from the **FOR**ests, managed by the Canadian Forest Service (CFS) of Natural Resources Canada. This program was completed several years ago.

Rotation Crops[i] for Bioenergy Systems', with the main objective "*to further develop the existing short rotation biomass production systems*".

How do woody biomass crops stack up against alternate energy crops? The short answer is: Very well! In terms of the energy output/input ratio, woody crops are more efficient than corn; corn being the current focus crop for purpose-grown biomass-based energy. A recent study [7] in southern Germany compared several energy cropping systems for their biomass production, energy efficiency and land use efficiency[ii] over a 4-year period. This study included a review of the impact of fertilization with nitrogen (N) at various levels and determined nitrogen budgets. The crops compared were SRIC willow (*Salix schwerinii*), miscanthus (*Miscanthus x giganteus*), switchgrass (*Panicum virgatum*), corn (*Zea mays*), and a 2-crop rotation system including winter canola (*Brassica napus*), winter wheat (*Triticum aestivum*) and winter triticale (*Triticale x triticosecale*).

At the highest N application level, corn produced the highest biomass at 19.1 ODT[iii]/ha/yr[iv] with the highest net energy yield of 350 GJ/ha/yr, followed by the perennial crops with miscanthus at 18.1 ODT/ha/yr and 277 GJ/ha/yr net energy, and SRIC willow at 15.2 ODT/ha/yr and 258 GJ/ha/yr net energy yield. The other perennial crop switchgrass was lower in yield than SRIC willow. The conclusion was "*perennial lignocellulosic crops such as willow and miscanthus best combine high biomass and energy yields with high land and energy use efficiency, N fertilizer use and environmentally benign production methods* (*on this specific site*)".

The focus of this report is on yield, crop density and crop cycle, and how these influence the choices of woody species and SRIC woody crops system (coppice vs. non-coppice crops). The objective is to provide background to help decide crop layout in relation to species choice and harvest system for coppiced crops. This report will only briefly review existing harvest approaches (section 9), but a technical review of harvest systems is beyond the scope of this report. Most other cultural practices, such as site preparation and planting, are not under review, with the exception of several cultural practices listed in section 7.

3 Species preferences

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In Europe and North America, the woody species used or considered most often for purpose-grown biomass are the willows (*Salix* spp.) and poplars (*Populus* spp.). In the case of poplars, much of the research regarding biomass production has concentrated on SRIC crops with multiple end products in mind. Most high density poplars were/are planted to produce pulpwood fibre, rather than 100% biomass feedstock; biomass fibre is the by-product. To illustrate, the US Department of Energy (DOE) funded much of the initial research and development of SRIC hybrid poplar in the US, where several companies in the Pacific North West States (PNW) took up the culture of poplar for the

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[i] "Short Rotation Crops" means woody crops such as willows, poplars, black locust and Eucalyptus with coppicing abilities, as well as other lignocellulosic crops.
[ii] Land use efficiency is the ratio of unit area of land used to produce 1 oven-dry-tonne (m^2/ODT).
[iii] ODT=oven-dry-tonne. One tonne (metric) equals 1 Megagram (Mg) equals 1,000 kg.
[iv] ODT/ha/yr means oven-dry-tonnes per hectare per year, also written as ODT ha^{-1} yr^{-1}.

production of pulpwood rather than purpose-grown biomass feedstock. Some have now converted their culture to produce even higher-value solid wood for saw timber and peeler wood.

Willow and poplar species make up the family of the *Salicaceae*. Besides their rapid initial growth, an important aspect willow and poplar species have in common is the ability to coppice from a cut stump. This allows repeated crop cycles without having to replant the crop. Both species (with some notable exceptions[i]) are also fairly easy to propagate vegetatively, using unrooted, dormant cuttings. However, this is where the comparisons stop. Most willow species and their hybrids that are used for biomass production are so-called 'shrub' willows; they do not grow to the tree form, whereas poplars grow to the tree form. This has important implications in deciding which biomass system to use. It is of interest to note that a few willow species do grow to a tree form (e.g. *Salix alba*) and are managed to produce saw timber and pulpwood in several countries in eastern and western Europe (for example a *Salix alba* cultivar[ii] is the 'cricket bat willow', used to produce cricket bats in England; *Salix* wood for traditional wooden shoes in Holland) and in South America - Argentina.

3.1 Canada

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Although poplar is considered a suitable biomass species, the focus has primarily been on producing fibre for the pulp & paper, lumber & veneer and engineered wood products industries. Developments of poplar as an SRIC crop have largely been the domain of several forest products companies, two Provincial Governments (Ontario and Quebec), the Canadian Forest Service and to a lesser degree the Shelterbelt Centre[iii] at the Prairie Farm Rehabilitation Administration (PFRA) of Agriculture and AgriFood Canada (AAFC) in Indian head (SK). In the Province of Saskatchewan the Saskatchewan Forest Centre has become actively involved in technology development of SRIC hybrid poplar crops. The Province of Ontario abandoned its direct involvement in the development of SRIC hybrid poplar crops approximately 15 years ago and the Canadian Forest Service has not been actively involved in new SRIC poplar initiatives since it closed off the Forest 2020 program several years ago.

Willow is considered by many the preferable biomass species when produced in a coppice system. There was a strong willow research and breeding program at the University of Toronto; however, that came to a halt after the retirement of the late Dr. Zsuffa. The University of Toronto willow research and breeding program contributed significantly to the success of the SRIC willow biomass program developments at the State University of New York – Environmental Science and Forestry (SUNY-ESF) in Syracuse (NY). An active willow research project at the Botanical Gardens of Montreal concentrates on use of willow in Canada in phytoremediation and biomass applications. In western Canada the University of Saskatchewan has recently initiated a research project involving willow for biomass. The Canadian Wood Fibre Centre in Edmonton

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[i] Difficult to vegetatively propagate are the aspens [*Populus tremuloides*, *P. tremula* etc., species in the *Populus* (used to be called *Leuce*) section] and many clones of eastern cottonwood (*Populus deltoides*).
[ii] A cultivar is a cultivated variety (cv.).
[iii] The Shelterbelt Centre's main focus has been on producing poplars for shelterbelt use.

has embarked on research of willow for various end uses such as phytoremediation and biomass production. Both the Botanical Gardens and the Canadian Wood Fibre Centre integrate use of municipal effluent in the successful establishment and culture of SRIC willow biomass crops. The University of Guelph has also been active in willow research in an agroforestry context. The Shelterbelt Centre (AAFC) has recently started a willow breeding and selection program to service the emerging interest in SRIC willow biomass crops.

In Canada several small companies have set up commercial enterprises producing willow planting stock for prospective growers who want to establish SRIC woody biomass crops.

3.2 United States

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In the US the four species of interest were willow (*Salix*), poplar (*Populus*), American sycamore (*Platanus occidentalis*) and silver maple (*Acer saccharum*). Poplar became the species of choice for the DOE [48].

For many years the DOE was the main source of funding for the research and development of hybrid poplar as a viable source of fibre for use in various wood products and biomass. It resulted in a very successful and still growing industry in Minnesota and the PNW of the US. Several companies embraced the concept and started managing these SRIC crops for the production of pulp and paper fibre (Minnesota and the PNW). Many of these crops in the PNW are now aimed at production of solid wood for higher value, with biomass as a possible by-product. Funding by the DOE was halted for several years; however, after '9/11' and the resulting rise in oil prices, the DOE has continued its funding of poplar research and its use as a source of renewable energy. There are several advanced and long term breeding programs with poplar, with the most notable at the Natural Resources Research Institute of the University of Minnesota (a cooperative) and GreenWood Resources, Inc. in Portland (OR), a corporate program.

Notwithstanding the DOE preference for poplar, a vibrant program with SRIC willow has taken root in New York State at SUNY-ESF in Syracuse (NY). A Salix Consortium, made up of over 20 organizations and led by SUNY, was successful in a bid to develop a woody crop energy feedstock system based on SRIC willow, which is funded by the Biomass Power for Rural Development Program with support from the DOE and the USDA [1] [www.esf.edu/willow/pdf/2001%20finalhandbook.pdf].

In its early days the SUNY program had a close connection with the University of Toronto willow research and breeding program led by the late Dr. Louis Zsuffa. Much of its original material came from that productive program; however, it proved too susceptible to *Melampsora* rust species. As material imported from Sweden was not successful either (it succumbed to the potato leaf hopper - *Empoasca fabae*), SUNY decided to initiate a willow breeding program in the mid nineties, which continues to date [45].

One of the reasons poplar is not pursued any further as a biomass crop in the SUNY program is the occurrence and persistence of *Septoria* stem cankers (*Septoria musiva*), rendering the use of hybrid poplar in biomass applications a risky affair [Tim

Volk – personal communication]. This should also be of primary concern for Canada in its pursuit of hybrid poplar as a biomass energy crop.

A commercial enterprise to produce willow planting stock was set up in New York State by 'Double A Vineyards' (Fredonia, NY); the willow enterprise is named 'Double A Willow'. The company will produce and sell whips for commercial scale-up (www.doubleawillow.com). This website contains many excellent fact sheets prepared by SUNY on willow clones[i] available for sale in New York State.

3.3 Sweden

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Sweden has concentrated primarily on willow as the species of choice for biomass crops.

Interest in willow has grown since the OPEC oil crisis in the early seventies. The willow area expanded to 16,000 - 17,000 hectares in 2004 [54] [55]. The forecast is for a total of 200,000 hectares of SRIC willow biomass crops by 2019 [52]. Due to its northern latitude, only southern Sweden is considered suitable for hybrid poplar. Several trials with various poplar species and hybrid poplars were established to verify their usefulness in future SRIC crops; however, these trials do concentrate on producing pulp fibre besides biomass feedstock [24].

The development of SRIC willow crop technology and the associated genetic improvement efforts were centered at the Swedish University of Agricultural Sciences (SLU) in Uppsala (SW). SRIC willow biomass crops are now fully operational in Sweden and widely accepted as a viable means to reduce the country's reliance on imported fossil fuels. The concept was commercialized by the company Lantmännen Agroenergi (earlier Agrobränsle AB), which is a part of the Swedish Farmers Co-operatives Lantmännen. Lantmännen Agroenergi AB today has licence rights to SRIC willow seed from Svalöf-Weibull AB[ii], the company that started commercial willow breeding in 1987 [32] and markets the planting material throughout Europe [www.agrobransle.se]. The company takes care of the harvest and delivery of wood chips to the heating plants and frequently coordinates planting and management with applications of municipal sewage biosolids in integrated "waste to energy" initiatives [www.shortrotationcrops.org].

3.4 United Kingdom

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In 2002 the UK Government introduced the "Renewables Obligation" (RO) as a policy promoting the generation of renewable power. The RO obliges power companies

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[i] In most papers the word 'variety' is used to identify willow clones. For instance, *Salix viminalis* is a distinct species and *Salix viminalis* cv. Jorunn is a subspecies of *Salix viminalis*. The subspecies is referred to as variety or cultivar (cultivar or cultivated variety or cv.). *Salix viminalis* cv. Jorunn can be propagated vegetatively into many genetically identical 'copies'. The copies are called clones. Clone is an individual or group of individuals reproduced asexually from a single organism, and therefore genetically identical to the parent. For simplicity the word clone will be used throughout this report for both poplars and willows to identify such a vegetatively propagated species or subspecies.

[ii] Svalöf Weibull AB is a Swedish-based international plant breeding and seed company

to use "renewables" (e.g. biomass feedstock) as a source for power generation, while reducing greenhouse gas emissions. The target is to produce 15% of power from renewables by 2015 [www.carbontrust.co.uk/climatechange/policy/renewables_obligation.htm].

The UK SRIC woody biomass crops consist of willow species, as there are several suitable clones available for immediate use. Recognizing the potential of increasing yields through a breeding program, a brief partnership developed between breeders in the UK and the Swedish company Svalöf-Weibull AB that delivered 8 new clones. Willow breeding is continuing in the UK through the "Biomass for Energy Genetic Improvement Network" ('BEGIN'), funded by the Department of Environment, Food and Rural Affairs [44].

Although poplar would also be suitable in general, there are no good hybrid poplar clones in the UK. To my knowledge there is no active breeding program for poplar in the UK; clones tested for various uses, including SRIC biomass crops, originated from the Belgian breeding programs [personal information].

As in Sweden, private enterprise developed to manage planting, crop management and harvesting of SRIC willow crops. Coppice Resources Ltd. is the dominant UK company that has been developing and manufacturing harvesting equipment since 1998. This company is also involved in all aspects of SRIC willow crops, from establishment to harvest and marketing [www.coppiceresources.co.uk/].

3.5 Italy

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There is great interest in the production and utilization of woody biomass in the Lombardy region of Northern Italy, where the first SRIC woody crop trials were established in the mid 1990's. Projects were developed in a joint venture between the Region of Lombardy-Agriculture Department, the CNR Ivalsa (Italian National Research Council), Agriteam (a special agency of the Milan Chamber of Commerce) and CNER (National Consortium of Renewable Agricultural Energy) [personal information]. The main focus has been on poplar; however, several other species (e.g. black locust and willow) are included in several trials. The overall aim is to promote and develop the entire production system revolving around woody biomass, including conversion to energy, as well as providing fibre to the wood panel industry, which has a substantial presence in Northern Italy. Several thousand hectares have been planted to SRIC woody crops over a 5-year period early this century.

CNER is actively involved in the development of better harvesters, based on the Claas Jaguar silage harvester.

Two organizations in Italy have been involved with breeding new poplar clones. The oldest poplar research organization in the world is Instituto de Sperimentazione per la Pioppicoltura (Poplar Research Institute) in Casale Monferrato, which is funded through the Italian Ministry of Agriculture. This Institute has bred many hybrids that are used the world over, particularly in South America and China. One private company, Alasia Franco Vivai, has also been developing its own (hybrid) poplars in competition with the Poplar Research Institute. It is concentrating on developing new clones specifically for SRIC biomass production [personal information]. Its breeding program is the largest in the world involving eastern cottonwood (*Populus deltoides*) [Brian Stanton – personal information], a North American species that thrives in the Po River region of Northern Italy.

4 Genetic improvement in Canada

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Genetic improvement breeding of poplar has been carried out by the Ministère des Ressources naturelles et de la Faune (MRNF) in Quebec. MRNF is maintaining an active role in the development of hybrid poplar as a crop. The Ontario Ministry of Natural Resources (OMNR) dropped its role in poplar technology development approximately 15 years ago. A recent breeding effort with poplar was undertaken by a partnership between the Shelterbelt Centre of AAFC and Alberta-Pacific Forest Industries Inc. in Boyle (AB); there were no firm plans to continue this cooperative breeding. This program is currently testing the new hybrid clones.

Genetic improvement of willow had taken place at the University of Toronto under the direction of the late Dr. Zsuffa. The program was halted some years ago. The major beneficiary of these efforts was the SUNY-ESF in Syracuse (NY), where an active willow breeding program is continuing to date. Many of the willows developed at the University of Toronto are considered of limited use in the Prairie Region due to climate. In 2006 the Shelterbelt Centre of AAFC initiated Phase I of a willow breeding program for the Prairie Region of Canada to develop high biomass yielding native hybrid willows. This phase involved assembly of a diverse population of native willow species and included collaboration with Alex Mosseler of Natural Resources Canada in Fredericton (NB) for eastern Canada populations. The collection is located at Indian Head (SK). Phase II has been initiated in February 2008 and will focus on intra- and interspecific hybridization using populations collected in Phase I [Bill Schroeder – personal communication]. The Montreal Botanical Gardens also have a project on native willow clone selection in partnership with Alex Mosseler of Natural Resources Canada in Fredericton (NB) [Michel Labrecque – personal communication].

4.1 Discussion and management implications

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Choice of clone is critical for the success of SRIC woody crops, be it for the production of biomass or for the production of solid wood in the case of hybrid poplar. Several trials carried out in Tully (NY) at the experimental grounds of SUNY-ESF used several willow clones and one hybrid poplar clone. Only one or two willow clone(s) proved successful in long term plots; the remainder was dropped due to poor performance [2] [26]. In order to grow these crops profitably, breeding and selection programs are the keys to success. This includes establishing multiple clonal trials throughout the expected range of operations and managing these trials under circumstances that mimic operational approaches. Verwijst [52] reports that willow breeding in Sweden results in yield increases of 10-20% per generation, indicating the potential for the Prairie Region in a long-term breeding program for willow.

It is encouraging learning about the recently initiated willow selection and breeding initiatives at the Shelterbelt Centre of AAFC for the development of SRIC willow biomass crops for the Prairie Region [Bill Schroeder – personal information].

Unfortunately a similar effort for hybrid poplar is lacking for the Prairie Region. Even though some limited proprietary breeding has taken place in a temporary partnership between Alberta-Pacific Forest Industries Inc. and the Shelterbelt Centre (AAFC), this appears to be a one-time only effort. The Shelterbelt Centre has no plans to start a long-term breeding program similar to that for willows; the poplar breeding that has been taking place is for the production and selection of poplars for use in shelterbelts; its purpose is not to produce new clones for use in SRIC hybrid poplar crops [Bill Schroeder – personal information].

Without such a program in place for SRIC hybrid poplar crops, the future of successful SRIC hybrid poplar crop systems in the Prairie Region will very much be in doubt. The yield improvements of 10-20% per generation reported for willow in the Swedish breeding programs [52] are certainly also achievable in hybrid poplar, as has been demonstrated by several breeding programs in the US and around the world. Of particular concern is the need to start addressing the threat of *Septoria musiva*, a fungal disease that causes stem cankers in many poplar hybrids; it is on the increase as a result of expanding SRIC hybrid poplar crops in the Prairie Region [personal observations and communication].

5 Yield, crop density and crop cycle

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It is difficult to separate a discussion about yield from that on crop density and crop cycle. To maintain readability and in an attempt to minimize confusion, section 5.1 will emphasize the topic of yields as reported in the literature and will, in some cases, tie this to crop density and crop cycle. Section 5.2 will address crop density and crop cycle, with several references to yield potential.

It should be noted that ‘crop cycle’ is the same as ‘rotation’, and ‘crop density’ is the same as ‘stand density’ or ‘density’. The preference for the word ‘crop’ in these expressions is a reflection of these woody crops being grown as agronomic crops.

5.1 Yields of SRIC woody biomass crops

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Early yield estimates for SRIC biomass crops were based on small plots, resulting in estimates that proved too optimistic due to the large ‘edge effect’. White et al [56] describe the ‘woodgrass’ concept of woody biomass production with willow, a concept that was introduced in the early eighties in eastern North America (New York State and Ontario). The crop would have to be planted at 40,000 to 440,000 spha[i] (0.5x0.5 to 0.15x0.15 m spacings) and be harvested annually or biennially in order to produce the projected yields as high as 50 ODT/ha/yr. In support of this claim, yields as high as 45 ODT/ha/yr are quoted in experimental plots in Sweden, Italy and New Zealand.

[i] Spha = stems per hectare

The woodgrass system for poplar was also investigated in the early nineties in Oregon [13]. Annual harvest yields of poplar woodgrass planted at 111,000 and 308,000 spha (0.3x0.3 and 0.18x0.18 m spacings) were compared to those of three wider spacings at 2,500, 10,000 and 40,000 spha (2x2, 1x1 and 0.5x0.5 m spacings) grown at a 5-year crop cycle. Mean annual harvests of the densest spacings were 6.4-7.0 ODT/ha (this is equal to the mean annual increment or mai[i]); for the wider spacings of the best hybrid poplar clone the mai was 15.7-18.8 ODT/ha/yr. The current annual increment (cai[ii]) in the 5th year of this good clone at wider spacings exceeded 30 ODT/ha. This indicates hybrid poplar at these wider spacings would not culminate their mai until after year 5. This is a significant finding and will be further discussed in section 5.3.2. It is important to realize that all these results were based on small plots and were reported before the onset of various leaf diseases that would become established in Oregon, Washington and south-western British Columbia [personal observations].

One paper [26] reports on the 10-year results of annual harvest cycles in SRIC willow and SRIC poplar trials planted at 0.3x0.3 m crop spacing (111,111 spha). Half the plots were fertilized and half were not. Several willow clones did not perform well due to poor adaptability to the site (Tully, NY), but at least one willow clone and one hybrid poplar clone performed well for the full 10-year period. These trials showed that it is possible to harvest woody stem biomass at these high densities annually without incurring a loss in productivity. Fertilization did not increase the maximum productivity level, but it did reduce by one year the time required to attain maximum annual biomass production. Although crop cycles of 3-5 years at lower crop densities are presently the norm in SRIC willow crops, the trials showed conclusively that annual harvests are possible without detrimental effect to the viability of the annual production of willow cuttings as planting stock. This is an important finding, as consistent production of planting stock in large quantities is considered critical for the success of SRIC woody biomass crop systems.

The woodgrass concept using willows and poplars has since given way to woody biomass crops at lower crop densities and longer crop cycles with generally tighter spacings for willows and wider spacings for poplars.

A 1993 study from the US Midwest [47] reports on several hybrid poplar clonal plantings in several trials at various spacings ranging from 0.3x0.3 m (111,000 spha) to 2.4x2.4 m (1,730 spha). The conclusions are: a) maximum mai does not differ much between the various spacings, b) at wider spacing, culmination of mai takes place later, and c) at wider spacing, tree sizes are larger, and thus "*Close spacings are clearly not an inherent requirement for high yields*" [47].

In trials in England [4], two hybrid poplar clones were planted at 1x1m (10,000 spha) and 2x2 m (2,500 spha) spacings at several different sites and on two different crop cycles, a 2-year crop cycles vs. a 4-year crop cycle (after initially being cut after the first year to promote coppicing). The range of mai was 6.4-13.6 ODT/ha/yr at the 1x1m spacing; at 2x2 m spacing the yield dropped to 4.3-9.7 ODT/ha/yr. In all situations the 4-

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[i] 'mai' stands for mean annual increment. It is the yield divided by the years in the crop cycle and is expressed as m^3 per hectare per year (m^3/ha/yr), or in the case of biomass crops as ODT/ha/yr or Mg/ha/yr.
[ii] 'cai' stands for current annual increment. It is the year-over-year increase of the volume per hectare and is expressed as m^3 per hectare (m^3/ha), or in the case of biomass crops as ODT/ha or Mg/ha.

year crop cycle outperformed the two 2-year crop cycles in terms of yield, regardless of clone or crop density. The authors concluded that one 4-year crop cycle not only produced better yields than the two 2-year crop cycles, but also could save money through a lower harvest frequency.

The early yield projections did not consider potential negative impacts from diseases and insects [14]. From personal experience I know this to be a common problem that manifests itself when starting a new high-yield woody crop project with hybrid poplar. Yield estimates tend to be too optimistic and the general absence of diseases and insects at the beginning of these trials (the 'honeymoon period') appears to be the norm in both poplar and willow trials. Early trials with willows in Sweden and the US Midwest indicate that diseases, insects and abiotic events (such as frost in willows and wind damage in poplars) were the most important factors impacting yield. Any potential yield gains from intensive culture and improved genetic material will be undone by yield losses. Hybrid poplars were most affected by *Septoria musiva* stem cankers in eastern North America and willows by frost damage in the US Midwest trials [20] and Sweden. Regarding the *Melampsora* leaf rust species, the realistic expectation is that these rust species will start to exact a toll from SRIC willow crops as the production areas increase; this would follow the experiences in Sweden with willow and that of poplars in many regions in the world.

Yield projections of SRIC woody crops have since been lowered substantially from 20 to 34 ODT/ha/yr in 1991 [57] to 10-15 ODT/ha/yr [16] in 2002-03 and 5-20 ODT/ha/yr in 2006, depending on material used, location and management intensity [14].

Swedish trials with various poplar species and hybrid poplars planted at a density of 5,000 spha reached yields of 3.3 ODT/ha/yr to 9.2 ODT/ha/yr in total above-ground biomass in 14 years for balsam poplar and 9 years for hybrid poplars [24]. Yields of hybrid poplars in southern Sweden are within the 5-20 ODT/ha/yr standard reported above. These trials also measured the amount of pulpwood generated and these crops can therefore not be considered purpose-grown biomass crops. The poplar yield equals that of SRIC willow biomass crops at 7-9 ODT/ha/yr on a 3-4 year crop cycle [24]. The general problem with the longer crop cycles of poplar (9-14 years) at high densities, in this case 5,000 spha, is that they are subject to serious wind damage, as was the case in these trials in southern Sweden [24]. The risk of wind damage of these SRIC crops is consistent with my own observations in the US PNW, where crops were planted too dense for the length of their crop cycle. SRIC hybrid poplar crops become very unstable when the diameter to height ratio (d/h ratio[i]) falls significantly below 1.0 [50]. This was certainly the case in the Swedish study, where the trees at age 9 had d/h ratios of 0.55.

A similar study in southern Finland [18] with hybrid poplar planted at 15,000 spha and 5,000 spha concluded that the mai of poplar planted at a density of 15,000 spha was highest in a 4-year crop cycle. The crop was more productive at the lower density of 5,000 spha, using crop cycles lasting 5-6 years. The conclusion was that hybrid poplars are not suitable for very short crop cycles of less than 5 years (in Finland). This is compatible with all the other findings.

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[i] The d/h ratio is the DBH (in cm) of a tree divided by its height (in m); it is referred to as the 'd/h ratio' or 'diameter over height ratio'

DeBell et al [12] tested three spacings (0.5x0.5, 1x1, 2x2 m spacing or 40,000, 10,000 and 2,500 spha respectively) with two very different hybrid poplars on a 7-year crop cycle (not coppiced). The total woody biomass yield did not differ significantly between spacings. Of course the individual tree sizes were significantly larger than at the two close spacings, a finding that corresponds with an earlier study from the US Midwest [47].

5.2 Impact of crop density and length of crop cycle on yield

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Crop densities and crop cycles differ substantially between SRIC poplar and SRIC willow crops as discussed in section 5.1 dealing with yield estimates. Shrub-willows, which represent the bulk of the SRIC willow biomass crops, are able to grow at a much higher density than hybrid poplar. Verwijst [52] reports that crop densities in willow are dynamic and need to be adjusted as genetically improved and higher yielding clones become available. Willow breeding in Sweden results in yield increases of 10-20% per generation, with the consequence that the crop spacing needs to be increased or harvest interval decreased to avoid self thinning.

Willebrand and Verwijst [58] reported that the average number of willow shoots per stool dropped from 16.6 to 3.9 after three seasons in the 2nd crop cycle. Stool survival dropped after each crop cycle regardless of crop density and an increase in stool mortality was positively correlated with an increase in crop density. Laureysens et al [35] also report a drop in stool survival in poplars after each crop cycle; the poplars were originally planted at 10,000 spha, although in follow-up paper [34] the drop in survival could also be attributed to *Melampsora* leaf rust. Verwijst [51] points out that the competitive hierarchy developed in the stools is being maintained and even strengthened in subsequent crop cycles. Rankings in a future competitive hierarchy are therefore directly related to the initial size and weight of the plant at the start of the crop, i.e. the cutting. This lends credence to the need to adhere to strict stock standards (e.g. cutting sizes) and to avoid a large variation in the starting stock by using uniform planting stock. Verwijst [51] also concludes that fill-planting of gaps in densely planted coppice crops is futile, as the fill-planted stock quickly gets relegated to a lower competitive hierarchy. This phenomenon does not only occur in densely planted coppice crops, but also in SRIC hybrid poplar crops at much lower densities (e.g. 3x3 m crop spacing or 1,111 spha), where fill-planting of small gaps is frequently an exercise in futility, unless done immediately following the initial planting [personal observations]. Verwijst [51] further makes the observation that not all stool mortality is competition-related. Stools (or rather their shoots) affected by *Melampsora* rust will be at an immediate competitive disadvantage vis-à-vis unaffected stools and will be relegated to a low competitive hierarchy and be subject to a higher risk of mortality. Laureysens et al [34] determined that poplar stool mortality, as reported in an earlier article [35], was not related to crop density, but by the occurrence of *Melampsora* rust. These findings confirm that any yield predictions for SRIC woody crops need to take the impact of diseases and insect pests into account.

In a high-density poplar biomass coppice trial established in Belgium [33] [35] at 10,000 spha with different poplar clones (both pure species and hybrids), the average number of shoots emerging after planting was 2 per cutting. The trials were cut after the first growing season to encourage coppicing and an average of 4-5 shoots per stool emerged, but only 1-2 shoots survived after four seasons in the 2nd crop cycle; these were the ‘leader’ shoots that suppressed all other shoots on the stool. It should be noted that there were significant differences between clones. Laureysens et al [35] noted that in poplar strong apical dominance resulted in only 1-2 shoots surviving per stool several years after being coppiced. In hybrid poplar stoolbeds in south-western British Columbia, planted at 20x30 cm (in excess of 165,000 spha) in 3 m wide panel beds, the norm is an average of 2 shoots per stool at the end of one season in the 2nd and later 1-year crop cycle(s), with 1 shoot dominating [personal observations]. This was the case for a range of different hybrids.

Studies in southern Ontario [30] [31] reviewed the impact of three different spacings (0.5x0.5 m, 1x1 m and 1.5x1.5 m) on the growth of one hybrid poplar clone after 4 years (non-coppiced). At this age, the 1x1 m spacing (10,000 spha) had the highest yield, but the stems planted at 1.5x1.5 m (4,400 spha) had the highest mean root collar diameter. The conclusion was that trees at the latter crop spacing did not utilize their full site in the 4-year crop cycle. It should be noted that these results only applied to one hybrid poplar clone, which was considered as very competitive. It implies that different clones should be tested at different crop spacings to assess their productivity potential.

In a crop spacing trial DeBell et al [12] tested two very different hybrid poplar clones at three spacings (0.5x0.5, 1x1, 2x2 m spacing or 40,000, 10,000 and 2,500 spha respectively) over a 7-year crop cycle (not coppiced). They concluded that the longer the crop cycle (7 years in this case), the wider the crop spacing needed to be (2x2 m in this trial) to achieve the best yield. This applied to both clones, even though they were considerably different in their growth characteristics. The best clone was rated as extremely competitive, growing well at even the densest spacings. The differences between the two clones continued to increase with increased spacing, with the best clone increasingly outpacing its counterpart. The main differences between these two clones were branching habits and growth patterns; the best clone produced sylleptic[i] branches and continued to grow well into the late season.

A German study [36] looked at the performance of aspen (*Populus tremula* and *P. tremuloides*) and hybrid aspen (*P. tremula* x *tremuloides*) coppice as an SRIC biomass crop in two distinct plantings, using different crop densities and crop cycles. Even on sites of low quality, the average annual yield over a 10-year period was 10 ODT/ha/yr. The comparison between two 5-year crop cycles at 8,333 spha (1x0.6 m spacing) and one 10-year crop cycle at 5,555 and 4,167 spha (2x0.9 and 2x1.2 m spacing respectively) showed that a 10-year crop cycle, starting from coppice, produced more than double the biomass of the combined two subsequent 5-year crop cycles. The authors also determined that the mai of SRIC aspen crops did not culminate within the 10-year crop cycle, implying that longer crop cycles are needed for aspen and that these would be even longer than for the more traditional hybrid poplars in use today. As an aside, hybrid aspens produced more biomass with higher survival rates than either parent species.

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[i] Branches that grow from the current year’s buds c.f. proleptic branches that grow from last year’s buds. The presence of sylleptic branches is known to be beneficial for stem biomass accumulation.

Aspen is of interest as they can grow on more marginal sites than the traditional hybrid poplars. The problem remains that aspens do not propagate well through vegetative means.

5.3 Discussion and management implications

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The significant differences between willow clones suggest matching the crop density (and possibly the crop cycle) to the clone in order to maximize yield potential. Bullard et al [9] concluded that of two tested willow clones, *Salix viminalis* could be planted at much higher crop densities than *Salix dasyclados*, due to a more upright stature of the shoots, whereas shoots of *Salix dasyclados* exhibited more of a lateral type growth. In a follow-up paper Bullard et al [8] determined that the *Salix viminalis* clone had superior radiation use efficiency, the "*efficiency with which intercepted radiation is converted into biomass*"; this clone had a more efficient canopy structure, allowing it to be planted at tighter spacings while still accumulating more biomass.

Similar findings were not reported for poplar. In fact the conclusion for poplar was that "*Close spacings are clearly not an inherent requirement for high yields*" [47].

From a practical perspective matching clone to crop density may not always be possible as existing clones are being replaced by new, more productive ones before information becomes available for operational use.

Sections 5.3.1 and 5.3.2 report on willow and poplar respectively; however, references to both species are made in either of the two sections.

5.3.1 Crop cycles and crop density – willow

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The following key findings reported in several papers on crop density, crop cycles and yield apply mostly to SRIC willow crops [25] [29] [58] [59].

1-Year crop cycles are less productive. Yields in the 2nd harvest of 1-year crop cycles are located near the self-thinning[i] line, indicating that the crop approaches maximum yield for that crop density. Yields in the 3rd harvest of a 1-year cutting cycle did not reach the self-thinning line, regardless of crop density, which indicates yield well below the potential due to mortality unrelated to crop density. Examples of the latter were provided by Verwijst [51] in the case of willow and Laureysens et al [34] for poplar, where *Melampsora* rust infections were determined as the cause of stool mortality rather than competition from increased crop density. The short vegetation season in Sweden, coupled with the high harvest frequency, put 1-year crop cycle coppice systems at a high risk of collapsing after approximately 5 years. This is mainly due to an adverse growing season (e.g. a frost event in the summer or very low number of growing degree days) in any of the 1-year crop cycles; for instance, a low number of GDD during one

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[i] The self-thinning theory states that total biomass per unit area increases exponentially without competition mortality until canopy closure, regardless of cop density. Further crop growth is not possible without a decrease in crop density. The self-thinning line is a logarithmic expression of the maximum yield-density relationship. When the yield at a specified crop density approaches this line, competition-induced mortality takes place.

summer in the first season after harvest in Sweden caused the collapse of biomass production that year, indicating there is a high risk associated with annual crop cycles in SRIC willow in northern climates. The same phenomenon was not observed in trials in Ireland and New Zealand due to their milder climates.

Longer crop cycles tend to be more productive: 2-6 year crop cycles showed the highest mai. The yield of a 2-year crop cycle following planting was more than double the yield of the same crop harvested twice at 1-year crop cycles. The 2^{nd} crop cycle lasting 2 or 3 years resulted in a higher mai than the 1^{st} crop cycle lasting 2 or 3 years.

A crop density of 10,000-20,000 spha is considered sufficient for 2-6 year crop cycles reaching maximum yield (culmination of mai) from the 2^{nd} crop cycle on; however, several authors did state that increasing the crop density to 20,000 spha (e.g. from 15,000 spha) does not lead to increased yields in SRIC willow crops. However, this is in direct contrast to Bullard et al [9], who reported that better yields were possible with increased crop density and a shorter 2-year crop cycle rather than the 3-year crop cycle. They tested two different willow clones of *Salix viminalis* and *Salix dasyclados* at five different densities, ranging from 10,000-111,000 spha and determined that 2- rather than 3-year crop cycles had higher annual biomass yields with increased crop density. Of the two clones *Salix viminalis* proved the more productive, showing a 34% yield increase at a crop density of 111,000 spha over that at 10,000 spha. *Salix dasyclados* did not fare that well and 'topped out' at a crop density of 23,700 spha; differences in canopy architecture caused this difference. Bullard et al [9] made no references to the absence or presence of *Melampsora* rust in their paper.

The above information supports the currently used 'middle-of-the-road' crop densities in SRIC willow biomass crops of approximately 15,000 spha for operational willow clones, recognizing there will be major differences between clones. Matching density to clone is a refinement that may not always be practical. The grower must assess the extra cost of cuttings against the benefit of extra yield. Major differences in clones can also be found hybrid poplar.

5.3.2 Crop cycles and crop density – poplar

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In section 5.1 the conclusion was drawn that maximum mai does not differ much between the various crop spacings, but that tree sizes and the ages at which culmination of mai occurs do. This is in accordance with the conclusion that SRIC hybrid poplar crops grown at a much wider range of crop spacings from 3x3m (1,077 spha) to 4.8x4.8 m (434 spha) can attain similar mai-s [49], recognizing that the wider spacings will generally take more time to achieve culmination of mai.

In a 2005 project completed for the Saskatchewan Forest Centre [49] on hybrid poplar crop density, an important conclusion was that diameter (DBH)[i] growth peaks at age 3-4, regardless of crop density and that mai does not culminate till 2-4 years later. Results from a hybrid poplar Nelder trial conducted in the Netherlands [17] confirm this for crop densities to 6,500 spha (higher densities were not tested in this trial). Mai did

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[i] DBH - Diameter as measured at breast height of 1.30 m above ground level. This is referred to as DBH (diameter breast height).

not culminate till 2-4 years following the peak of DBH growth in the higher crop densities. The implications are that high-density hybrid poplar biomass crops are not likely to culminate mai within the short biomass crop rotations of 1-6 years used today. Although no data were found, I suggest this probably also holds true for tree-willow used in these short rotation high-density biomass crops. To 'fit' hybrid poplar, grown as a high-density SRIC biomass crop, to the harvest system used for SRIC willow biomass crops, the grower must accept a lower yield.

An important advantage of wide-spaced poplars is that yield can be sustained close to the culmination level of mai over a longer period of time than for denser spacings; i.e. the mai curve is flattening off around the age at which it culminates and only gradually declines [personal observations] [47], whereas mai curves for the tightest spacings is peaking more abruptly, after which it rapidly declines [47]. The significance is that, at wider spacings, the grower has the flexibility to 'leave the crop on the stump' without incurring a penalty of a steep decline in mai. That flexibility does not exist in the tighter spacings typically used in purpose-grown woody biomass crops.

5.3.3 Climate

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One aspect that was only sporadically mentioned was the impact of the growing degree days (GDD) on the annual biomass yield [26] [59] in northern climates. Kopp et al [26] reported that over a 10-year period and after an establishment period of 2 years in fertilized and 3 years in unfertilized plots respectively, the annual biomass harvest of several willow clones and the one hybrid poplar clone peaked in years with the highest GDD and 'tanked' in years with low GDD (5ºC base). According to the authors this was also reported in Sweden[i], where growing season temperature was the most important limiting factor in irrigated and fertilized SRIC willow crops and led to a collapse of the annual-coppice biomass harvest system. The phenomenon of unexplained decreased growth in irrigated stoolbeds in northern Alberta poplar stoolbeds in 2006 may well be tied to a low number of GDD [personal observations]. This information is increasingly important to anyone wanting to grow willow and poplar nursery stock, SRIC willow/poplar biomass crops in the Prairie Region.

Although this phenomenon was not observed in milder climates, similar observations on the impact of a low number of GDD were made in the cai of hybrid poplar yield plots planted at 1,111 spha on Vancouver Island [personal observations]. Across a range of sites and clones the cai peaked in years with ample summer heat and dropped off in years of cool summers.

6 Monoclonal vs. polyclonal crops

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The concept of clonal mixtures in willow biomass crops is a topic of great interest and is being researched in Northern Ireland [40], mainly to determine how so-called

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[i] The reference is listed under [12] in the paper by Kopp et al [26].

intimate[i] mixtures could help control the spread and intensity of infection by *Melampsora* rust species; the authors reported on survival, yield and rust disease. Stool survival of monoclonal plots was 80-98% with no significant differences between clones. In clonal mixtures large differences in stool survival from 35-98%, depending on clone, indicated severe inter-clonal competition. The mixtures started out at 20,000 spha and stabilized at 13,000 spha over time. Yields of polyclonal crops after coppicing were greater than those of the monoclonal counterparts after the 2nd and 3rd season of the 2nd crop cycle; however, several clones contributed more of the increased yield, while others contributed far less, pointing to differentiation between dominant and suppressed clones. The onset of *Melampsora* rust was delayed in the clonal mixture, in some cases by 3 weeks and the disease build-up was slowed, resulting in a much lower infection level than observed in the monoclonal plots. Questions remained about the best clones to use, the impact of crop density and the optimum clonal mix. In the trials 4-, 5- and 6-way clonal mixtures proved beneficial.

In Sweden Willebrand and Verwijst [58] concluded that intimate clonal mixtures appear better from a yield perspective than monoclonal crops in 1-4 year crop cycles; stronger clones take over the growing space of the weaker ones which may lead to the "*extinction*" of the latter ones. There was no difference in yield between polyclonal and monoclonal crops on a 5-year crop cycle as there was sufficient time for surviving stools to fully occupy any growing space vacated through stool mortality. They did not consider the aspect of leaf diseases, which can account for significant stool mortality [34] [51]. Polyclonal mixes of only 2 or 3 clones are deemed insufficient; should one or two clones fail, the remaining good clone(s) might not be able to recover the growing space lost [52]. This is in accordance with the findings in Northern Ireland [40] reported above. The authors did not detect any difference in yield between polyclonal and monoclonal crops in 5-year crop cycles and attributed that to the fact that by year 5, all gaps in the initial crop had already been fully occupied. The same was observed in trials in the US [11] and France [6] with polyclonal mixes of (hybrid) poplar.

The Swedish study [58] concluded that the performance of each willow clone in a polyclonal mix cannot be predicted from its performance in a pure crop. For hybrid poplar a similar result was confirmed in the US [11] and France [6]. It was also observed in intimate mixtures in hybrid poplar clonal trials (grown at wider spacings), where dominant clones quickly occupied the growing space of sub-dominant neighbour clones, despite the fact that some of the sub-dominant clones would actually perform up to par when planted as a monoclonal crop [personal observations].

DeBell and Harrington in the US [11] tested four clones (three hybrids and one black cottonwood - *Populus trichocarpa* - clone) at three spacings (0.5x0.3, 1x1, 1.5x1.5 m, or 40,000, 10,000 and 4,444 spha respectively) in intimate polyclonal mixtures and monoclonal plots, and grew them for a 3-year period (not coppiced). They used large plots and buffers to avoid the 'small plot' bias. The clones were not related to each other. Survival after three years was high and averaged 92%. In all monoclonal plantings at all three spacings, the above-ground biomass of the three hybrid clones were similar; that of the lone black cottonwood clone was somewhat (statistically significant) lower. The

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[i] Intimate mixture is an even or random mix of individual clones in a polyclonal mix. Mosaic mixture refers to small monoclonal blocks of different clones distributed across the site.

polyclonal plots produced similar biomass yields to those of the monoclonal plots at all three spacings; however, the biomass contribution of each of the clones was disproportionate to their performance in the monoclonal plots. The polyclonal plots showed pronounced clonal differences. At the two densest spacings the black cottonwood contribution was reduced to almost zero; its growing space was readily absorbed by one of the three hybrid clones. At the widest spacing the black cottonwood held its own. The authors concluded that "*Differences in relative performance of clones across spacings can be attributed to (1) clonal branching habits and the effects of spacing on the expression of branch development and (2) clonal differences in physiological responses to self-shading and other aspects of intraclonal competition*". Relative differences between clones in intimate polyclonal mixes become less pronounced with decreasing crop density. Although they recognize there are proponents of polyclonal mixes for (theoretical) reasons of higher yields and better protection from diseases, pests [39] [40] and abiotic disasters (e.g. wind throw), their study "*failed to show any yield advantage of polyclonal plantings*".

Berthelot [6] tested intimate clonal mixtures in France of three hybrid poplar clones on two different sites, planted at 3,000 spha; the density dropped to approximately 2,100 spha by age 7 on both sites. Results of only one site[i] were reported. The coppiced poplars were grown in a 7-year crop cycle in three monoclonal blocks (clones A, B and C) and four blocks of intimate clonal mixtures (clones A&B, B&C, A&C and A&B&C). Two of the clones (A and B) were full-sibs (same father and mother); the third clone (C) was their half-sib (same mother). In pure monoclonal blocks, all three clones produced similar amounts of biomass. The full-sib mixture (clone A&B) produced the same biomass in total, more or less evenly distributed between the two clones. In the mixtures with clone C (the half-sib), this clone exerted dominance over its half-sibling clones A and B. In the 3-clonal mix clone C had a greater proportion of the biomass than clone A, which dominated clone B. Total biomass produced in all the clonal mixtures was approximately the same as for the monoclonal blocks.

6.1 Discussion and management implications

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In SRIC hybrid poplar crops polyclonal mixtures are generally not used much, if at all, and certainly not in the longer crop cycles for pulpwood or solid wood production. This is in contrast with recommendations made by several researchers [39], who contend that so-called polycultures (polyclonal crops) promote crop heterogeneity, which can slow down insect problems. The same argument can be made in the control of diseases as discussed above in polyclonal mixtures of willow crops [40].

I have not come across any papers that investigate the role of polyclonal mixtures in poplar to decrease the risk of windthrow, which has been so prevalent in densely-spaced (3x2.5 m spacing) SRIC hybrid poplar pulpwood crops in the US-PNW. From personal experience I can report that windthrow risk is very much a clonal (and sometimes family) trait and windthrow has manifested itself in the wind-sensitive clones in many polyclonal mixtures of clonal trials in south-western B.C and the US-PNW.

[i] The second site, not discussed further, suffered serious mortality due to a species of bindweed.

Monoclonal crops will in all likelihood continue to be used in SRIC poplar (biomass) crops, unless truly compatible clones can be identified for a mixture. A compelling argument in favour of monoclonal SRIC woody crops is the assurance of consistency and homogeneity of the fibre supply, something the wood-using industrial plants value above all else [6] [personal observations & communication]. At this point it is still unclear how important crop homogeneity is in biomass feedstock.

The challenge in polyclonal mixes in biomass crops is then to match clones that limit inter-clonal competition, so stools can survive and remain productive through several crop cycles. If clonal mixtures are not compatible, dominant clones will outperform the slower starters, leading to their stools' mortality and jeopardize yields in subsequent crop cycles. The concept of warding off disease development and spread in SRIC willow crops as reported in Northern Ireland [40] merits further work, as diseases and insect pests are going to be a certainty in densely-spaced SRIC willow and poplar biomass crops.

7 Impact of cultural practices

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7.1 Fertilization

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Weih [55] reports that biomass production rates (mai) exceeding 20 ODT/ha/yr were achieved after 3–5 years in fertilized willow stands grown in Sweden and Canada and that yields were similar to those reported in SRIC hybrid poplar crops in the US PNW and southern Europe, where "*the growing season length is considerably longer than that in the boreal regions*" and where crop cycles are 12-15 years. He argues that conditions in the boreal zone can be very conducive to plant growth; for instance, there are many days of extended day length with daytime temperatures exceeding 20ºC. The shorter crop cycles used in SRIC biomass crops are more of a drain on soil nutrient reserves than the longer crop cycles used in hybrid poplar and thus may require a fertilization regime [2].

An extensive study in New York State [2] analyzed wood biomass production, annual removal of nutrients and nutrient use efficiency in various willows and one hybrid poplar at three spacings (0.3x0.3, 0.3x0.9 and 0.6x1.1 m). Although data were collected and analyzed for all the clones, the emphasis of the study was on two willow clones (*Salix dasyclados* – SV1 – and *S. alba*), as these proved well adapted to the site in New York State; unfortunately *S. alba* became seriously affected by an insect pest. Biomass production, annual removal of nutrients and nutrient use efficiency are very clone-dependent. Clone SV1 had the highest biomass production and the highest nutrient use efficiency. The differences among the three spacings were reported as non-significant. The authors concluded that the best annual biomass accumulation occurred at the longest (3-year) crop cycle, confirming findings reported on earlier (section 5.2). The length of the crop cycle did have a significant impact on nutrient use efficiency, but crop density did not. Not only did nutrient use efficiency improve with a longer crop cycle, biomass accumulation also increased. The authors concluded that nutrient removals through harvesting are substantial and that nutrient replacement is needed.

With the frequent removal of biomass in a coppice system, fertilization is required to replenish the soils' resources. In a Quebec study [27] of SRIC willow crops, clones reacted differently to fertilization and this complicates efforts to prescribe an appropriate fertilization regime. Two different willow clones (*Salix viminalis* and *S. discolor*) were planted on two different soils (sandy and clay); biosolids were used as a source of fertilizer (at 18.8 tonnes dry matter per hectare or the equivalent of 100 kg of available N per hectare) on the treatment plots; the control plots were left unfertilized. The response of both clones was more significant on the sandy site than on the clay site. The sandy site was poorer in terms of soil fertility and fertilization with N paid off on this site; this payoff did not materialize on the richer clay site. Both clones had their best growth on the clay soil; however, their response to fertilization differed significantly; *Salix viminalis* responded much better than *Salix discolor* and was reported as producing the best-ever recorded biomass yield in Canada at the end of its second 3-year crop cycle (a little over 70 ODT/ha, which equates 23 ODT/ha/yr). The authors concluded that the application of biosolids did not completely replace the nutrients taken off the site in harvest. As a result of the different clonal outcomes of fertilization, the challenge is how to formulate a long term fertilization plan to ensure repeated biomass harvests remain sustainable. The authors recommend that "*A fertilization plan of long duration has to take into account the replacement of exported elements by the biomass harvested according to the type of soil*". This was also suggested in the New York State study [2]. Only careful monitoring of nutrient exports will provide the grower with an estimate of what he has to put back into the site on an annual or periodic basis.

Another interesting finding was that, although fertilization increased height and diameter of the two clones, the number of shoots after coppicing remained the same cf. the control [27].

Adler et al [3] investigated the bark proportion of an SRIC willow biomass crop. They found that the bark-to-wood ratio of the *Salix viminalis* clone was quite high in small stems, but remained stable in stems greater than 20 mm in diameter (at a height of 55 cm) at around 19%. Bark had significantly higher concentrations of almost all of the macronutrients[i] (except S-sulphur) and several heavy metals[ii]. This implies that the export of essential nutrients can be minimized by decreasing the bark-to-wood ratio of the harvest by managing shoot size distribution through choice of clone, density and length of crop cycle.

7.1.1 Discussion and management implications

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There is every expectation that growers need to replenish the soil with nutrients that are removed through successive harvests. How much fertilization is needed and which fertilizer combinations to use is the tough question, as there are substantial clonal differences in SRIC willow to fertilizer response. This has also been the case with SRIC hybrid poplar, where not all clones react similarly to fertilization [personal observations and communications].

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[i] The macronutrients are nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), and magnesium (Mg).

[ii] Cadmium (Cd), lead (Pb), cobalt (Co) and zinc (Zn).

The recommendations by Labrecque and Teodorescu [27] and by Adegbidi et al [2] to determine the total export of nutrients from the site and to replenish those nutrients through annual or periodic fertilization seem reasonable in the case of SRIC willow biomass crops that are of relative short crop cycles. One of the main causes of the high nutrient removal in SRIC willow biomass crops is the high bark-to-wood ratio; bark contains a high amount of nutrients cf. wood [2]. This will be less of an issue for the typically longer crop cycles of SRIC hybrid poplar, where nutrient use efficiency is higher due to the longer crop cycle and the fact that the bark-to-wood ratio is lower [2] as a result of the larger stems. This is consistent with findings by Adler et al [3].

Another important aspect of lowering the bark-to-wood ratio is that the nitrogen (N) content of the resulting chips will be lower, leading to lower emissions of nitrogen oxides when using the biomass in wood pellet boilers [3]. Many of the European countries for example set strict limits on the N content of wood pellets and do not accept high bark content, if any [Fabrizio Nardin - personal information].

The use of municipal biosolids and/or municipal effluents offers an excellent opportunity to combine the needs of a sustainable crop system with an environmental service and should be encouraged at every opportunity, especially in such a compact production system as SRIC willow. One of the main benefits of organic fertilizers is that the costs will probably be substantially lower than for inorganic (chemical) fertilizer; this is an important consideration for a commodity crop where input costs need to be as low as possible in order to become or remain competitive.

7.2 Weed control

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Effective weed control is critical to SRIC woody crops, regardless of species and the length of the crop cycle. Crop density will have an impact on the duration of needed weed control, as crops planted at high crop densities (e.g. >20,000 spha) may be able to control the site within the first crop year due to shading. Canopy closure also depends on crop layout, for instance square spacing spread evenly over the site, or condensed row spacing (e.g. twin-row system) with room for equipment between the twin-rows. In the latter case weed control between adjacent twin-rows would be simpler.

The first order of business in weed control in the crop is elimination of weeds that threaten to overtop new shoots emerging from the planted cuttings or coppice; both poplars and willows are extremely shade intolerant. A 1999 willow study in England by Sage [43] observed that tall weeds competed more for light and growing space in year one than for moisture and nutrients. This competition for light caused a smaller number of taller shoots to emerge from willow coppice in the first year of a 2-year crop cycle then from coppice in a well-weeded crop, leading to a lower shoot biomass. The number of shoots held steady in the second year of the 2-year crop cycle in both the weeded and non-weeded plots. There was a linear relationship between the growth in weed-free conditions and the index of weediness during the first year of the 2-year crop cycle; a decrease in weediness was correlated with an increase in growth. This relationship did not exist in the second year of growth; weediness did not affect growth. Researchers measured photosynthetically active radiation (PAR) inside the crop in the second year of the 2-year crop cycle and determined that the values for PAR inside the well-weeded crop were significantly lower than inside the non-weeded crop. This reflected a measure of canopy density and indicated better light interception in the well-weeded crop and thus better biomass accumulation. Sage further commented that weed competition was most severe in the period April to June, when (annual) weeds are most vigorous and abundant; late season weediness was of less concern. The vigour and abundance of annual weeds in the period April to June coincides with a high incoming PAR early in the growing season, as reported in a 2002 paper by Proe et al [41]; this occurs before crop canopies have fully expanded. As crop canopies expand during the summer, they intercept more of the incoming PAR at a point when PAR has peaked and/or is already declining. This may explain why Sage [43] was less concerned with late season weediness. The amount of early season PAR interception by the crop canopy increases as the crop gets older in years, resulting in negligible differences in PAR interception by the crop planted at various crop densities.

Secondly, weed control is needed to eliminate below-ground competition for moisture and nutrients. Effective weed control provides an irrigation and/or a fertilization effect by diverting moisture and nutrients away from weed competition and towards crop growth. This would be especially important in areas with a summer soil moisture deficit. Interestingly enough the English study [43] could not detect a reduction in available soil moisture between the weeded and non-weeded plots.

Effective weed control can be achieved mechanically, chemically or by combined mechanical & chemical methods. A fourth method is the use of mulches, in particular plastic mulch.

A 1994 Quebec paper by Labrecque et al [28] reports on the impact of five weed control methods (mechanical, chemical, mechanical & chemical, plastic mulch and control) on two willow clones (*Salix viminalis*, a European willow and *Salix discolor*, native to Quebec) on a well- and a poorly-drained site. On both sites mechanical and mechanical & chemical weed control resulted in the lowest weed biomass on the site; weed biomass after chemical control was significantly higher, but was not significantly different from use of plastic mulch. After the first season of establishment, the best height and diameter growth on the well-drained site for both willow species was achieved with the mechanical, mechanical & chemical and the plastic mulch methods, with plastic mulch being slightly better in *Salix viminalis*, producing similar amounts of biomass. The chemical method (two applications of glyphosate) was not as effective. On the poorly-drained site plastic mulch offered superior height and diameter growth in both willow species; chemical control resulted in lower height and diameter growth than the mechanical and mechanical & chemical methods, which were 'middle-of-the-road'.

On both sites the use of chemical weed control (two applications of glyphosate) was not considered an effective weed control method. The plastic mulch method used on the poorly-drained site was superior in terms of biomass yield.

A Michigan study [38] investigated the impact of three relatively low crop densities (2x3m, 1x 2m, and 0.5x1m spacing) of one hybrid poplar clone in weedy and weed-free plots over a 3-year period (non-coppiced). Weed competition had a greater impact on growth of the poplars than intratree competition; poplars grown in plots with weed competition were smaller than those grown in weed-free plots. Crown architecture of the poplars was influenced both by the presence of weeds and by crop density. In the second season the branches in the weed-free plots were longer than those in the weedy plots; however, this difference diminished as the crop density increased and started to shade out the weeds. Trees in weedy plots initiated fewer branches and had fewer live branches, pointing to a lower biomass than trees in weed-free plots. Basal diameters and heights in the weed-free poplars decreased significantly as crop density increased, with the basal diameter showing an especially steep decline as a result of increased intratree competition. For the weedy treatments basal diameter, which was almost at half the value of the weed-free poplars, did not decline much; however, tree heights (also lower than those in the weed-free poplars) increased as density increased. One possible explanation suggested by the authors was that under conditions of sufficient soil moisture (and nutrients) weed competition decreases as crop density increases and trees can now shift carbon resources from root growth to much more needed top growth to capture more light.

7.2.1 Discussion and management implications

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The finding that good weed control in the first year of a 2-year crop cycle of willow (from coppice) is much more important than good weed control in the second year of the 2-year crop cycle [43] has important implications for management. It is reasonable to assume that this effect carries on in subsequent years of a crop cycle lasting more than two years. In order to capture the maximum amount of biomass from a coppice, weed control in the first year of the 2-year crop cycle is therefore an absolute must. The researchers used several soil active, residual herbicides to achieve good weed control. This will be difficult in Canada without registered soil active, residual herbicides. The crop density in the study [43] was 20,000 spha, planted in a twin-row configuration. With good weed control in the first year, the crop would more than likely have been able to shade out the weeds more effectively in the second year. This was shown through the higher interception of PAR inside the well-weeded crop than inside the non-weeded crop and reflects higher canopy density. This is a possible explanation why 2nd year weed control in the ‘weed-free’ plots did not have a measurable impact on yield.

In a weeding-duration study in British Columbia in hybrid poplar planted at 2x2 m crop spacing [personal information – unpublished study] weed control in the 1st and 2nd year resulted in better growth than weed control in the 1st year only, as the crop canopy was not yet able to shade out the weed competition. When weed control in the 1st, 2nd and 3rd year was compared to weed control in the 1st and 2nd year only, growth was not significantly better. The explanation was that by the start of the 3rd growing season the crop fully occupied the site and started to exert competitive pressure on the weeds. Once this occurred, 3rd year weed control became ineffective, even though there were still weeds.

The finding of weed competition influencing crown architecture in a hybrid poplar trial in Michigan [38] is very significant, even though the weeds did not overtop the poplars. This implies that trees must allocate carbon resources to their root systems at the expense of their tops under weedy conditions and also that trees will shift resources to height growth at increasing crop densities (and thus decreasing weed cover) in order to compete for light with their neighbour trees. There is every reason to expect that the same applies to willow crops as well, whether starting from a coppice or not. The researchers in Michigan had access to soil active, residual herbicides to achieve weed-free conditions.

As discussed above, one of the weed control methods used in the Quebec study [28] consisted of two applications with glyphosate, using a wick applicator. This was obviously not an effective method to provide lasting weed control. Use of soil active, residual herbicides, would have provided a different outcome, especially on the poorly-drained site. No soil active, residual herbicides are registered for use in SRIC willow crops.

The benefits of plastic mulch are well-documented. Its main benefits, besides keeping out the weeds, are improved soil temperature and soil moisture retention. Based on the English study [43], the main benefit of weed control would have been accrued in the first year of the crop cycle. From a practical perspective, there are a few downsides. Plastic mulch is not cheap, requires maintenance, is easily damaged (especially when the crops are harvested in short crop cycles) and offers a safe haven for rodents (e.g. vole species) that can seriously damage these crops [personal observations]. I can only speculate on the status of the plastic mulch at the start of the second crop cycle, when good weed control is again critical.

7.3 Miscellaneous practices

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7.3.1 Harvest season

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Harvest normally takes place in the dormant season to ensure continued stool survival and to avoid yield losses in subsequent crop cycles. Harvest of non-native willow during the growing season in Finland decreased stool survival, with a very steep drop when cut between the end of July and the beginning of August [21]. Stool survival of native willow species (and local birch) during the growing season did not decrease noticeably and remained above 80%. Summer harvest resulted in the lowest number of living sprouts. Of interest here is that summer harvest does result in an abundance of short sprouts/shoots; however, they did not survive the winter and were be absent the following spring. Local willow (and again local birch) did not follow this pattern and new shoots survived.

There is some potential to shift harvest to the ‘shoulder’ seasons of the dormant season for harvest flexibility. For instance this may be an important option in heavy snowfall years, when mechanical harvesting systems cannot operate efficiently or cannot operate without doing unacceptable damage to the stools.

7.3.2 Soil compaction

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Soil compaction has not been considered an issue in areas where the soil is frozen during the harvest and very little has been published on this subject for SRIC willow biomass crops. In milder climates soil compaction has been a concern. This was addressed in a UK study by Souch et al [46] on two different soil types, a clay loam and a sandy loam. Of the two soil types, the sandy loam was subject to greater compaction and impacted biomass production in the first season following the compaction (at harvest); however, the authors pointed out that the crop on the sandy loam was only 1-year old. In contrast, there was no impact on biomass production on the clay loam site after the first season following compaction; this crop's root system was already 3-years old. They concluded that, if compaction can be avoided through the first several years of a newly established crop, normal compaction from harvesting will have no significant impact on biomass production over the (multi-year) crop cycle. They point out that other studies in the UK have led to the same conclusion.

A word of caution: The lack of a significant impact on biomass yield applies to soils that are at least 1 m deep; the situation on shallow soils might be quite different.

7.3.3 Harvest damage

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Methods of mechanical harvesting in SRIC willow crops were simulated using manual pruning shears and brush saws in a study in Finland [21]. There were only small differences in survival, height and biomass yield between the two harvest methods used; brush saw cutting actually resulted in an increase of the number of shoots (no explanation given).

The same study also determined that damage caused to stools (simulated by using a sledge hammer and by driving a small forwarder over the cut sumps) had negative effects on stool survival and shoot height, which resulted in a lower shoot biomass.

The impact of extensive mechanical harvest damage, caused by driving a loader over the cut stools, caused 9-21% reductions in shoot biomass (dry) on two soil types in a study in the UK [46]; this resulted in the production of fewer shoots per stool following the damage.

Much of this damage can be avoided by choosing the right harvesters and by selecting an appropriate crop layout (section 9).

7.3.4 Stump height

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The impact of stump height in coppiced SRIC willow crops was also studied in the Finnish study [21]. Stump heights at 0, 10, 20 and 40 cm had no significant effect on stool survival for the first two 2-year crop cycles. Yield of the second 2-year crop cycle decreased significantly with increasing stump height; that trend continued in the third crop cycle. With stumps at 40 cm height, biomass yield dropped 70% cf. biomass yield with stumps at 20 cm height, which in turn yielded 45% less biomass with stumps at 10 cm height. Biomass yield proved superior over multiple crop cycles with a stump height of 10 cm and was slightly better than stumps cut at ground level.

This has important implications for the type of harvesters used and the harvest timing. For instance, deep snow would result not only in a loss of harvested biomass (wood left in the high stumps), but also in a yield drop of subsequent crop cycles.

7.3.5 Planting stock size

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Most, if not all, SRIC woody biomass crops will be established with unrooted, dormant cuttings. Due to the high crop densities required in these crops, the cost of the planting stock must be minimized without jeopardizing establishment success. It would be unrealistic to consider rooted planting stock for crop establishment.

In a Finnish trial [42] the effect of cutting lengths on survival and growth was tested. Cutting lengths ranged from 10-50 cm with a caliper (diameter) of 10 mm. All cuttings were planted with the top 1cm sticking out above ground level. The length of the cutting was positively correlated with survival and growth; the longer the cutting, the better the survival and growth. The longest cutting length (50 cm) produced 7x the above-ground biomass of a cutting of 10 cm in a 5-year crop cycle. Longer cuttings also produced more shoots than the short ones; it was unclear whether the additional shoots emerged from additional buds below ground level. One of the explanations provided for the better results with longer cuttings was the depth at which the cuttings were planted; deeper planting accessed additional soil moisture.

The impact of the cutting size is well documented for poplars [15] [50], especially the impact of the caliper (diameter) on survival and growth. In an unpublished report [personal information] the outcome of several trials with hybrid poplar cutting sizes clearly indicated that size matters. Increased caliper (diameter) and length positively impacted survival and growth; however, increased caliper was more important than increased length; an increase in caliper contributes more to the increase of carbohydrate reserves than an increase in length.

8 Impact of crop layout on yield

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Several of the publications reviewed used a crop layout where distance between crop rows was increased, while in-row crop spacing was decreased to mimic an operational crop layout.

Several studies, using the scotch plaid design, reviewed the impact of rectangularity[i] on yield, growth of individual trees, branch development etc. Maithani and Sharma [37] reported improved yield per hectare with increasing rectangularity in a eucalypt biomass crop that had 1 m^2 of growing space per tree. They offered no hypothesis on why that was so. The most rectangular spacing (rectangularity of 9) had the best growth to six years. Johnstone [22] also utilized a scotch plaid design to review a range of crop spacings (494-4,444 spha) and rectangularities (not exceeding rectangularity of 3) in three hybrid poplar trials in British Columbia. He reported no effect on either diameter or height development and concluded that in the absence of a rectangularity effect it would be possible to increase between-row spacing and reduce in-row spacing to maintain the required crop density. This flexibility provides access for crop maintenance, such as weed control. In a follow-up (unpublished) paper [23] he

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[i] Rectangularity is the ratio between the long and short sides of a rectangle. A rectangularity of 9 indicates a 9/1 ratio of between-row spacing and in-row spacing, i.e. 9 units between rows to 1 unit of in-row spacing. Spacing at 4x3 m has a rectangularity of 4/3; a spacing of 8x6 m has the same rectangularity of 4/3 etc.

confirmed his findings after 9 years of growth data. An Australian study by Gerrand and Neilsen [19] with eucalypts could not detect significant differences for tree growth between square and rectangular crop spacing. They tested densities from 278 to 2500 spha (4 m^2 to 36 m^2 per tree). The authors also tested the effect of rectangularity on branch size or abundance of branches and were not able to report any.

A study by Bergkvist and Ledin [5] examined 16 different crop layouts with willow (9 twin-rows and 7 single rows) at varying crop densities. Their aim was to investigate how different crop layouts influence yield. The crop was planted in 1989, cut back the following winter and then grown for an additional 4 years; the authors considered this a 5-year crop cycle. During this 1st 5-year crop cycle, the crop density at 20,000 spha proved best for biomass yield and no significant differences were noted between the different layouts. Densities higher than 20,000 spha in the 1st cutting cycle were not cost-effective. The superiority of this density (20,000 spha) began to diminish after two years into the 2nd crop cycle. Although the authors did not speculate on the yield-density relationship towards the end of the 2nd crop cycle, they acknowledged the fact that other researchers had concluded 10,000 spha as sufficient in 2nd or later crop cycles of longer duration. Their conclusion on crop layout was: in "*willow stands with low or normal development, planting design has a marginal influence on biomass production*". They point out that crop layout is important to allow machine access without undue damage to the crop and soil (compaction).

9 Impact of harvest equipment on crop layout

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In dealing with coppice systems, such as in SRIC willow and poplar, mechanized harvest systems are based on the concept of corn silage or sugarcane harvesters. Entire stems, including branches and bark, are cut and processed into chips in a single operation. Harvest is carried out in the dormant season (section 7.3.1) to facilitate coppicing without the need to replant. Harvesting during the active growing season would diminish the crop's ability to re-grow successfully. The main disadvantages of this harvest system are:

- The high capital costs;
- The seasonal nature of the harvest;
- The need to transport the chips off-site to a chip handling facility or to a converting plant.

On-site chip storage may not be feasible and conversion facilities may be reluctant to store a large inventory and carry its associated cost. There are several different silage harvesters that have been modified to handle SRIC woody crops. These harvesters target SRIC woody crops with crop cycles from 2-6 years and can be used to harvest both willow and poplar.

An alternate system still under development is a cutter-shredder-baler; this is being developed in Quebec in a partnership between AAFC and Université Laval – Department of Soils and Agricultural Engineering. The main advantages of this system are:

- An expected lower capital and operating cost than the silage harvesters;
- Simpler logistics by being able to store harvested bales of biomass on-site for later transport and processing. This could be an important factor in providing

an even-flow feedstock to conversion facilities during the growing season when coppice harvest is not carried out.

It is still in the prototype stage and will not be considered further in this report, as it is unlikely to require a crop layout any different from that of the modified silage harvesters, even though it is a row-independent system.

This report will only consider proven harvest technology in the context of its impact on crop layout and assumes a systematic layout of the crop to facilitate mechanized crop tending activities and to minimize crop damage. In the case where crop dimensions (e.g. cutting diameter) exceed machine-specified upper limits, the type of harvester will have to shift from the modified silage harvester to more conventional single- or multiple-stem tree harvesters. Although this shift is not expected for SRIC willow biomass crops, it must be considered for SRIC (hybrid) poplar crops grown at longer crop cycles in order to capitalize on improved average annual yields (mai).

In a system where conversion facilities utilizing woody biomass must have access to even-flow feedstock, biomass could be provided by a mix of feedstock from coppiced SRIC willow/poplar crops, SRIC hybrid poplar crops on longer crop cycles that require replanting and other more conventional sources of woody fibre. Questions about these harvest mixes, combinations with other woody feedstock sources and the desirability of lower bark content are beyond the scope of this report.

9.1 Modified silage harvesters

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The Swedes have the most experience with woody biomass crops and were the first ones to develop dedicated technology for the establishment and harvest of woody biomass. The Bender is a harvester/chipper system that was introduced in 1993 and has gone through several modifications. It is very much like a silage harvester and is a "non-row specific" harvester that can also harvest systematically laid out woody biomass crops [www.salix.se/index]. Besides the Bender, the Swedes are using harvesters based on the Claas Jaguar forage (silage) harvester [Ioannis Dimitriou - personal communication] with a modified harvesting unit. Although these systems are well suited for Swedish circumstances, the harvesting units (the cutting & chipping head) had to be modified to work in other regions.

In the UK, Coppice Resources Ltd. [www.coppiceresources.co.uk/CaseStudies.asp] developed a cutting head which is operated on a Claas Jaguar forage (silage) harvester [10]. It has been in use since 1999/2000. Stems are cut, chipped and the chips are blown into a chip trailer travelling in tandem with the harvester. The chip size can be adjusted to meet the customer's specifications. The harvesting unit was exported to New York State for testing.

In New York State, SUNY-ESF tested the Bender willow harvester, which was developed in Sweden; however, it produced inconsistent chip quality, causing chip handling problems in the field. The machine was also not robust enough for conditions in New York. In cooperation with Cornell University and Case New Holland (Holland, PA), SUNY-ESF developed and tested a willow biomass crop harvester based on a New Holland FX45 forage harvester. They settled on a cutting head designed and built by the UK firm Coppice Resources Ltd. [53]. This system produced consistent chip quality.

The upper cutting diameter limit is 7-8 cm at stump level for optimal efficiency [Larry Abrahamson-personal communication].

In Italy most harvesters are based on the Claas Jaguar 850 and 880 series silage harvesters, which harvest (hybrid) poplar. The optimum harvest diameter at stump level is 6 cm for the Claas Jaguar 850 harvester and 8-10 cm for the Claas Jaguar 880 with a new harvesting unit that is still in the prototype stage; it can reportedly cut 10-12 cm diameter stems. The Region of Lombardy-Agriculture Department, the CNR Ivalsa (Italian National Research Council), Agriteam (a special agency of the Milan Chamber of Commerce) and CNER (National Consortium of Renewable Agricultural Energy) tested the Claas Jaguar 850 and 880 harvesters [personal information].

9.1.1 Crop layout

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Willow crops

There are no reports of willow crops being harvested in 1-year crop cycles any more. In Sweden, the UK and the US (NY State) the standard crop density is approximately 15,000 spha with a crop cycle of 2-3 years, not including the 1st-year coppice cycle to encourage coppicing after establishment. The optimum harvest diameter at stump level is 7-8 cm. The length of the crop cycle depends on the site and the clone. In some situations the crop cycle needed to be reduced by a year when a new and more productive clone with better diameter growth was used. As reported previously (sections 5.3.1 and 8), 10,000 spha is also considered an adequate density for longer crop cycles. The decision which crop density to select depends very much on the clone, the site and must be driven by an economic rationale.

- The typical layout is 1.5 meters between sets of twin-rows, with 0.75 m between individual rows in each set of twin-rows. The in-row spacing varies from 50-60 cm for a density of approximately 14,800-17,500 spha. In-row spacing can be adjusted according to clone.

Poplar crops

Of the countries discussed, only Italy (section 3.5) has developed purpose-grown SRIC (hybrid) poplar coppice crops to be harvested by modified silage harvesters.

The Italians are experimenting with various crop layouts and are using several layouts in their SRIC poplar crops.

- The common layout appears to be 2.8 meters between sets of twin-rows, with 0.75 m between individual rows in each set of twin-rows. The in-row spacing varies from 40-60 cm for a density of approximately 9,500 – 14,000 spha. In-row spacing can be adjusted according to clone;
- An alternative layout is 3.0 meters between single rows with an in-row spacing 50-60 cm for a density of approximately 5,500-6,600 spha. In-row spacing can be adjusted according to clone. This lower crop density favours production of larger individual stems and requires a longer crop cycle, 2 years under Italian conditions.

Due to the favourable climate in the Po River Valley and the productive poplar clones, the crop cycle rarely exceeds 2 years for the single row configuration and is frequently only 1-year for the twin-row configuration. This can vary depending on the productivity of the clone [personal observations]. The result is that many crops get harvested before mai culminates (section 5.3.2).

Using the modified silage harvester system to harvest poplar before the cutting diameter exceeds the machine specifications (6 and 8-10 cm respectively for the Claas Jaguar 850 and 880 harvesters) depends on the economics. If a longer crop cycle is required to maximize yield and the economics prove that out, a harvest system using more conventional tree harvesters needs to be considered instead (section 9.2).

Comments

For twin-row configurations in both willow and poplar, the distance between the individual rows in each set of twin-rows is 0.75 m. This is an important distance that allows the hydraulically driven counter-rotating saw blades of the harvesting unit to cut and pull the stem inwards for a better in-feed. In some instances triple rows have been planted by the Italians; they must all be within the same 0.75 m width for efficient harvest.

The difference in distance between the harvest rows (either twin-rows or single rows) of willow at 1.5 m and poplar at 2.8 or 3.0 m is a function of species need; poplars need more growing space than willows. The area between the harvest rows allows the harvester to comfortably straddle them for easy access without damaging the stools. The area between the sets of twin-rows or between single rows permits access for standard cultivation and pesticide spray equipment.

The Italians have experimented with a Spapperi prototype harvester (an Italian-made cut and chip harvester) for SRIC poplar on a biennial crop cycle. This equipment fits the conventional farm tractor (minimum 140 hp), is able to harvest single row crops and can handle a maximum harvest diameter of 10 cm at ground level[i]. Productivity is substantially lower than for the Claas Jaguar harvesters, but its capital costs are also substantially lower. The system cuts, chips and blows the chips into a chip van travelling in tandem with the harvester. This equipment could eventually fill the needs of small biomass harvesting operations [personal papers].

9.2 Conventional tree harvesters

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When upper diameter limits for efficient harvesting with the modified silage harvesters are exceeded, more conventional tree harvesters must be considered. Although this does not generally apply to willow, it does to poplar. This equipment is typically in use for the harvest of SRIC pulpwood crops.

The Italians appear to be the most advanced in these systems; they have done a substantial amount of work on conventional individual tree harvesters for purpose-grown

[i] Data cards were included in a field trip package received in October 2006. The manufacturer claims a diameter up to 18 cm.

SRIC poplar biomass crops on 5-year crop cycles[i] [personal papers]. These are non-coppice crops that require replanting after harvest. Although not reviewed in detail, many of the publications on these dedicated biomass harvesters originate from Italy.

- The typical layout is a rectangular spacing of single rows, with 3.0 m between rows and 2.0 m in-row spacing, for approximately 1,660 spha. The in-row spacing can vary depending on the desired end product.

The use of conventional single tree harvesters allows for larger harvest diameters and provides flexibility to leave the crop ‘on the stump’ for one or two additional years, without having to change harvesting systems. Many of these systems can merchandize the trees by producing a mix of logs and chips to improve financial returns.

All but one of the systems tested by the Italians harvest trees and bunch them on-site for in-field chipping at a later stage. Several machines can also delimb and merchandize the trees; however, none can chip trees in a single operation, with the exception of one prototype harvester (the Gandini Bio Harvester 500) [personal papers].

10 Recommendations for Saskatchewan

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High-density SRIC woody biomass crops of poplar or willow on a coppice harvest system offer the opportunity of frequent harvests without the need to replant. The expectation is that crop cycles for either species will be longer than those used in Sweden, the UK and NY State due to climate differences and the lack of selected material suited for a biomass coppice system.

An important issue will be disease and insect management in these high-density and short-crop-cycle coppice crops. Especially diseases such as *Melampsora* leaf rust will present a major challenge in both poplars and willows. Of particular concern is the progression of *Septoria musiva* stem canker disease in poplars, which will seriously hamper any SRIC poplar biomass coppice crop system, as it has done in New York State [Tim Volk – personal communication].

The coppice crops will also be a favourite target for wildlife, deer, elk and especially moose. Whenever possible, trials should be fenced in. This is an important lesson I have learned in many years of trials with and without fencing. Fences are not cheap to construct and maintain, but the value of the trials justify the expense.

The following sections 10.1.1 and 10.2.1 summarize recommendations for Saskatchewan trials with willow and poplar and will have some duplication.

10.1 Willow

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Although an active willow breeding program has recently been started at the Shelterbelt Centre of AAFC at Indian Head (SK) (section 4), no willow clones have been fully tested in clonal or yield trials.

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[i] Data cards were included in a field trip package received in October 2006. This data set was produced by the Region of Lombardy-Agriculture Department, CNR Ivalsa and Agriteam for conventional individual tree harvesters.

Frost and cold damage were important issues in Swedish willow crops (sections 5.3.1 and 5.3.3) and will also be of importance in Saskatchewan. The expectation is that many of the clones suitable for southern Quebec, southern Ontario and southern Manitoba will not be cold-hardy enough for Saskatchewan conditions; however, there may be a few clones tested by the Canadian Wood Fibre Centre (CWFC) and possibly the Shelterbelt Centre of AAFC that could be suitable for Saskatchewan conditions. I recommend that Richard Krygier at the CWFC, Ken Van Rees at the University of Saskatchewan and Bill Schroeder at the Shelterbelt Centre be consulted. Several local willow clones were already identified by the Saskatchewan Forest Centre as possible candidates for biomass trials starting in 2008.

10.1.1 Willow –recommendations

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Crop layout - willow

The first and foremost priority should be to establish and successfully manage an SRIC willow biomass (coppice) crop through its various crop cycles, including the consideration of a coppice cut at the end of the 1st growing season to encourage stooling (better coppicing) in the 2nd year. This is really meant to learn the mechanics and logistics of establishment and crop management rather than to determine yields; i.e. these trials are meant to make (unintentional) mistakes and learn from them.

Preferably a minimum of three clones should be tested in a preliminary screening trial. At this point there is no need to enter into a complicated statistical design, as the objective is to screen the various clones in a layout that will eventually be used operationally and to gain experience in planting, tending and crop protection.

If a comparison is to be made of irrigated vs. non-irrigated, it may be necessary to randomize the design. A decision must be made what the main target areas will be for these crops and whether or not irrigation (H_2O and/or effluent) will become a standard feature of these crops. If irrigation will become the standard, the trials must reflect that.

Crop layout should follow the generally accepted crop layout used in Sweden, the UK and NY State (section 9.1.1):

- Aim for approximately 15,000+ spha;
- 1.5 Meters between sets of twin-rows;
- 0.75 Meters between individual rows in each set of twin-rows;
- In-row spacing of 50 cm should be used for a density of approximately 17,500 spha. This offers a buffer of 2,500 spha that allows for cutting or stool mortality as a result of drought, animal damage, poor cutting stock etc. If not enough stock is available, in-row spacing can be increased to 60 cm.

There is no need at this point to fine-tune in-row spacing, as nothing is known yet about the willow clones in this crop layout.

Stock to be used should meet strict stock standards, as discussed in section 7.3.5. Stock dimensions should not be adjusted downward to fit planting machines that can only handle small caliper stock; no compromise. Stock should also be as uniform as possible to avoid differentiation in growth patterns during establishment.

There must be an active disease and insect survey on a regular basis. There are no labelled fungicides to control the *Melampsora* leaf rust that will surely develop in these SRIC willow crops. Efforts are underway to obtain labelling for an affective fungicide; however, labelling is at least two years away.

10.2 Poplar

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There is no poplar breeding program for the Prairie Region (section 4.1). Without a breeding program for SRIC hybrid poplar crops, the future of successful SRIC hybrid poplar crop systems in the Prairie Region will be in serious jeopardy (section 4.1) for both the longer crop cycles (for value wood) as well as the shorter biomass crop cycles.

There are several hybrid poplar clones that have been used in the Prairie Region for shelterbelt purposes that are also in use in SRIC hybrid poplar crops of longer crop cycles. Of these only a few have adequate resistance to disease and adequate cold tolerance. For a listing of these clones, please refer to the 2006 ‘Hybrid poplar crop manual for the Prairie Provinces’ - Project 2005050 [50].

10.2.1 Poplar –recommendations

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Crop layout - poplar

All the recommendations of section 10.1.1 apply, except for the dimensions of the crop layout.

The crop layout of poplar should follow the generally accepted crop layout used in Italy (section 9.1.1):

- Aim for approximately 11,300 spha;
- 2.8 Meters between sets of twin-rows;
- 0.75 Meters between individual rows in each set of twin-rows;
- The in-row spacing 50 cm should be used for a density of approximately 11,300 spha. This offers a buffer against cutting or stool mortality as a result of drought, animal damage, poor cutting stock etc.

There is no need at this point to fine-tune in-row spacing, as nothing is known yet about the poplar clones in this crop layout.

There is a registered fungicide available to control *Septoria* leaf spot in poplar (three Senator products with the active ingredient thiophanate-methyl: PCP numbers: 12279, 25343 and 27297). **I strongly recommend** using these fungicides in two applications per season to control *Septoria* leaf spot. Septoria stem canker is caused by inoculum of the leaf spot being transmitted to a leaf petiole or small branch into the bark. By keeping the leaf spot under control, the probability of controlling the stem cankers will improve. A by-product of using this fungicide for Septoria leaf spot is reasonable control of *Melampsora* leaf rust (an unintended effect – not a labelled use). This product also controls *Marssonina* leaf spot, for which the product is a labelled.

Hopefully there will be an additional labelled fungicide product as early as 2010. I foresee that the use of the Senator fungicide (and other products in the future) will have to be a standard preventative treatment to keep control of *Septoria* stem canker infections. In the long run this may be alleviated by resistant or tolerant clones resulting from a future breeding program.

Cees van Oosten

Nanaimo, B.C., 31 March 2008.

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