The Implications of Growing Short-Rotation Tree Species for Carbon Sequestration in Canada

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Executive Summary

Short rotation forestry (SRF) plantations have been identified as a possible mitigation strategy for climate change. Short rotation trees reduce greenhouse gas (GHG) emissions in two direct ways: by afforestation, which has the potential to increase carbon storage in the landscape compared to growing agricultural crops, and by sustainably-produced plantations, which act as a closed-loop biofuel to substitute fossil fuels. Indirectly, the end use of the SR tree plantations as a fibre source could also reduce GHG emissions by relieving pressure on the intensity of natural forest harvesting in Canada, thereby leaving the standing carbon levels in the natural forests unscathed.

The most important SRF species that have been identified to date are hybrid poplar (*Populus* sp.) and willow (*Salix* sp.). Poplar is typically grown on a 10-15 year rotation at densities of 1,100-1,400 stems ha^{-1}. The estimated yield ranges in Canada vary by region, with the southern mainland of British Columbia having the highest potential productivity (9-12 oven-dried megagrams per hectare (odMg $ha^{-1}yr^{-1}$)), followed by Ontario and Québec (2.5-7 odMg $ha^{-1}yr^{-1}$), the Atlantic provinces (2-6 odMg $ha^{-1}yr^{-1}$) and the Prairies (1-5 odMg $ha^{-1}yr^{-1}$). Short-rotation willow is grown at 12,000-15,000 cuttings ha^{-1}, is harvested on a 3-4 year cycle, and can have a plantation life of 20-25 years. The southern mainland of British Columbia has the highest potential productivity (10-15 odMg $ha^{-1}yr^{-1}$), followed by Ontario and Québec (7-12 odMg $ha^{-1}yr^{-1}$), the Atlantic provinces (5-10 odMg $ha^{-1}yr^{-1}$) and the Prairies (2-6 odMg $ha^{-1}yr^{-1}$).

Few investigations of SRF root dynamics have been carried out due to the tediousness of sampling procedures. Varying conditions such as planting density, clone differences, nutrient inputs, age of rotations, timing of coppice and differences in sampling methodologies have added to the variability in the results reported. Root biomass is approximately equivalent to 20% of the aboveground matter, however, SR tree species are found to have relatively lower root production at higher soil nutrient levels. Carbon content of structural and fine roots has been observed to be about 45% and 30-45%, respectively, whereas the carbon concentration of SR tree stems has been found to be in the range of 40-50%.

Few studies have been undertaken on the potential for soil carbon sequestration under SRF systems. Soil carbon storage data have typically been collected at single sampling dates rather than providing information on long-term soil carbon dynamics. These methodological limitations have made it difficult to assess the true impact of the various SRF systems on soil carbon storage levels. Nonetheless, rotation length is a key factor in the ability of plantations to remove carbon from the atmosphere over the long-term. The longer the rotation length, the greater the soil carbon storage potential. Very short rotations (less than 10 years) may therefore not lead to soil carbon sequestration. In fact, carbon is most probably lost during the establishment phase of the plantations. As well, under improper soil fertility management, there may not be any advantages of growing SR plantations for soil carbon storage.

In terms of establishing SR plantations, the technology to grow SR trees has advanced rapidly in the last 15 years in temperate climatic zones. No major production constraints exist for producing or harvesting hybrid poplar or willow, although further improvements in cultural practices can be made. Greater investment in plant breeding may improve productivity, reduce risks of stand

failure, and reduce disease and insect problems. One of the constraints to increasing yields was the high water demand.

Extensive research has been performed on the environmental impacts of SRF systems. When properly managed, SRF plantations have a positive impact on the environment, compared to agricultural crops. Short rotation forestry systems limit soil erosion, decrease pesticide impacts and fertilizer applications, and increase biological diversity. However, negative impacts may occur, especially during the establishment and harvest phases. As well, increasing the management intensity of SR plantations by establishing large-scale operations, increasing chemical and irrigation usage, and the use of genetically engineered crops, may lead to a loss of these positive impacts.

Costs involved in growing SR willow and hybrid poplar were estimated using *BIOCOST-Canada* and *BIOCOST-USA* softwares. Estimates of the variable (vc) and full economic costs (fc) of production for both crops were performed for all regions of Canada. In general, regions with longest growing seasons and most favourable climates had the lowest cost of production. The cost of producing willow was lower than poplar due to higher productivity levels. The lowest cost of willow production was in British Columbia (vc \$50-64 odMg^{-1}; fc \$60-78 odMg^{-1}), where highest productivity were observed, followed by Ontario and Québec (vc \$57-82 odMg^{-1}; fc \$69-102 odMg^{-1}), and the Atlantic provinces (vc \$64-92 odMg^{-1}; fc \$78-116 odMg^{-1}). Highest costs were in the Prairie provinces where productivity was lowest (vc \$92-106 odMg^{-1}; fc \$115-134 odMg^{-1}). Similarly, the lowest cost for poplar production was in British Columbia (vc \$62-73 odMg^{-1}; fc \$80-97 odMg^{-1}) followed by Ontario and Québec (vc \$82-112 odMg^{-1}; fc \$112-160 odMg^{-1}), the Atlantic provinces (vc \$91-115 odMg^{-1}; fc \$127-164 odMg^{-1}) and the Prairies (vc \$104-120 odMg^{-1}; fc \$146-173 odMg^{-1}).

Potential industrial uses of SR tree species include fibre markets and energy markets. Most commercial interest lies in the production of single-stemmed poplars for fibre applications. There is little commercial interest in coppiced willows as an energy crop with the current market conditions. However, closed-loop biofuels have the potential to reduce greenhouse gas emissions significantly.

As a renewable energy source, willow appears to be uncompetitive in most current applications. Eastern Canada has the greatest bioenergy opportunity, as fossil energy prices are generally higher than in other regions of the country. Obstacles to the commercialization of SR willow as an energy crop include low cost forest and agricultural crop residues, and the lower cost of production of perennial grass biomass feedstocks. As well, there is some farmer preference for agricultural crop residues and herbaceous energy crops. Liquid fuel and electricity production from dedicated SR tree plantations in large industrial plants are the least viable option for bioenergy production. The direct heat applications of wood chip heating and pelleting are the most promising economically viable options and warrant a comprehensive analysis. A large number of small- and medium-sized wood chip combustion systems could be installed for space and process heat applications in many rural areas of Canada. As well, willows could be densified and burned in gasifier pellet stoves and furnaces to replace oil, propane and electricity. The decentralized production and utilization of bioenergy crops is well adapted to rural energy applications, where fossil fuel energy costs are higher.

A strong commercial interest in the planting of poplars in many regions of Canada exists, as many industry analysts are concerned about the sustainability of fibre supply. Poplar can be used for a variety of fibre products including pulp and paper, oriented strand board, particle board, some solid wood products, and engineered lumber. Current industry procurement costs are approximately $100 per tonne, which is considerably higher than bioenergy market values. There is generally a lack of production information on the cultivation of poplars on longer rotations for the solid wood products industry. Poplars have a strong market potential in the rapidly evolving engineered lumber industry.

Afforestation programs in the northern United States and Canada are based almost exclusively on poplars for the production of pulp and paper and oriented strand board. In the United States, rapidly developing programs are underway. The Pacific Northwest region has 26,900 ha of poplar in cultivation. The North-Central region has less acreage, but forecast plantings suggest it will lead the United States in acreage in the next 5 years due to the concerns about fibre supply in the region. In Canada, in Eastern Ontario, approximately 2,400 ha of poplars have been planted on privately-leased and land owned by *Domtar Forest* products. In British Columbia, a total of 3,600 ha of poplars have been planted by *McMillan Bloedel* and *Scott* paper company. There is an industry consortium interested in the production of poplars (and aspen) in the region north of Edmonton, Alberta. However, the long harvest rotations forecasted and the unproven SR tree productivity in this northern region make it a high risk SR tree growing area. The main reason for the plantations in the area is the forecasted fibre shortages.

Three factors were identified to develop a successful afforestation program: 1. A perceived need for fibre by industry, 2. Requisite talent in the form of silviculturalists and tree breeders with adapted materials and 3. A suitable land base. No region in Canada has all three components in place at the present time, however, southern Québec has been identified as a region with high potential. British Columbia has attractive growth rates and costs but lacks a significant land base in the southern mainland to create a significant industrial impact. Currently, eastern Ontario has no strong demand requirements for hardwood fibre. Northern Alberta has a strong industry demand, but limited experience with plant materials and a northern land base with modest rainfall, which would suggest low potential productivity. Southern Manitoba and Nova Scotia also hold good potential for afforestation programs, but there is limited experience in these areas.

Class 4 and 5 agricultural land was identified as the main land base for afforestation. An afforestation program using SR hybrid poplar and willow, possibly in the order of 4.25 to 12.75 million ha could be available. However other bioenergy and agri-fibre crops such as perennial grasses would be competing for access to these lands for energy and fibre markets and are better adapted to lower rainfall regions and soils with a low water-holding capacity. A more detailed analysis is required to more effectively analyze the land base availability for SR tree plantations.

One of the main issues to address when developing policies to mitigate GHG emissions is the relative cost of each policy option that is required to achieve the desired objective. All carbon sequestration scenarios investigated in this study included a soil organic carbon accumulation rate of either 1.5 or 3.0 Mg C ha^{-1} yr^{-1}, with some scenarios including an additional carbon sequestration from increases in biomass carbon stocks compared with previous land-use. Carbon sequestration values were computed both over the entire life span of the plantations (12 and 20 years for hybrid poplars and willows, respectively), and over the first commitment period of the Kyoto period, 2008 to 2012. The cost of sequestering carbon varied generally between \$14-\$54 Mg^{-1} of CO_2 for hybrid poplar and \$4-\$49 Mg^{-1} of CO_2 in willow, for all scenarios involving a soil organic carbon accumulation rate of 1.5 Mg C ha^{-1} yr^{-1}. Doubling soil organic carbon accumulation rate (3.0 Mg $ha^{-1}yr^{-1}$) reduces the amount of carbon sequestered by approximately half.

Overall, this study indicates that the least risky strategy to rapidly implement afforestation programs, for carbon sequestration in Canada, involves the production of SR hybrid poplars for fibre applications. Commercial risk with poplars is reduced compared to SR willow plantations, as SR poplars are already grown for fibre in North America and competitive market prices for the chips is approximately twice that for energy applications. This can be achieved, while at the same time incurring costs of carbon sequestration similar to those of willows. The main limitation of the study is that the carbon offset occurring over the complete life-cycle of the biomass produced from hybrid poplars and willow is not estimated.

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CAN $	Canadian dollar
cm	centimeter
F.C.	Full economic cost
GJ	Gigajoule – 4.184 kcal
g	gram
ha	hectare – 2.47 acres
kg	kilogram
m	metre
Mg	Megagram – one metric tonne – 2,200 lbs – 1.1 ton
mm	millimetre
MW	Mega watt
n.a.	not available
odt	oven dried tonne (metric)
ppm	parts per million- 1 mg L^{-1}
t	one metric tonne- one Megagram – 1.1 ton
yr	year
U.S. $	United States dollar – 1.5 Canadian dollar
V.C.	Variable costs

Introduction

In light of the recent signing of the Kyoto Protocol, Canada has committed to reduce its greenhouse gas emissions by an average of 6% below the 1990 levels, by the year 2012. The most abundant greenhouse gas (GHG) is carbon dioxide (CO_2). The emissions of CO_2 have increased over the past century due to anthropogenic effects (mainly due to increased industrialization, urbanization, as well as the usage of transportation). The atmospheric CO_2 levels have risen to unproportional levels, compared with those found in nature, and are consequently causing a net warming of the atmosphere. The warming is primarily attributed to the trapping of incoming solar radiation, which heats the surrounding areas, by convective forces. In order to reduce this so-called "greenhouse gas effect" means of reducing CO_2 levels must be found.

Curbs on industrial emissions, the use of cleaner fuels and alternative sources of energy, as well as emission trading may be some of the potential solutions. However, one of the more pertinent issues, related to the Kyoto Protocol, is the need to conserve and enhance greenhouse gas sinks and reservoirs, while implementations for GHG reductions and credit trading are put in place. Canada possesses a multitude of forests and forest-related soils as well as peatlands, which belong to the most important natural biological stores of carbon. The capacity of a forest to act as a sink is based on its annual net growth and, possibly, its additional soil carbon sequestration potential. The use of fast growing tree species in short rotation forestry (SRF), such as hybrid poplar and willow, has been identified as a way to increase carbon storage (Vitousek, 1991), due to their short rotation lengths, anywhere from 5-30 years.

In theory, SRF plantations can reduce GHG emissions in two ways. The first potential is the increased carbon storage in their landscape compared to the use of agricultural crops. Fast growing trees have a large aboveground biomass, which accumulates carbon annually. Their perennial root system is a further source of soil carbon storage, and finally, soil disturbance is minimized during their production, which helps to maintain or increase soil organic matter build up.

The second potential is by harvesting SRF plantations periodically to use them for renewable energy. This produces a closed-loop biofuel to replace the use of fossil fuels. However, there are several barriers to overcome before this strategy can be realized. The first is the relatively low cost and convenience of fossil fuels in many parts of Canada (particularly in the west). The second barrier is the more economically viable biomass energy resources, such as wood residues from the forest product industry, agricultural crop residues, and herbaceous biomass feedstocks, such as perennial grasses, which are well adapted to marginal lands (Samson and Girouard, 1998). A survey of farmers in the Great Lakes region also indicated that farmers would prefer using agricultural residues or grasses as biomass feedstocks prior to growing trees (Campbell, 1986).

The emphasis of this analysis is on the carbon sequestering potential of fast growing trees. In particular, to summarize the knowledge in areas where little previous information is available. The analysis attempts to develop realistic estimates of fast growing forest species' growth potential in Canada, based on literature searches of existing published commercial and field plot data, as well as discussions with industry people, foresters and scientists. As well, a complete analysis of root biomass accumulation and impact of fast growing trees on soil carbon accumulation in a temperate SR tree plantations is provided. An overview is also provided of the current status of the technology of fast growing trees, environmental issues and current afforestation programs. An assessment of the energy and fibre market opportunities is also undertaken. However, a thorough overview of these opportunities is not within the scope of the study. More emphasis has been placed on the energy aspects of the material, not because this is where the greater commercial market opportunities are at present, but because this is where the greatest greenhouse gas abatement potential exists.

In terms of tree productivity, Canada faces a difficult task of competing with the more southern climates, where forest plantations have become commonplace since the 1970's. It remains to be determined if planting moderately fast growing trees in Canada can be a viable solution to providing large supplies of low cost wood fibre to the Canadian wood fibre processing industry. There are current examples of commercial wood fibre production in Canada from SR plantations, mainly from British Columbia and eastern Ontario with fast growing poplars. However the programs are small compared with the millions of hectares being planted in southern countries such as Brazil, Chile and Indonesia. The current analysis looks at the various regions within Canada to determine if there are regional advantages for the competitiveness of this industry.

The study is divided into seven components. Task 1 examines the above- and belowground biomass of SR willows and poplars, and their related carbon sequestration potential. The potential soil carbon sequestration involved in growing the plantations is also examined. Task 2 presents information on several issues related to the production of SR plantations, and the associated environmental impacts. Task 3 provides production costs for growing SR willow and poplars, while Task 4 focuses on existing and potential industrial markets for SR tree production. Task 5 presents an overview of the economics involved in SR carbon sequestering, and Task 6 analyzes the land base potentially available in Canada for growing SR forestry. Finally, Task 7 discusses various successful afforestation programs recently carried out in North America.

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Task 1. Estimates of Short-Rotation Forestry Growth and Carbon Sequestration Potential

1.1. Aboveground Biomass

1.1.1. Productivity[†]

1.1.1.1. Introduction

There is considerable research and plantation experience concerning the growing of short-rotation forestry (SRF) species in Canada. On Canada's west coast poplar planting programs were developed by the wood fibre industry forty years ago and were followed by an aggressive research and development program with hybrid poplars in Eastern Ontario in the 1970's and 1980's. Less yield data is available on hybrid willow production, as commercial sized plantings are fairly recent. Overall, there has been much effort placed into fast growing tree production during the 1970's and 1980's in this country. However, the research base of the development of this industry has had serious funding problems in the 1990's. This was evident when gathering data for summarizing the yield tables, as many of the researchers and silviculturalists formerly responsible for programs were no longer involved in fast growing tree programs.

1.1.1.2. Major Findings

The most important SRF species that have been identified to date are hybrid poplar (*Populus* sp.) and willow (*Salix* sp.). Other species also hold potential as SRF systems, however these species have not been subjected to rigorous evaluation. These include: hybrid aspen (*Populus* sp.), hybrid larch (*Larix* sp.) and grey alder (*Alnus* sp.) for northern regions, red alder (*Alnus* sp.) for southern British Columbia, and black locust (*Robinia pseudoacacia*) in southern Ontario. Assessments in this section will focus exclusively on hybrid poplar and willow since they are the most likely candidates for immediate scale up of SRF in Canada.

At present, hybrid poplar is the most commonly scaled up SRF species in the United States (U.S.) and Canada. It is typically grown on a 10-15 year rotation at densities of 1,100-1,300 stems ha^{-1} for the pulp and paper industry. In Canada, most of the available data has been collected in eastern Ontario, Québec and British Columbia. Limited information on this species has been found in the Canadian Prairies (Manitoba, Saskatchewan, Alberta) and Atlantic provinces (New Brunswick, Nova Scotia, Prince Edward Island, Newfoundland). Yield ranges in Canada vary by region (Table 1.1a). For instance, the southern mainland of British Columbia has the highest potential productivity (9-12 odMg (oven dried megagrams) ha^{-1}yr^{-1}), followed by Ontario and Québec (2.5-7 odMg ha^{-1}yr^{-1}), the Atlantic provinces (2-6 odMg ha^{-1}yr^{-1}) and the Prairies (1-5 odMg ha^{-1}yr^{-1}). Productivity data from the northern United States are presented in Table 1.1c.

Short-rotation willow yields have not been scaled up to the same levels as hybrid poplar; thus, data available are limited to Ontario and Québec. Moreover, field-scale trials were only initiated in 1993. Although a limited amount of support information is available from the northern U.S.

[†] productivity is the rate of change in biomass per unit area over the course of a year

states, extensive research experience using this species has been developed in northern Europe. Willow is generally grown at 12,000-15,000 cuttings[‡] per hectare (cph), is harvested on a 3-4 year cycle, and can have a plantation life of 20-25 years (NYSERDA, 1997). Yield ranges in Canada vary by region (Table 1.1b). For instance, the southern mainland of British Columbia has the highest potential productivity (10-15 odMg $ha^{-1}yr^{-1}$), followed by Ontario and Québec (7-12 odMg $ha^{-1}yr^{-1}$), the Atlantic provinces (5-10 odMg $ha^{-1}yr^{-1}$) and the Prairies (2-6 odMg $ha^{-1}yr^{-1}$). Productivity data from the northern United States are presented in Table 1.1c. The estimates for regions outside of Ontario and Québec have been computed from what little field data from willow production was available.

Few direct comparisons of poplar and willow growth parameters are available. However, willow is a more favourable biomass species due to its ability to efficiently intercept solar radiation, particularly when planted at high densities and when subjected to frequent coppicing[†]. This physiological feature of willow results in earlier canopy closure compared with single-stemmed poplars, and maximum annual growth levels being attained over a longer period of the rotation. Overall willow average annual productivity, as compiled in Tables 1b and 1c, is estimated to be approximately 20% greater than poplar productivity.

[‡] cuttings are sections of 1-year-old stem woods of specified length (usually 25 cm) and diameter (1 to 3 cm) used to establish new, SR tree plantations

[†] sprout growth originating from the cut stem of a tree

Table 1.1a. Poplar merchantable yield data available in Canada.

Author	Location	Plot Characteristics		Productivity
		Age (yr)	Density (plants/ha)	MAI (odt $ha^{-1}yr^{-1}$)
	Commercial Plots			
Hendry, 1990	Eastern Ontario	14	n/a	2 - 3
OMNR, 1983	Eastern Ontario	6.5	1,000	2.9
OMNR, 1983	Eastern Ontario	7	1,000	2.2 - 4.6
Zsuffa, 1973	Eastern Ontario	12-14	n/a	2.4 - 6.6
Zelenski, 1999	Eastern Ontario	12-14	1,100	3.5 - 4.6
Vallée, 1975	Matane, Québec	10	600-1,400	3.5 - 4.0
	Québec	10		3.5 - 6.9
	Berthierville, Québec	10		2.1 - 2.5
Vallée, 1994	Québec	20		3.3
	Québec	10-15		4.4 - 6.6
	Bas-St.Laurent	14		1.4 - 2.3
	Bas-St.Laurent	8		4.3 - 5.1
	Saquenay/ Lac St-Jean	5		1.1 - 1.8
	Saquenay/ Lac St-Jean	7		0.4 - 0.7
	Southern Québec	11		2.5 - 4.0
Périnner, 1999	Southern Québec	15	1,100-1,200	5.0 - 6.6
Périnner, 1999	Northern Québec	15-20	1,100-1,200	2.6 - 4.0
Van Oosten, 1999	British Columbia	10-12	1,200	10 -13.2
Stenersen, 1999	British Columbia	15	800-900	6.6-10
	Research Plots			
Zwart et al., 1995	Ontario	5	n/a	1.6 - 4.2
Zsuffa, 1973	SE Ontario	7-15	n/a	2.7 - 7.5
McCabe & Glen, 1985	PEI	4	n/a	6.0

n/a not available

Table 1.1b. Willow aboveground productivity data available in Canada.

Author	Location	Plot Characteristics		Productivity
		Age	Density	MAI (odt ha^{-1}yr^{-1})
	Commercial Plots	(yr)	(plants/ha)	
Labrecque & Teodorescu, 1998	Haut-St. Laurent (Québec)	3	20,000	5.3 - 8.3
				10.3 - 15.1
				6.2 - 11.0
Girouard et al., 1998	Southern Québec	5	10,000	7.5
				8.9
	Research Plots			
Labrecque et al. 1993	Southern Québec	3	27,000	11.2 - 13.6
Labrecque et al., 1997	Southern Québec	3	20,000-30,000	1 - 5
				2 – 8.5
				3.5 - 13.5
				2.5 - 15
Robertson 1990	Newfoundland	n/a	25,000	8 - 11

n/a not available

Table 1.1c. Poplar and willow aboveground productivity data available in the U.S.

Author	Location	Plot Characteristics		MAI
	Poplar Commercial Plots	Age (yr)	Density (plants/ha)	(odt ha^{-1}yr^{-1})
Riemenschneider, 1999	Minnesota	9-11	n/a	5.2 - 6.0
	Minnesota			5.0
	Minnesota			5.0
	Minnesota			3.6
	South Dakota			3.0 - 3.4
	North Dakota			4.6
	Wisconsin			5.4 - 6.5
DeBell et al., 1993	Washington	5	n/a	[a] 8.2 - 18.8
DeBell et al., 1996	Washington	7	2,500-20,000	[a] 9.6 - 28.5
DeBell & Harrington, 1997	Washington	3	4,000-20,000	[a] 12.6 - 16.1
Heilman et al., 1994	Washington	4	n/a	[a] 1.7 - 7.4
Heilman & Stettler, 1985	Washington	4	n/a	8.7
	Poplar Research Plots			
NYSERDA, 1997	New York	9	n/a	[b] 8.7 - 9.5
	Willow Commercial Plots			
Fillhart, 1999	New York	2	15,000	5.0 - 10.0
	Willow Research Plots			
NYSERDA, 1997	New York	9	n/a	[b] 4.2 - 10.9
NYSERDA, 1997	New York	5	15,000-111,000	[b] 11.0 - 14.3
NYSERDA, 1997	New York	3	n/a	[a] 9.3 - 17.0
				5.8

n/a not available; [a] irrigated; [b] periodically irrigated

Several factors complicate the ability to adequately assess growth rates of willow and poplar within SRF plantations. In hybrid poplar, for instance, productivity is frequently reported as cubic metres (m^3) of merchantable fibre deliverable to the mill, whereas for willow, productivity is typically expressed as oven-dried megagrams (odMg) per hectare (ha) of standing biomass in the field. Moreover, for poplar, approximately 25% of the material is comprised of branches and bark, however new debarking equipment now enables larger branches to be recovered in the harvesting process. Nonetheless, bark and small branches left in the felling site can still represent up to a 10% loss of material. Thus, standing yields are approximately 10% greater in poplar, since yield data is based on delivered yields to the mill (Burrel, 1999).

The tendency of researchers and silviculturalists to use maximum annual increment as the basis for projecting yields within a rotation has also contributed to difficulties in assessing actual growth rates in these systems. In poplar, yields are generally not optimized until about midway into the rotation. Very low annual increments are typically experienced in the first 2-3 years of plantation establishment. Hence, while peak accumulation rates may attain 9 odMg $ha^{-1}yr^{-1}$, productivity for the entire rotation may only reach 5-6 odMg $ha^{-1}yr^{-1}$.

Recent increases in field-scale research within SR systems has provided more realistic assessments of yield levels of SR trees than in the past, when yield data obtained from small plot trials were extrapolated to large-plots and often resulted in unrealistically elevated expectations. Nonetheless, overestimation of yield potentials remains a current problem. For example, in the north-central region of the U.S., operational yields of 7-9 odMg $ha^{-1}yr^{-1}$ have been reported (Wright and Tuskan, 1997). However, field research studies in the region have only shown field yield levels of approximately 3.5-6.0 odMg $ha^{-1}yr^{-1}$ (Riemenschneider, 1999). These "operational-scale" yield estimates appear overly optimistic. If large plantation areas are to be established, less-than-ideal locations will be part of the land inventory, and pest and disease outbreaks will increase with the larger land base in production. Nonetheless, improvements in clonal material should enable productivity improvements in the future, however, dramatic improvements should not be anticipated in the short term.

Forage yields at experimental stations across Canada (Table 1.1d) provide another reference point for measuring potential tree yields. Perennial species utilizing a C_3[†] photosynthetic pathway, such as alfalfa, have similar water demands to poplar and willow. Since water is frequently the most important factor limiting productivity, yields from these crops provide a good comparative base (particularly of upper yield limits in a region). Provincial forage yields at each station (Table 1.1d) vary because of differences in soil quality, winter survival and rainfall during the study years. In addition, yields in Ontario and Québec are lower than yields in Alberta because Québec and Ontario testing sites are primarily located in more northerly regions. Nonetheless, these data provide a useful reference yield for other C_3 perennial biomass species, particularly where no SRF data are available for commercial plantings.

[†] C_3 species are those species having a 3-carbon compound as the first intermediate product in their metabolic pathway. These species are generally less efficient at photosynthesis than C_4 species.

Table 1.1d. Average forage yields obtained from various Canadian regional testing sites.

Province	Species	Averaged from	Yield Ranges (odt ha^{-1})
British Columbia	Tall Fescue	1994-1996	13.7-14.0
Alberta	Alfalfa	1997-1998	5.8-12.2
Saskatchewan	Alfalfa	1997-1998	4.7-5.3
Manitoba	Alfalfa	1997-1998	8.3-11.7
Ontario	Alfalfa	1996-1998	6.0-10.8
Québec	Alfalfa	1995-1997	5.5-11.1
Atlantic Provinces	Alfalfa	1997-1998	8.8 (average)

1.1.2. Carbon

The carbon concentration (percent carbon content) of SR tree stems has been found to be quite variable (Horwarth et al., 1994). For instance, a study on hybrid poplar systems determined stem carbon concentration to be 43% in early summer, compared with 41% in late summer to early fall (Horwarth et al., 1994). Another hybrid poplar study conducted in Saskatchewan determined the carbon concentration of stems to be 48.2% (Turnock and Kort, 1996). In southwestern Québec, Zan (1998) determined willow stems to consist of between 40-50% carbon. Hence, for the carbon sequestration economic analyses developed in Task 5, a carbon concentration of 45% will be utilized.

1.2. Root Biomass

1.2.1. Productivity

1.2.1.1. Introduction

Roots are a major source of soil carbon in both agricultural and natural systems. The annual input of carbon by actively growing plant roots has been estimated to be between 1 and 3 Mg ha^{-1} for agricultural and forest soils, respectively (Kuikman *et al*., 1991). Roots are a major contributor to soil carbon following harvest of aboveground biomass (Grigal and Berguson, 1998).

By implementing SRF practices, the growing and subsequent coppicing of SR tree stems should result in a large root input to the soil, and therefore a major source of soil carbon. Most of the roots of SRF are fine roots, which are located near the soil surface and have higher turnover rates, thus contributing to the soil carbon pool. Although information remains sparse, more research has been conducted on quantifying belowground biomass than on the carbon sequestration potential associated with the belowground biomass.

To obtain a range of root productivity (amount of roots found in a 1-hectare area) expressed at various ages of SRF plantations, studies that took actual measurements were examined. Productivity values for poplar plantations were gathered from studies conducted in Ontario

(Barkley, 1983), Washington (Heilman et al., 1994) and England (Matthews et al., 1994). Willow productivity data were obtained from research conducted in southwestern Québec (Zan, 1998), Sweden (Ericsson, 1994; Rytter, 1997), Scotland (Cannell et al., 1987), and England (Matthews et al., 1994).

1.2.1.2. Limitations

Few investigations of root dynamics have been carried out for SRF plantations (Barkley 1983; Ericsson 1984b; Cannell 1987; Heilman 1994; Matthews 1994; Rytter 1997; Zan 1998) and even fewer on root carbon (Horwarth et al., 1994; Zan, 1998) due largely to difficulties and tediousness of sampling procedures. Hence, it is extremely difficult to quantify and compare production and carbon allocated to roots within such systems. Nonetheless, those studies where actual total root productivity measurements were collected are outlined in Table 1.2a. Estimates of belowground carbon attributed to root production are outlined in Table 1.2b.

1.2.1.3. Major Findings

The structural root biomass of trees is known to increase with that of the aboveground portion and is generally about 20% of aboveground biomass for mature trees (Grigal and Berguson, 1998), and typically reaches a peak early in stand development (Ericsson, 1984a). Given an aboveground biomass production of 10-12 Mg $ha^{-1}yr^{-1}$, structural root production of SR plantations can be expected to be 2-3 Mg $ha^{-1}yr^{-1}$ (Cannell and Smith, 1980). Willow roots have been found to make up between 15-30% of total dry matter production (Ericsson, 1984a). For example, willow roots were found to increase in weight within the first 6 years, and by year 6 peaked at 3.47 odMg ha^{-1} (Ericsson, 1984a). In contrast to structural roots, the fine root biomass of forests is relatively constant with most observations in the 4-7 Mg ha^{-1} range (Grigal and Berguson, 1998). Nadelhoffer et al. (1985) found forest fine root ranges to be between 1.6-5.9 Mg ha^{-1} at 0-20 cm.

Most of the root production in SR systems consists of fine roots (Rytter, 1997; Zan, 1998). For instance, fine roots contributed to nearly 60% of total root biomass in two willow plantations, from a soil depth of 0-60 cm, investigated in southwestern Québec (Zan, 1998). It has also been shown that the biomass of the aboveground parts increases faster with age than belowground parts, ultimately leading to a decreasing percentage of belowground biomass with time (Rytter, 1989; Rytter et al., 1991; Hermann, 1977). With increased plant nutrition, there tends to be a decreased fine-root mortality (Linder and Axelsson, 1982), as well, properly fertilized willow plants expend less of their photosynthetic products on root growth than do nutrient deficient plants (Ericsson, 1984b).

The production of roots has been reported to be strongly influenced by the nutrient availability in the soil (Ericsson, 1981; Hansson et al., 1991; Ericsson et al., 1992, Linder and Axelsson, 1982; Granhall et al., 1983; Ericsson, 1984b). For example, Ericsson (1981) found willow root production to vary between 15-30% of total dry matter production depending on the nutrient status of the plant. Similarly, in the fourth year of willow production, Zan (1998) observed differences varying between 30-50% of total dry matter production depending on whether willow was grown on a relatively more or a relatively less inherently fertile site. Rytter (1997) found fine root production of willow to be between 30-50% of annual net primary production during the first 3 years of growth. In a hybrid poplar plantation, the root/total biomass ratio was about 35% following 2 growing seasons (Friend et al., 1991). In another hybrid poplar study, root biomass of large trees was found to comprise 25% of total production (Howarth et al., 1994). Similar trends have also been reported for grey alder in Sweden (Granhall et al., 1983; Elowson and Rytter, 1993). In a 4 year old Swedish alder plantation, root biomass made up 50% of total biomass (Elowson and Rytter, 1993).

Short rotation tree root biomass is concentrated near the soil surface, up to a depth of 30 cm (Elowsson and Rytter, 1984; Ericsson, 1984; Rytter, 1989; Hansson et al., 1991; Rytter and Hansson, 1996; Zan, 1998). For example, in two willow plantations investigated in southwestern Québec, approximately 50% of all fine roots were found within the top 15 cm, and close to 90% in the top 30 cm (Zan, 1998). In addition, slightly more roots (6%) were found in the deeper layers (45-60 cm) of a relatively less fertile site compared with levels (2%) found in a more fertile site. Similarly, in a Swedish study, 40% of willow roots were concentrated in the top 10 cm of soil, and about 80% in the top 30 cm (Rytter and Hansson, 1996). In other willow plantations in Sweden, most fine roots were concentrated at 0-45 cm (Rytter, 1997). Finally, in a study of hybrid poplar plantations in eastern Ontario, between 60-70% of fine roots were concentrated within the soil's A horizon (Barkley et al., 1983). Short rotation plantations have generally been found to have greater root depths than typical agricultural crops, typified by willow stands in southwestern Québec (Zan, 1998).

Factors that have been shown to affect root distribution and productivity in SRF systems include nutrient availability, soil bulk density, aeration, pH, stand age, and plantation density (Ericsson, 1984b). Nitrogen concentrations in the roots of SR crops have been shown to be less variable than in aboveground parts (Eckersten and Slapokas, 1990; Rytter et al., 1991). In nutrient solutions, under laboratory conditions, willow fine root nitrogen was 3.18% of the total dry weight (Ericsson, 1984b), whereas mean fine root nitrogen concentration varied from 0.15% to 17% of the root dry matter weight in willow plantations, sampled from April to October (Rytter, 1997). Pregitzer et al. (1990) found the major site of nitrogen storage in poplar trees to be in the large structural roots. However, the coarse root system of willow was a minor storage organ of nitrogen compared to the shoots, during the first 3 years (Rytter, 1997). In general, lignin to nitrogen ratios are much greater in root material than in aboveground plant material and root tissue therefore tends to decompose less easily (Trujillo et al., 1998). In addition, since root products are introduced directly into the soil clay matrix, this allows them to be physically protected from microbial attack (Oades, 1995; Balesdent and Balabane, 1996).

1.2.2. <u>Carbon</u>

Carbon content of structural roots has been observed to be about 45% in some SRF systems (Zan, 1998). Fine roots are an important source to soil carbon, especially since fine root total mass has been reported to turn over at least on an annual basis (McClaugherty et al., 1982; Hendrick and Pregitzer, 1992; Burke and Raynal, 1994). Rytter (1997) found the rate of willow fine root turnover to be between 4.9-5.8 yr^{-1} in plantations. Carbon content of fine roots has been observed to range from 38 to 43% in willow (Zan, 1998) and between 30 to 41% in poplar (Horwarth et al., 1994), and seems to depend on root diameter (Horwarth et al., 1994; Zan, 1998). Estimates of belowground carbon attributed to root production are outlined in Table 1.2b.

1.2.3 Conclusion

It is very difficult to assess root production, and thus root carbon storage under SR systems since root production is strongly influenced by the nutrient availability in the soil, as well as other factors such as soil bulk density, aeration, and plantation density. Root biomass is approximately equivalent to 20% of the aboveground matter, however, there is a general agreement and sufficient research demonstrating that tree species used in short rotations have relatively lower root production at high nutrient levels. Fine root carbon content of willows was found to range from 38-43%, and from 30-41% in poplars. Few studies have evaluated root productivity and turnover rates in SR plantations. Comparison between root dynamic studies that have been carried out remains difficult at best. Varying conditions such as planting density, clone differences, nutrient inputs, age of rotations, timing of coppice and differences in sampling methodologies have all added to the variability in the results reported.

Table 1.2a. Belowground biomass (odMg ha^{-1}) of SRF plantations in North America and Europe at various stages of development.

		Plantation Age (years)							
Poplar	**Source**	**1**	**2**	**3**	**4**	**6**	**7**	**11**	**22**
Ontario	Barkley (1983)						7 - 9		
Washington	Heilman et al., (1994)				(19 - 38)[a,b]				
England	Matthews et al., (1994)		2 - 3 (3 - 4)		5 (12)			6 (14)	
Willow									
Québec	Zan (1998)				7 - 12				
Sweden	Ericsson (1984b); Rytter (1997)	2	2 - 3	2 - 3					
Scotland	Cannell et al., (1987)	3							
England	Matthews et al., (1994)				3 - 5 (8)	4 - 6 (8)		7 (13)	20 (34)

[a] Irrigated plots.

[b] Values expressed within brackets ( ) include aboveground stump biomass.

Table 1.2b. Belowground carbon content[a] (Mg ha^{-1}) potential of SRF plantations in North America and Europe at various stages of development.

		Plantation Age (years)							
Poplar	**Source**	**1**	**2**	**3**	**4**	**6**	**7**	**11**	**22**
Ontario	Barkley (1983)						3.2 - 4.1		
Washington	Heilman et al., (1994)				(8.6 - 17.1)[b,c]				
England	Matthews et al., (1994)		0.9 - 1.4 (1.4 - 1.8)		2.3 (5.4)			2.7 (6.3)	
Willow									
Québec	Zan (1998)				3.2 - 5.4				
Sweden	Ericsson (1984b); Rytter (1997)	0.9	0.9 - 1.4	0.9 - 1.4					
Scotland	Cannell et al., (1987)	1.4							
England	Matthews et al., (1994)				1.4 - 2.3 (3.6)	1.8 - 2.7 (3.6)		3.2 (5.9)	9 (15.3)

[a] Assuming a 45% carbon content of belowground biomass.

[b] Irrigated plots.

[c] Values expressed within brackets ( ) include aboveground stump carbon.

1.3. Soil Carbon Sequestration

1.3.1. Introduction

Soil organic matter acts as a reservoir for plant nutrients and plays a major role in stabilizing soil structure (Allison, 1995). It maintains quality and productivity of soils and is a very important reservoir of carbon, thus playing an essential role in carbon cycling (Gregorich et al., 1994; Bolinder and Angers, 1997). The quantity of organic matter has important implications for both natural and agricultural systems since the major pool of terrestrial carbon is found in soils (Goudriaan, 1995). The amount of carbon stored in soil is 3 times that found in aboveground and root biomass and twice the amount found in the atmosphere (Eswaran et al., 1993). The soil carbon inventory is dependant on both the amount of carbon input as well as its turnover time. The turnover time depends largely on soil temperature and moisture. In temperate regions, estimates of this turnover rate have been reported to average 30 to 40 years (Schlesinger, 1986).

Forests are a major carbon sink and therefore play an essential role in the global carbon cycle (Schroeder, 1992). Since approximately 70% of all carbon actively exchanged with the atmosphere originates in forest ecosystems (Waring and Schlesinger, 1985), expansion of the world's forest land area could present an excellent opportunity for increasing the terrestrial carbon sink, and thereby slowing the increases in atmospheric CO_2 concentration (Schroeder, 1992).

1.3.1.1. Hypothesis

The growing of SR forests for bioenergy production may provide an excellent opportunity for CO_2 mitigation not only through their increased above and belowground biomass (compared with agricultural crops), but also in the form of increased soil carbon storage. Compared with agricultural crops, SR plantations can play a key role in carbon storage (Ranney et al., 1991) especially since belowground additions of organic matter from SR plantations are very high compared with the levels added from typical row crops. SR tree plantations have a number of specific characteristics that contribute to increasing soil organic carbon, including greater biomass inputs through litterfall and mulch applications, increased soil shading, a more lignified organic matter input, and deeper root systems (Ranney et al., 1991). These important features may explain the potential for soil carbon increases under SR plantations. In contrast, conditions under row crops such as drainage installations may result in increased soil oxygen, thereby reducing the carbon storage potential. In addition, decreased shading throughout the year may render the organic matter more susceptible to decomposition (Grigal and Berguson, 1998).

1.3.1.2. Limitations

Little is known about the potential for soil carbon sequestration under SRF systems since relatively few studies have been conducted (Hansen et al., 1993; Grigal and Berguson, 1998; Zan, 1998; Mehdi et al., 1999). Table 1.3 summarizes research within SRF systems where actual soil carbon measurements were obtained, as well as studies that provide soil carbon estimates based on appropriate modeling. Data from these studies are difficult to compare due to the varying methodologies employed. Moreover, in all of the investigations, soil carbon storage data were collected at single sampling dates (i.e. static measurement) rather than providing information on long-term soil carbon dynamics. These methodological limitations have made it extremely difficult to assess the true impact of the various SRF systems on soil carbon storage levels.

1.3.2. Major Findings

In Canada, two studies have examined soil carbon storage levels under the same SR willow plantations (Zan, 1998; Mehdi et al., 1999) (Table 1.3). Findings indicated that in the fourth year of production, willow plantations were sequestering carbon at an average annual rate of between 5 and 13 Mg $ha^{-1}yr^{-1}$ at 0-60 cm compared with adjacent agricultural crops (i.e. corn), with a greater accretion at the inherently more productive site (Zan, 1998). However, in the sixth year of production, the rate of carbon sequestration had decreased to between 0.8 and 2.2 Mg $ha^{-1}yr^{-1}$ at 0-60 cm, compared to corn (Mehdi et al., 1999). The high sequestration rate obtained in the fourth year of production was attributed to the coppicing of the trees one year prior to sampling. Since willow was allowed to grow undisturbed for 3 consecutive years before being coppiced, part of its extensive root system died off and may have contributed substantial amounts of carbon to the soil (Zan, 1998). It is therefore probable that a large proportion of soil carbon measured in the fourth year of production represented a transient pulse associated with coppicing, which was ultimately returned to the atmosphere, as exemplified by the low carbon sequestering rates in the sixth year of production. Similarly, in a study by Ford-Robertson (1997), roots of recently harvested deciduous trees were shown to release substantial amounts of carbon of which some of the root-derived carbon was incorporated into the soil fraction. Figure 1.1 graphically represents the typical effect of tree harvesting on soil carbon content. Assuming a linear increase in soil organic carbon after 6 years, approximately 1.5 Mg $ha^{-1}yr^{-1}$ (with larger increases on relatively more fertile land) of organic carbon is being sequestered at the willow plantations in southwestern Québec. However, soil organic carbon increases are likely not linear (Schroeder, 1992), but probably cyclical or incremental.

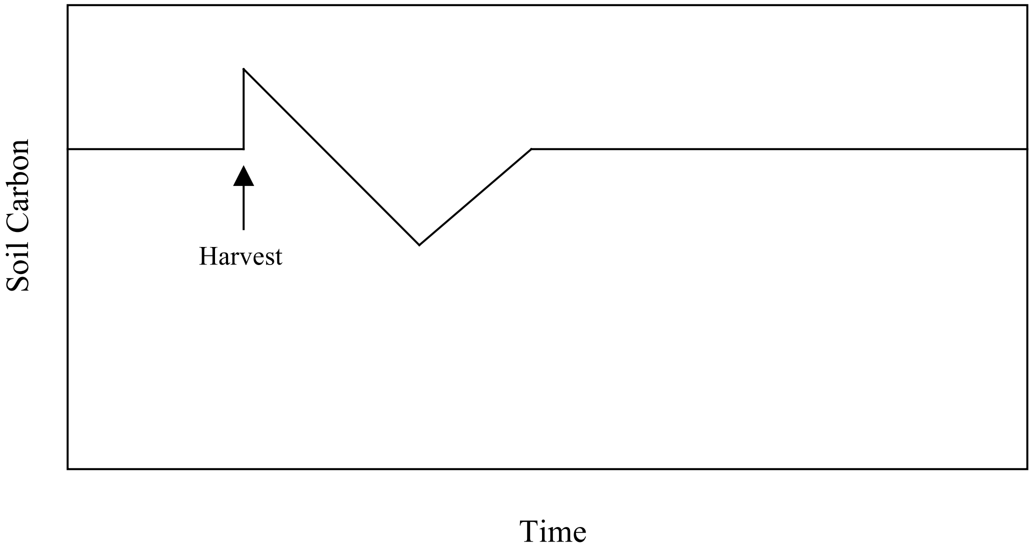

Figure 1.1. Soil carbon content following harvest of trees (Source: Moore et al., 1981).

In the U.S., two separate soil carbon studies were conducted on several hybrid poplar plantations (Table 1.3) (Hansen et al., 1993; Grigal and Berguson, 1998). The Hansen et al. (1993) study was conducted in a number of north-central U.S. sites. Data were collected from 12-18 year old poplar plantations showing *c.* 25 Mg ha^{-1} more soil carbon from 0-100 cm than adjacent land uses (row crops and grassland), but indicated that poplar plantations between 4-6 years old may actually lose soil carbon. Since most of the losses were found to occur at 0-30 cm depth, the losses were attributed to mineralization[†]. When soil organic carbon increases were averaged over 30 years, they found an accumulation rate of 3.2 Mg $ha^{-1}yr^{-1}$ compared to adjacent row crops. Hansen (1993) derived a regression equation to exemplify this (see Table 1.3). In a study conducted by Grigal and Berguson (1998) on 7-8 year old Minnesota plantations, no difference in soil carbon was found from 0-100 cm when compared with agricultural land uses (corn, wheat, hay or grass). However, based on estimates and data obtained for the 7-8 year old plantations, Grigal and Berguson (1998) concluded that soil carbon was most probably lost during the establishment phase of the plantations causing sharp decreases in soil carbon, and slow gains in carbon by the fifth year. By year 10-15, assuming a linear rate of change, the rate of soil carbon storage would eventually rise to between 1-1.7 Mg $ha^{-1}yr^{-1}$.

Research conducted by Dewar and Cannell (1992) in the U.K. (using data estimates) concluded that if the objective was to store carbon rapidly over a period of 20-30 years and to achieve a high total carbon storage over the longer term, the best option would be to grow *Populus* plantations on 26-year rotations, on fertile land (Table 1.3). Soil carbon storage rate estimates of 7.3 Mg $ha^{-1}yr^{-1}$ over the first rotation have been reported largely due to the high biomass and litter inputs (Dewar and Cannell, 1992). Similarly, short rotations of *Salix* (8 years) were estimated to store carbon rapidly over the first rotation (5.9 Mg $ha^{-1}yr^{-1}$) but were less efficient at long-term carbon storage, due to low levels of carbon in the tree biomass and low litter inputs (Dewar and Cannell, 1992).

A number of studies on carbon sequestration in SR plantations have been carried out in tropical regions (Schroeder, 1992; Kürsten and Burschel, 1993). In a study examining the energy tree plantations of *Leuceana* sp. (5-year rotation) and *Eucalyptus* sp. (2.5-year rotation), Kürsten and Burschel (1993) reported a soil carbon sequestration rate of 2.0 and 3.6 Mg $ha^{-1}yr^{-1}$, respectively. Schroeder (1992) estimated rates of carbon storage of 6 Mg $ha^{-1}yr^{-1}$, based on a 7-year rotation of a fuelwood crop established on bare ground.

[†] mineralization is defined as the conversion of an element from an organic to an inorganic state as a result of microbial decomposition

Table 1.3. Rate of soil carbon increase (odMg/ha) compared to adjacent agricultural crops for a number of SRF plantations at different developmental stages in both North America and Europe.

Source	Location	Species	Depth sampled (cm)	Plantation Age (years)	Carbon $(\mathrm{Mg\ ha^{-1} yr^{-1}})$
Zan, 1998	Québec	Willow	0 - 60	4	5 - 13
Mehdi et al., 1999	Québec	Willow	0 - 60	6	0.8 - 2.2
Hansen, 1993	North-central U.S.	Poplar	0 - 100	12 - 18	1.6
				30	3.2
Grigal & Berguson, 1998	Minnesota	Poplar	0 - 100	7 - 8	0
Estimated Data					
Dewar & Cannell, 1992	United Kingdom	Willow	-	8	5.9
		Poplar	-	26	7.3
Hansen, 1993	North-central U.S.	Poplar	0 - 100	4 - 6	Loss (not quantified)
				0 - 30	[a]C =(-43.5 + 4.48age) / age
Grigal & Berguson, 1998	Minnesota	Poplar	0 - 100	1	-3.5
				5	-2.6
				7 - 8	-1
				15	1.2

[a] C = soil carbon accumulation
age = age of plantation
Equation $r^2 = 0.76$, $p = 0.000$

1.3.3. Conclusions

All studies investigating soil carbon sequestration within SR plantations have examined soil carbon levels at one point in time rather than over the long-term, or at least over an entire rotation. Thus, data largely represent static effects of SR plantations on soil carbon storage rather than more long-term carbon dynamics. Such limitations substantially hindered the capacity to fully understand the various interactions occurring in these systems. Hence, before any accurate and realistic conclusions can be made about the potential for soil carbon sequestration in SR plantations, more research investigating this key process is required.

Nonetheless, based on the limited information available, a number of general conclusions can be made. From the U.S. studies, it appears that rotation length is a key factor in the ability of plantations to remove carbon from the atmosphere over the long-term. The longer the rotation length, the greater the biomass accumulation over time, and therefore the greater the soil carbon storage potential. Very short rotations (i.e. less than 10 years) may therefore not lead to soil carbon sequestration. Hence, if the aim is to sequester carbon, longer rotations may be required (Schroeder, 1992; Hansen et al.,1993; Grigal and Berguson, 1998).

The Canadian research indicated that SRF plantations, if properly managed, may be reasonable, additional carbon sinks. It was shown that SR plantations in southwestern Québec, when grown under soil conditions with appropriate soil fertility management (i.e. use of inorganic fertilizers and/or organic amendments), have the potential to increase soil carbon levels compared with agricultural systems. Consequently, under unfavourable soil conditions and improper soil fertility management, it may not be advantageous to grow such crops for the purpose of carbon storage (Zan, 1998).

Therefore, the benefits of SR plantations are more likely to come from the replacement of fossil fuels, rather than from carbon sequestration itself, especially if grown on marginal lands. The relatively short harvest cycle of many plantations limits to a large extent the amount of above- and belowground carbon storage in these systems.

1.3.4. Suggestions For Future Research

More research investigating soil carbon sequestration within SR plantations is required. Specifically, there is a pressing need to pursue further work into:

- the continuous monitoring of soil carbon changes over at least several rotations or longer periods, in order to avoid transient soil carbon dynamics and to provide a more accurate reflection of long term trends, as well as to verify the assumption of a linear soil organic carbon increase with time;

- short- and long-term effects of coppicing on soil carbon levels, as well as root turnover and decomposition rates;

- the effects of soil fertility management, such as the use of various rates of inorganic fertilizers and organic amendments on soil carbon levels;

- the effect of various plant nutrients (e.g. N, P, and S) on carbon sequestration in soils;

- standardizing methods of analysis to facilitate comparison between studies.

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Task 2. Issues Related to Short-Rotation Forestry Culture

2.1. Introduction

This section presents information on several issues related to the production of SRF systems. Short rotation forest plantation establishment, fertilization regimes typically employed, harvesting techniques, and the establishment of breeding programs are discussed. Moreover, environmental issues related to the culture of SRF systems, such as disease and insect management, concerns about nutrient and pesticide loading to the environment, water use, soil erosion, and biodiversity impacts are also reviewed.

2.2. Production Practices of SRF

There is a substantial amount of research data and production experience available for both SR willow and poplar cultivation. Much of the willow production information has been developed in Europe, and a large database on poplar production is available from North America. The two species are discussed separately due to differences in production strategies.

2.2.1. Willow

2.2.1.1. Production

Many of the operational constraints for willow production have been resolved through extensive research in Europe. Sweden has the largest willow program with 17,000 ha under production. However, the program in Sweden has recently been scaled down to 500-600 ha yr^{-1} planted annually (Carter, 1999).

The standard willow production system currently in use is to grow willow at approximately 12,000-15,000 cph on a 3-4 year rotation, with a plantation life span of 20-25 years. A twin-row planting system with paired rows set 0.75 m apart and with 1.5 m spacing is used to accommodate wheel traffic for machine operations. Mechanized systems of willow establishment are now well developed with 1.8 m long willow rods being used in an automated step planter that can cover approximately 0.6 ha hr^{-1}. After the first year, the crop is coppiced to stimulate shoot production. Effective weed control remains a challenge but is usually achieved through pre-site preparation during the previous fall using a broad-spectrum herbicide. Spring applications during the planting year can include a residual herbicide such as simazine followed by mechanical cultivation and use of a graminicide for control of annual and perennial grasses. Fertilization strategies are not well defined and are difficult to implement because of stand height. In Canada, the approach proposed by REAP-Canada is to fertilize in late spring, the year after coppicing, followed by an aerial application of fertilizer in spring, in the third year of a four-year rotation. This fertilization regime will reduce expenses, yet provide a reasonable level of fertility for the crop during the four-year rotation. Another approach proposed is the use of dried sewage sludge (Labreque et al., 1997).

2.2.1.2. Harvest

The reduction of harvesting costs has been an ongoing challenge, given that the harvesting phase represents a major cost component in SRF willow production. Cutting and chipping during one single pass is the most effective option for harvesting SRF willow coppice. From a storage perspective, harvesting and chipping during two separate stages may be desirable but is generally considered to be too expensive. Spinelli and Kaufman (1997) recently reviewed the current status of willow harvesting technology and reported a high harvest productivity as well as the availability of reliable cut-and-chip harvesting equipment. In Europe, the *Austoft* and *Class* harvesters are now in use for large commercial operations.

The *Class* harvester has been modified from a conventional forage harvester. The main modification to the conventional equipment was the requirement of a header (consisting of two disk saws placed side by side) for harvesting SR willow coppice. The use of a precise planting pattern designed specifically for the harvest head is also required. The *Class* harvester is considered well-suited to farmland having flat, firm soils. Harvesting losses using the *Class* harvester are slightly greater than for the *Austoft* harvester, but the *Class* harvester can travel on roads and generally causes less damage to stools[†] (Spinelli and Kaufman, 1997).

The *Austoft* harvester is a self-propelled sugarcane harvester, adapted for SRF harvesting. This harvester is a sturdy, steel-tracked machine that although is unable to travel on roads, is considered more reliable (i.e. low downtime) compared with other harvesters. Moreover, harvesting losses using the *Austoft* harvester are limited and seldom exceed 4% of the standing crop (Spinelli and Kaufman, 1997).

2.2.1.3. Breeding Programs

A major contributor to further reducing production costs is the improvement of yields through the adoption of effective plant breeding programs. Unfortunately, limited research in this critical area has been carried out in North America. Dr. Louis Zsuffa, a retired plant breeder at the University of Toronto, was responsible for conducting much of the willow breeding research in North America. A substantial amount of germplasm, which Dr. Zsuffa developed, is currently being assessed at the State University of New York, where a doctoral student is involved in a willow-breeding project. In Europe however, there are well-established, long-term willow breeding programs including at the Long Ashton Research Centre near Bristol, England where 800 new test clones are produced annually. Similarly, a breeding program at Svalof Weibel in Sweden produces 2,000 new test clones each year. Seven to ten years are typically required to develop a new clone. The two European breeding programs produce approximately 3-5 new commercial willow clones for introduction into Europe each year. The main objectives of these breeding programs are to improve yields as well as disease (i.e. *Melamspora* rust) and insect (i.e. Chrysanalid beetle) resistance (Carter, 1999).

2.2.2. <u>Poplar</u>

2.2.2.1. Production

[†] Stools are stumps from which coppice originates

Poplar production systems are at a relatively advanced stage of development. This crop is typically grown at a density of 1,100-1,400 cph. Mechanized planting systems have been developed, but most commercial crops are hand-planted in order to establish the crop earlier. Planting frequently occurs at an equidistant spacing to promote cross-cultivation and good canopy closure. Weed control strategies are similar to those employed for willow production, but mechanical weeding is more extensive, since canopy closure does not occur until the third year.

Fertilizer additions in poplar are minimal since the longer rotations employed (12 years) are less nutrient-demanding than the shorter rotation cycles used in willow. However, current practices indicate that band-applied fertilizer after canopy closure can increase performance (Baldock and Burgess, 1995)

In the Pacific Northwest, insecticides are generally applied aerially or through the use of drip-irrigation systems when pest problems first appear.

One problem with poplar productivity is its low annual growth increment during the initial establishment years. There is interest in using longer cuttings (e.g. 45-60cm) to improve productivity during this early establishment period, as well as to minimize weed control requirements. The use of larger poplar cuttings is likely to be most viable for lower density plantings destined for solid wood product markets.

2.2.2.2 Harvest

Advances have been made in poplar harvesting technology, as reviewed recently by Hartsough et al. (1997). Harvesting is geared to the pulp and paper industry and in some instances, by-products are targeted for biomass energy production. Currently, harvesting is carried out with conventional forestry equipment, enabling the production of clean pulp chips. Typically, the trees are felled and bunched with a "tricycle" or using an articulated rubber-tired drive tree feller buncher. In recent years, manufacturers have produced machines known as delimber/ debarker/ chippers, which combine a chain flail and a disk chipper into a single machine. Engineers currently believe that the most radical improvement to be made for harvesting poplar biomass would be the development of continuous-travel felling equipment, such as that used for willows. However, this would depend on an effective, economic process to upgrade whole tree chips to pulp quality. One system of upgrading whole tree chips that has been developed, and referred to as the *Masahake Process*, separates whole tree chips into clean chips and residues based on the physical strength property differences of bark and wood, followed by an optical sorter (Hartsough et al., 1997). This differentiation, based on chip strength, is similar to the *Paprifer Process* that was assessed for separating willow bark from white chip material (Berlyn, 1995).

2.2.2.3 Breeding Programs

Several poplar-breeding programs are underway in North America. These have been traditionally government funded university based programs. Some industry led consortiums have also been developed. More recently in the US, some companies in the Pacific northwest such as Boise Cascade have decided to set up programs. In the North-Central states, a program is also based out of the University of Minnesota. The most recently developed breeding program has been the

Western Boreal Aspen Cooperative led by Barbara Thomas, adjunct professor at the University of Alberta. The program presently focuses mainly on plant material collection and early field performance evaluations. Promising material will subsequently be used for developing breeding lines.

2.2.3. Conclusions

In reviewing silvicultural aspects of SR tree plantations, it is clear that significant progress has been made in converting SR tree plantations into more commercial, farm-like operations. From a productivity standpoint, willow plantations are more productive than poplar plantations and willow biomass can be produced at a lower cost (see Task 3). This is due to more efficient harvesting operations for willow combined with an on-the-go cut-and-chip process, and greater willow productivity rates because of more light interception (i.e. higher planting densities). If a system to separate bark from wood fibre could be developed through a combination of engineering and plant-breeding efforts, this may reduce the cost of fibre delivered to mills, especially for oriented strand board and medium density fibre board, where a higher tolerance of dark material is considered acceptable.

Further research needs to be performed on longer poplar rotations for solid wood products. Moreover, thinning of poplar plantings needs assessment so that plantations could be used for an early pulp and paper harvest, followed by a solid wood product harvest.

2.3. Environmental Impacts Associated with Growing SRF Systems

Extensive research has been performed on the environmental impacts of SRF systems (e.g. Hopkin and Cheliak, 1995; Hubbes and Lin, 1995; Christian et al., 1994; Crawford, 1995; Biewinga and van der Bijl, 1996; Sage and Robertson, 1996; Tolbert et al., 1997; Christian et al., 1998; Kort et al., 1998). All generally agree that SR tree plantations, if properly managed, can have a positive impact on the environment compared with agricultural crops. However, negative impacts may occur especially during the establishment and harvest phases. It is also emphasized that SRF systems should not be employed as replacements of natural forest habitats.

2.3.1. Insect and Disease Damage

Short rotation forest systems are prone to a variety of insect pests and diseases (Hopkin and Cheliak, 1995). However, damage suffered rarely leads to entire plantation mortality and therefore large economic losses (Hopkin and Cheliak, 1995). Trees are most susceptible to injury during the establishment phase of plantations (Dickmann and Stuart, 1983), and resistance varies depending on clones used (Hubbes and Lin, 1995). In addition, within plantations composed of single clones, insect and pest damage can be extremely devastating if a poor clone selection is made (Hubbs and Lin, 1995). Damage can result in mortality, yield loss, and deformation. Table 2.5 outlines the major insect and diseases affecting willow and poplar plantations (*OMNR*, 1993; Hopkin and Cheliak, 1995). Prevention is often the best measure to undertake against insect damage and diseases. Maintaining a healthy plantation by ensuring proper growing conditions and effective weed control is crucial in order to avoid serious injuries. Planting poplar clones resistant or tolerant to diseases such as septoria stem canker (*Septoria musiva*) is important. The planting of clonal mixtures of willow is now being investigated in Europe as a control strategy against pathogenic diseases, such as rust. Such clonal mixtures increase the genetic diversity within plantations rendering them more resistant to disease damage caused by pathogens (Pei et al., 1997).

Table 2.1. Major insect pests and diseases afflicting SR willow and poplar systems.

Pest	Host	Damage	Prevention/Control
Sawfly (*Nematus* spp.)	Willow foliage	Defoliation; Shoot dieback	Selection of resistant clones
Imported willow leaf beetle (*Plagiodera versicolora*)	Willow/Poplar Leaves	Skeletonized leaves; Holes and notches in leaves	Difficult in large areas; Insecticide spraying in small areas
Cottonwood leaf beetle (*Chrysomela scripta*)	Poplar leaves	Skeletonized leaves; Growing shoots killed	Difficult in large areas; Insecticide spraying in small areas
Septoria canker (*Septoria musiva*)	Poplar shoot/stems	Cankering and death of shoots, branches, stems	Harvest early and replace with resistant stock
Melampsora leaf rust (*Melampsora* spp.)	Poplar leaves	Defoliation; Decreased growth/vigour	Establish away from conifers; use wider spacing
Poplar borer (*Saperda calcarata*)	Poplar shoot/stems	Boring and weakening of stems and roots; tree breakage	Remove heavily infested trees; apply insecticide to stem in early spring and summer
Poplar-and-willow borer (*Cryptorhynchus lapathi*)	Willow/Poplar Shoot/stems	Weak, deformed, broken shoots and stems	Remove heavily infested trees; apply insecticide to stem in early spring and summer

2.3.2. Pesticide Loading

There are several levels at which pesticides can have a negative impact on the environment. First, energy is used to produce, transport, and apply the pesticides. Of most concern however, are the pesticide emissions occurring during the application process in the field. As a result of pesticide emissions during and after application, considerable amounts of pesticides end up in soil, ground water, surface water and air, posing a great health risk to ecosystems, wildlife, and humans (Biewinga and van der Bijl, 1996).

Chemical weed control is generally considered essential when establishing SRF systems, and is often used in addition to mechanical methods (Sage, 1998). Weed control in established plantations and following a harvest is usually not required. (Sage, 1998; Perttu, 1998). Severe weed infestations are often local and can be treated on a local scale (Sage, 1998). Less competitive shade-tolerant herbs and grasses can colonize within plantations, however they often do not cause yield reductions (Sage, 1998).

For insect and disease control, insecticide and fungicides have seldom been used in the past due to the cost of application (Sage, 1998). Moreover, substantial damage needs to occur before yields become affected (Sage, 1998). In general, negative impacts from pesticides are generally limited to the establishment phase of plantations. In Canadian poplar plantations, there has been limited use of insecticides during the production phase. However, there is growing use of insecticides in the U.S. In the north-central region, aerial insecticide applications are occurring due to cottonwood leaf beetle (*Chrysomela scripta*) infestations (Riemenschneider, 1999). Insect infestations in the Pacific Northwest are less problematic, and stands are sprayed approximately once during the production cycle (Tuskan, 1999). In a Portuguese study examining emissions of pesticides into the environment, a score for harmfulness were issued to several agricultural practices and energy crop systems. Both willow and poplar contributed far less pesticide emissions than all agricultural crops tested (rapeseed, sugar beet, winter wheat, sweet sorghum, silage corn, hemp, and miscanthus) (Biewinga and van der Bijl, 1996).

2.3.3. Water Use

Water is fundamental to the process of photosynthesis and is influenced by many factors. A review of some existing studies in temperate regions will provide insight into the impact of water use on biomass accumulation.

In recent years, there has been a significant amount of research in Sweden indicating that the annual water consumption by fast growing willow trees creates water deficits (Grip et al. 1989; Persson and Jansson, 1989). Several models developed from field studies indicate that annual evaporation exceeds the Penman open water evaporation rate of 430 mm by between 5% and 40% (Grip et al. 1989; Persson and Jansson, 1989). In a simulation study, Grip et al. (1989) estimated that 526 mm of water was used for a normal willow stand producing 12 t $ha^{-1}yr^{-1}$ of aboveground biomass. Of this amount, 375 mm was transpired, 56 mm was intercepted, and 95 mm was evaporated from the soil. The rate of evaporation was 22% higher than the Penman open water evaporation rate. A biomass crop producing 12 t ha^{-1} of biomass would therefore represent a water use of approximately 44 mm t^{-1} if 526 mm was used.

Persson and Jansson (1989) estimated a reasonable range for actual evaporation of willow to be between 370 and 420 mm during the third year of a willow stand coppiced after the planting year. No yield data was provided in this study, but assuming a mean annual increment of 10 t ha^{-1}, typically obtained in Sweden, then approximately 40 mm of water would be required per tonne of biomass.

The yield-limiting potential of water on tree growth is present even in moderately high rainfall regions of Canada. For example, in Québec, if 400 mm of water was available for growth (i.e. 40% of the 1,000 mm average annual rainfall) then the upper yield limits for willow would be approximately 10 odt $ha^{-1}yr^{-1}$ (Samson et al., 1995). Slightly higher amounts of water may be available on higher quality soils but these would likely not be available for willow production. A clear demonstration of the yield limiting impact of water can be observed from a willow study in New York (Abrahamson et al., 1994). This study found willow yields of 8.9 odt $ha^{-1}yr^{-1}$ under rainfed conditions compared with 27.5 odt ha^{-1} yr^{-1} obtained under irrigation.

Hybrid poplars also have large water demands. It is estimated that consumptive water demand is 1,000 mm ha^{-1} at mid-rotation in the north-central U.S. (Hansen et al., 1993). It is evident from these studies that large-scale plantings of SRF could have a negative impact on ground water recharge, and significantly increase subsoil water use. This analysis also clearly demonstrates that SRF productivity is highly sensitive to water availability. Therefore, efforts to improve productivity through plant breeding may not be feasible as yields are likely to plateau due to water-use efficiency restrictions on productivity. For example, with alfalfa it took a long period of time to replace the leading alfalfa variety (Vernal) used in the 1950's by new, improved cultivars. These new cultivars, however, have only reached yields that are 9% greater than variety Vernal (CPVQ, 1995). With this C_3 alfalfa species, a substantial breeding effort by seed companies and government research scientists has created a genetic gain of only 0.25 % per year over the past 40 years. It is evident that C_3 species, such as fast growing trees will have a more restricted upper yield potential than more water-use efficient biomass crops such as C_4[†] perennial grasses (Samson and Chen, 1995).

2.3.4. Soil Erosion

The impact of SR crops on soil quality depends on several factors including the crop itself, soil, the land use it is replacing, and climate (U.S. Congress, 1993). In general, SRF systems lead to a reduction in soil erosion (U.S. Congress, 1993; Kort et al., 1998) by increasing water movement into soil, lessening the deleterious effects of water droplets, intercepting precipitation, and stabilizing soil by their roots and leaf litter (Kort et al., 1998). Soil structure and aggregate stability were also improved in SR tree plantations (Tolbert et al., 1997a). Tree plantations are generally better at reducing erosion than conventional row crops and are similar to well-maintained pastures. (U.S. Congress, 1993). For instance, in a Danish and Swedish study, it was found that significantly less soil erosion occurred under willow compared with wheat production. However, erosion rates under willow were similar to those occurring under green fallow (Hadders and Olsson, 1996; Jørgensen, 1996). Poplar plantations have been recommended on slopes subject to erosion, especially on sides and bottoms of gullies to reduce water flow and act as a trap for loosened materials (Kort et al., 1998). They have also been recommended for streambank protection, especially where waterflow can be high (Kort et al., 1998).

[†] C_4 species are those species having a 4-carbon compound as the first intermediate product in their metabolic pathway. These species are generally more efficient at photosynthesis than C_3 species, especially in warm, dry climates.

Soil erosion can occur under SR systems (Turhollow et al., 1985; U.S. Congress, 1993; Hadders and Olsson, 1996; Jørgensen, 1996; Heilman and Norby, 1998; Kort et al., 1998), particularly in early years of establishment and following harvest because of lack of soil protection during these periods (Heilman and Norby, 1998; Kort et al., 1998; Kuch and Crosswhite, 1998). This is often experienced after a forest clear-cut where large increases in water erosion are seen (Kort et al., 1998). For example, in an Iowa poplar plantation free from herbaceous vegetation, soil erosion within the plantation was problematic especially during periods of heavy rainfall (Kort et al., 1998). Hence, without a constant dense vegetation cover, erosion rates can increase.

Since growing SRF systems will likely occur on marginal lands, impacts on soil erosion must be addressed particularly during the establishment phase since these lands are often easily eroded (Turhollow et al., 1985; Kort et al., 1998). Site preparation, weed control, and reduced tillage will be of great importance to prevent negative environmental impacts caused by soil erosion (*GRRBEP*, 1986).

2.3.5. Nutrient Losses

Short rotation tree plantations have minimal potential to cause nutrient loading to the environment. However, when nutrient loading to the environment does occur, it is mainly during establishment and harvesting activities, and not during the main production years.

Nutrient losses associated with leaching, runoff, and erosion are more likely to occur during plantation establishment years and following a harvest because of lack of soil protection and absence of nutrient uptake by the crop (Heilman and Norby, 1998). In some instances, runoff of nitrogen and phosphorus from SRF systems in the establishment years can be negligible (Tolbert et al., 1997a). After establishment, potential for nutrient loss from surface runoff is minimal as the canopy intercepts rainfall intensity. In a study conducted in the Netherlands, it was shown that both poplar and willow had low surpluses of residual nitrogen (40 kg ha^{-1}) compared with annual crops (greater than 100 kg ha^{-1}) such as rape seed, sugar beet, winter wheat, sorghum and silage corn. Willow and poplar nitrogen surpluses were comparable to those of grass fallow (Biewinga and van der Bijl, 1996).

The development of an extensive root system also plays a significant role in the uptake of nutrients and minimizing nutrient movement through runoff (Tolbert et al., 1997a). For instance, willow has been found to be efficient in the uptake of nutrients because of its well-developed root system (Ledin, 1996). Depth of rooting is also important in preventing the leaching of nutrients, such as nitrate (Heilman and Norby, 1998).

When nutrients are lost through harvesting practices, quantities of nutrients removed vary with yield, species or clone, and time of harvest (Heilman and Norby, 1998). For instance, in a study comparing nutrient losses of 6 four-year old cottonwood clones, nutrient removal from harvest (not including leaf harvest) varied from 95 to 420 kg ha^{-1} of nitrogen (Heilman and Stettler, 1986). If leaves are included in the harvest, the quantity of nutrients removed will increase. Therefore, nutrient removal will also vary depending on the timing of the harvest (affecting presence or absence of leaves) in the growing season and degree of removal of leaves from the site (Heilman and Norby, 1998). It has been shown that winter harvests of plantations improve nutrient retention because leaves are not removed from the site (Graham et al., 1996).

Nutrient extraction rates are generally lower in species of longer rotations, such as poplar, since a greater percentage of its biomass lies within the wood rather than the bark. Leaving bark and fine branches at the felling site can minimize nutrient extraction from poplar plantations. Poplars can show significant response to fertilization during the production cycle. Band application of fertilizer as in the case of row crops provides for a more efficient use of fertilizer than broadcasted applications (Baldock and Burgess, 1995).

In willows, shorter rotations are employed and higher fertilization rates are required since frequent removal of all harvestable biomass occurs from the site. The increased amounts of nitrogen fertilizer inputs increase the fossil energy input requirements of willow compared to poplar. Nonetheless, since willow is an efficient converter of solar radiation, its energy balance is favourable, having an energy output/input ratio of 20 (Girouard et al., 1999).

2.3.6. Biodiversity

Wildlife can either be positively or negatively affected by SR plantations depending on the way the crop is managed, the location of the plantation with respect to other land uses, and which land use it displaces (Wolfe 1993; Christian et al., 1998). If properly designed and established, such plantations can provide a favourable habitat for wildlife and serve as effective travel corridors (Wolfe, 1993). For example, a number of studies have demonstrated that SR systems to provide useful habitat for wildlife (Christian et al., 1994; Crawford, 1995; Sage and Robertson, 1996; Tolbert et al., 1997; Christian et al., 1998). In studies conducted in the Pacific Northwest and upper Midwest, hybrid poplar plantations did provide habitat for breeding and migrant birds (Tolbert et al., 1997b). Bird species were found to use hybrid poplar plantations to a greater extent than agricultural crops, but to a lesser extent than natural forests (Tolbert et al., 1997b).

Several factors can affect biological diversity in SRF systems. Major factors include the structural complexity of the plantation system, plantation age, rotation cycles, harvesting activities, adjacent land use, and the time scale within which the plantations are managed (Wolfe, 1993).

In general, the more complex the vegetation structure within a system, the more diverse the community of animals associated with it. Therefore, as vegetative structure becomes simplified, so does the community it supports (Wolfe, 1993). Vegetative diversity therefore plays a critical role in increasing biodiversity within SR plantations. Short-rotation systems that are intensively managed have little ground vegetation due to chemical and mechanical weed control early in the rotation, and shading later on. Such systems may therefore offer little to increase biodiversity. These plantations lack the structural complexity that is required for increasing biodiversity, such as the presence of canopy gaps to encourage other plant growth and dead trees (Christian, 1997). Conversely, in less intensely managed systems, where vegetative diversity occurs usually because of incomplete weed control, increased biodiversity ultimately takes place. For example, in a midwestern U.S. poplar plantation, a high proportion of small-mammals were found to occur in portions of the plantation that were poorly established (i.e. other vegetation/weeds present) whereas mammal communities in the well-maintained portions had fewer and less diverse species (Christian et al., 1997). In the midwestern U.S., well-maintained poplar plantations had only 0 to 49% of the plantation being utilized by birds and mammals (Crawford, 1995). Therefore, in areas where weed control is very effective, and thus little vegetative diversity present, the possibility to increase biodiversity is lost (Christian et al., 1998). Hence, the use of genetically engineered trees to enable broad-spectrum herbicide use would be expected to provide extremely clean plantations and low biodiversity potential. This is of particular concern with the introduction of genetically engineered poplars, which may outcross native poplar species (Tolbert, 1999).

The use of SRF systems for wildlife is also affected by plantation age since the habitat offered within a plantation will change with time (Wolfe, 1993; Sage and Robertson, 1996). In a Minnesota study, the amount and diversity of breeding birds utilizing young hybrid poplar plantations was initially similar to those utilizing grasslands and row crops. However, as the plantations approached canopy closure, successional species became predominant (Tolbert et al., 1997b). Another, midwestern U.S., study also demonstrated that shortly after planting poplars, the bird species frequently observed within the plantations were typically associated with those observed in open fields. However, between ages 2 and 4 years, a change in bird species composition had occurred (Hanowski et al., 1997). In a British study, more migrant bird species were recorded from a 2-year old than a 1-year old willow plantation after coppice and most resident species selected older willow or poplar coppice growth (Sage and Robertson, 1996).

Species composition of small mammals also changes with plantation age. For instance, shrews were found to be absent from young, well-maintained poplar plantations, but appeared in well-vegetated patches on both young and older plantations (Christian et al., 1997). In addition, mammal communities in young plantations were dominated by a single species generally found in open habitats (Christian et al., 1997). In older plantations however, a more diverse array of species was present, including species generally associated with more complex vegetation structures and forest habitats. However mammals requiring forest habitats were almost completely absent from older plantations (Christian et al., 1997; Christian, 1997). Therefore, plantations even late in the rotation will likely harbour species primarily seen in open habitat but not those associated with forest (Christian et al., 1997; Christian, 1997; Christian et al., 1994).

Harvesting activities and rotation cycles may also negatively impact biodiversity. For instance, in the case where a winter harvest will remove all or most vegetative cover, this will ultimately leave wildlife with no adequate cover for winter, no protection from predators, and destroy their nesting ground thus disrupting nesting activities the following spring.

Biodiversity within biomass plantations is greatly affected by the surrounding landscape (Christian et al., 1998). As observed in a study conducted in Ontario poplar plantations, bird communities were influenced by the surrounding landscape. Forest birds were more abundant in plantations that were surrounded by natural forest than by those that were not (Christian et al., 1998). In addition, more species occurred on plantations located adjacent to both forested and open habitats than on those located in a less diverse area. In the U.S. Midwest, bird species associated with forest habitat were also found on plantations in close proximity to forest (Hanowski, 1997). Similarly, species associated with open habitats were more commonly observed on plantations surrounded by open and agricultural landscapes (Christian et al., 1998).

In closing, it should be mentioned that another threat to biodiversity posed by perennial biomass crops is their ability to compete with the natural flora. In Ontario, introduced potential biomass crop species; black locust and miscanthus, have escaped into natural areas. Genetic pollution is another such threat.

2.3.7. Conclusions

Extensive research has been performed on the environmental impacts of SRF systems. Most evidence suggests that afforestation of SR tree plantations has a more positive impact on the environment than conventional agricultural crops because of limited soil erosion, decreased pesticide impacts and fertilizer applications, and increased biological diversity. However, increasing the intensity of management of SR plantations through the establishment of larger-scale operations, increased chemical use, and the use of genetically engineered crops may eventually lead to a loss of these potential positive impacts.

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Task 3: Costs of Production

3.1. Introduction

Costs involved in growing hybrid poplar and willow managed under SR systems were estimated using *BIOCOST-Canada* and *BIOCOST-USA* softwares. Default parameter values were adjusted to mimic as closely as possible the commercial cropping practices and the Canadian cropping regime environment. Once the default parameters were established, the same set of cropping practices was used for different regions in Canada, for each crop. Any variation in total cost was a result of annual productivity variations among regions.

3.2. Assumptions

Using 1995 dollars, production costs per ha are estimated for each year of a plantation lifespan and discounted to present value using a 10% discount rate. Similarly, expected harvestable biomass yields over the entire plantation lifespan are discounted to present value and used to determine the present value of cost per odMg. Estimates for SR willow are computed using *BIOCOST-Canada* while estimates for hybrid poplars are generated by *BIOCOST-USA*. The latter estimates were adjusted to be expressed in Canadian dollars and metric units. Detailed assumptions used by the softwares are outlined in Girouard et al. (1999) and in Walsh and Becker (1996).

The main parameters used to conduct the current study are presented in Table 3.1. Hybrid poplar default values and cropping practices are based on averages of commonly used practices in Canada and in the U.S. Short-rotation willow values are based primarily on practices carried out in research and demonstration sites in southwestern Québec (Samson et al., 1995). For both crops, it is important to note that variations exist within specific studies and commercial applications, and that the estimates developed in this study aim at providing an order of magnitude of costs incurred in growing SR tree species rather than providing estimates for specific field locations.

Both hybrid poplar and willow are assumed to be established on farmland, where no brush removal is necessary. A broad-spectrum herbicide is applied to the sites in the fall, prior to planting and plowing. Disking may be performed in the fall for hybrid poplar, and preferably in the following spring for willow. Hybrid poplar planting is performed manually using 25-cm long cuttings and at a spacing of 2.5 m by 3 m (1,389 trees ha^{-1}). Willow 30-cm long cuttings are mechanically planted at a spacing of 0.92 m by 0.92 m (11,800 trees ha^{-1}). Default values for hybrid poplar cutting and planting costs are 25 cents (¢) and 16 ¢ $cutting^{-1}$, respectively. Default values for SR willow are 5.0 ¢ $cutting^{-1}$ for the planting operation and 2.0 ¢ $cutting^{-1}$ for the cuttings.

Weed control after planting hybrid poplar involves one application of Simazine and three passes of soil cultivation. In addition, one application of Linuron herbicide is performed in year 2 and 3, along with two and one passes of soil cultivation, respectively. Weed control in SR willow after planting is accomplished by spraying Simazine and Assure herbicides, and with three passes of soil cultivation in the establishment year. No weed control measures are required in the years thereafter. The use of insecticides on either crop is not considered in this study.

Fertilization requirements in hybrid poplar plantations appear to be relatively small compared with annual agricultural crops and SR willow. Since fertilization is site-dependent, it is sometimes not required. Poplar production default values from *BIOCOST-USA* are used in this study and assume fertilizer applications of 83.5 kg of nitrogen (N), 22.5 kg phosphorus (P), and 39 kg of potassium (K) per ha over a 12-year harvest cycle. Fertilization requirements for SR willow are currently under investigation and are very site-specific. This study assumes applications of 200 kg N, 47 kg P and 147 kg K per ha over each 4-year harvest cycle of a willow plantation (Samson et al., 1995).

Hybrid poplar is assumed to be harvested after 12 years of growth, and involves felling and bunching of the trees, skidding of the bunched trees to the edge of the field, and on-site chipping, with direct loading onto a van (Walsh and Becker, 1996). Willow is harvested every 4 years with a self-propelled direct chipping harvester. Both crops are transported to a mill located within a 60-km radius. Transportation costs are estimated to be \$11.47 $odMg^{-1}$ based on a study by Girouard et al. (1998). Hybrid poplar is replanted after each harvest, whereas willow is replanted after 5 harvest cycles (a total of 20 years).

Table 3.1. Summary of cropping systems used for the economic analysis.

Activities	Hybrid Poplar	Willow
Soil Preparation	Plowing/disking	Plowing/disking
Cuttings	25 cm long, \$0.25 $cutting^{-1}$	30 cm long, \$0.05 $cutting^{-1}$
Spacing/Density	2.5 m x 3 m / 1389 trees ha^{-1}	0.92 m x 0.92 m / 11800 trees ha^{-1}
Planting	Manual	Planter
Chemical Weed Control	- 1 application in the fall preceding planting (Roundup) - 1 applications in the planting year (Simazine) - 1 application in years 2 & 3 (Linuron)	- 1 application in the fall preceding planting (Roundup) - 2 applications in planting year (Assure and Simazine)
Mechanical Weed Control	- 3 times in the planting year - 2 times in year 2 - 1 time in year 3	- 3 times in the planting year
Insecticides	None	None
Fertilization	83.5-22.5-39 kg ha^{-1} $cycle^{-1}$	200-47-147 kg ha^{-1} $cycle^{-1}$
Custom Harvest	Feller, skidder, buncher, chipper	Direct chipping (Class-Jaguar)
Transportation to Mill	60 km radius / \$11.47 $odMg^{-1}$	60 km radius / \$11.47 $odMg^{-1}$
Harvest Cycle	12 years	4 years
Plantation Lifespan	12 years	20 years

3.3. Production Cost Estimates

This study provides two sets of production cost estimates for each crop: one only includes direct variable cash expenses, while the other provides the full economic cost. A provision for land rental (or repayment) is not included in either set, as a result of the difficulty in estimating an accurate value for the various land-uses in each region investigated.

Estimates based on variable cash costs only include expenses related to cuttings, chemicals, fertilizers, fuel, repairs, custom harvest, and transport of chips to a mill. The estimates are delivered cost estimates at the mill gate and represent the minimum market price required by tree growers for the chips to cover variable cash expenses. Estimated delivered costs are presented in Table 3.2 and 3.3, and more detailed information can be found in Appendix 1. As previously mentioned, cropping practices are assumed to be constant across the regions and variations in delivered cost estimates are the result of variation in expected yields. In response to favorable growing conditions, the lower mainland of British Columbia has the lowest cost by region, followed by central Canada.

Table 3.2. Estimates of the costs of production incurred in SRF willow production.

Canada	Yield Range odMg $ha^{-1}yr^{-1}$	Variable Costs Only (\$ $odMg^{-1}$)	Full Economic Cost[a] (\$ $odMg^{-1}$)
Atlantic Provinces	5 - 10	64-92	78-116
Québec	7 - 12	57-82	69-102
Ontario	7 -12	57-82	69-102
Prairie Provinces	2 - 6	92-106	115-134
British Columbia (lower mainland)	10 - 15	50-64	60-78

[a] excludes land rent

Table 3.3. Estimates of the costs of production incurred in SRF poplar production.

Canada	Merchantable Yield Range odMg $ha^{-1}yr^{-1}$	Variable Costs Only (\$ $odMg^{-1}$)	Full Economic Cost[a] (\$ $odMg^{-1}$)
Atlantic Provinces	*2 – 6*	91-115	127-164
Québec	*2.5 – 7*	82-112	112-160
Ontario	*2.5 –7*	82-112	112-160
Prairie Provinces	*1- 5*	104-120	146-173
British Columbia (lower mainland)	*9 – 12*	62-73	80-97

[a] excludes land rent

Full economic costs estimated in this study include the variable cash expenses previously computed in addition to fixed cash costs (overhead, taxes, interest payments) and the cost of owned resources (producer's own labour, equipment depreciation, and the opportunity cost of capital investments). Typically, farmers place more emphasis on variable cash expenses when making planting decisions since their resource set remains fixed in the short-term. Long-term survival of the farm nonetheless requires that returns from farming activities cover all cash expenses, provide a return for the farmer's labour, as well as allow for capital replacement, land repayment, and a return on the farmers investment.

The gross margin per ha (difference between market returns and variable cash expenses), provides an actual estimate of how much money is available to cover fixed cash costs and cost of farmer's owned resources. In Canada, this value varies substantially and is dependant on land-use, the nature of farming activities (i.e. extensive agricultural cropping in the Prairies versus more intensive farming in the eastern Canada), and farm support programs in place. It is beyond the scope of this study to estimate contribution margins by region and land-use in order to develop delivered cost estimates for hybrid poplar and willow. Rather, in this study, these values are estimated by computing the full economic cost of growing hybrid poplar and willow, as previously described, while excluding any allocation for land opportunity cost. These values can be regarded as estimates of maximum delivered costs that could be encountered in a practical situation. Table 3.2 and 3.3 present these estimates, and further details are found in Appendix 1. As a rule of thumb, full economic cost estimates computed in this study are 24% higher than variable cost estimates for willow and 40% higher for hybrid poplar. The higher biomass productivity of willow reduces the effect of fixed charges on an odMg basis.

3.4 Conclusion

Using estimates from variable costs and the fill economic costs, the delivered cost of hybrid poplar was computed to vary between \$82 and \$160 odMg^{-1} in central Canada, with lower values in the British Columbia lower mainland. Similarly, delivered cost of willow is estimated to vary between \$82 and \$102 odMg^{1} in central Canada, with lower values also in the lower mainland of British Columbia.

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Task 4: Industrial Use and Market Returns

4.1. Introduction

The development of SR tree species is driven by two main factors:

1. the limited amount of natural forest resources available to meet forecast growth increases in traditional solid wood and pulp and paper markets;

2. the need to develop a large supply of biomass to enable bioenergy to capture a significant share of the Canadian energy market.

Fibre applications from SR tree species, mostly with hybrid poplars, are already in progress in some regions of Canada. However, as a result of poor economics, SR tree species grown for the Canadian energy market, are only at a demonstration stage, although internalizing environmental costs associated with fossil fuel use may open a window of opportunity for biomass in the future. Short rotation tree plantations may have a difficult role to play in bioenergy applications, as wood residues and agricultural residues will likely increase in importance in this industry as they represent the lowest cost bioenergy feedstocks. As well dedicated herbaceous feedstocks such as perennial grasses have a lower cost of production per gigajoule (GJ) of energy and can be used for some of the same energy applications (Girouard et al., 1995). Furthermore, the fibre value of SR tree plantations is substantially higher than energy markets. The following section outlines some of the main potential fibre and energy markets for SR tree species, and the potential market price required for these crops to be cost competitive with current feedstocks, without any credit for GHG emissions abatement.

4.2 Electricity Generation

Despite the relative abundance of biomass material (i.e. forest and agricultural residues, peat, municipal solid waste (MSW)), it has been shown to represent less than 1% (approximately 1,000 megawatts (MW)) of the total electricity generation capacity and only 0.5% of electricity production in Canada (Rouleau, 1995). Most of this electricity originates from cogeneration facilities installed in pulp and paper mills. With the exception of wood mill and logging residues, electricity generation from traditional sources has been less expensive in the past. For instance, in 1993, the average resident in Canada was estimated to pay 8.26 cents per kilowatt hour (¢ kWh^{-1}), while electricity generation from biomass sources, other than forestry residues (i.e. peat, MSW, straw and energy crops), was estimated to range between 8.7 and 13.5 ¢ kWh^{-1} for direct fired technology (Rouleau, 1995). Electricity from mill and logging residues was estimated to range between 5.5 and 8.6 ¢ kWh^{-1}.

In general, provinces which can substantially rely on hydro-electrical potential (Québec, Manitoba, British Columbia and Newfoundland) offer a more hostile environment for biomass power than those relying heavily on coal (i.e. Ontario, Saskatchewan, Alberta, New Brunswick and Nova Scotia). It is also in these coal-dependent provinces that biomass could be most effective in reducing carbon emissions resulting from electricity generation. It is beyond the scope of this study to factor in the impact of the deregulation occurring in the North American electricity market for biomass-derived electricity, however this issue certainly requires further investigation.

From a study conducted by Rouleau (1995), the provinces which have been projected to have the greatest potential for biomass power by the year 2010 are Alberta, Ontario, Saskatchewan, New Brunswick, Nova Scotia and Newfoundland. Residential and industrial electricity rates for these provinces in 1993 are presented in Table 4.1. Long-term trend values estimated from time series data from 1982-1993 (Rouleau, 1995) are also presented.

Table 4.1. Electricity rates in several Canadian provinces.

Provinces	**Residential Electricity Rates**[a] **¢ kWh^{-1}**		**Industrial Electricity Rates**[b] **¢ kWh^{-1}**	
	1993	**Estimated Long-Term Trend**	**1993**	**Estimated Long-Term Trend**
Newfoundland	8.64	8.1	5.04	5.7
Nova Scotia	9.58	8.6	5.58	5.5
New Brunswick	7.69	7.5	4.65	4.8
Ontario	10.01	7.2	6.80	5.2
Saskatchewan	8.39	7.2	4.80	5.1
Alberta	7.12	6.3	4.53	3.9
Average	8.57	7.5	5.23	5.0

Adapted from Rouleau (1995).

[a] Residential rates based on monthly consumption of 1,000 kWh

[b] Industrial rates based on monthly consumption of 3,100,000 kWh

As presented in table 4.1, biomass-derived electricity must be produced for a total cost of 6.3 to 8.6 ¢ kWh^{-1} to be considered as being competitive in the residential market. In order to fall into this range, mill and logging residues ranging in price from \$16 to \$35 $odMg^{-1}$, must be employed either in a conventional direct fired technology, or in a currently-developing gasification technology (Table 4.2). Estimates for these technologies are computed for plant sizes of 25 and 50 MW.

Table 4.2. Estimated cost of electricity for various biomass feedstocks and selected biomass cost.

Biomass	Transportation Distance	Cost	Direct Fired Technology		Gasification Technology	
	Km	\$ odMg^{-1}	¢ kWh$^{-1\ b}$		¢ kWh$^{-1\ b}$	
			25 MW	50 MW	25 MW	50 MW
Mill Residues	40	15.79	**5.5**	**6.7**	**6.4**	**6.3**
	100	19.28	**5.9**	**7.0**	**6.7**	**6.5**
Logging Residues[a]	40	31.38	**7.4**	**8.3**	**8.0**	**7.4**
	100	35.21	**7.8**	**8.6**	**8.4**	**7.7**
Peat sods	40	84.92	13.0	12.7	13.0	10.9
	100	89.89	13.5	13.1	13.4	11.3
MSW	40	47.14	10.9	11.0	11.0	9.5
	100	51.47	11.4	11.5	11.4	9.8
Straw	40	39.37	8.7	9.1	8.8	7.8
	100	45.53	9.2	9.8	9.4	8.3
Energy Crops	40	56.38	10.4	10.7	10.5	9.1
	100	60.21	10.9	11.1	10.9	9.4

Adapted form Rouleau (1995).

[a] road side

[b] cost of electricity is set to provide a return equivalent to the weighted average cost of capital employed to finance the project.

Gasification technology, though still at a developmental state, is viewed by many experts as the most promising technology for reducing long-term costs of biomass-derived electricity generation. In an analysis conducted in 1992, the U.S. Department of Energy predicted that further improvements in direct-fired technology may result in only minor cost reductions (less than 10%). However, reductions may be significantly higher, in the order of 25%, for the gasification process (USDOE, 1992). A scenario for gasification technology was developed by Rouleau (1995) where plant capacity was increased to 103 MW, gasifier efficiency to 85%, and capital cost reduced to \$1300 MW^{-1}. In Table 4.2, when plant capacity is either 25 or 50 MW, gasifier efficiency is at 80% and capital cost ranges between \$1,996 and \$2,306 MW^{-1}. The former scenario assumes that energy crop biomass is delivered to the plant for \$48 odMg^{-1}. The resulting cost of electricity produced is 7 ¢ kWh^{-1}, a 25% cost improvement over the 50 MW scenario presented in Table 4.2 (energy crops).

Assuming that logging residues, such as presented in Table 4.2, produce cost competitive electricity in the future, and that improvements in gasification technology warrant the use of biomass priced at \$48 odMg^{-1}, the competitive market price range for biomass produced from SR tree species is estimated to be \$30-\$50 odMg^{-1}.

4.3. Space and Process Heat Energy Applications

In northern Europe, one of the primary markets for wood chips from SR willow plantations is as a fuel source for district heating systems. In Canada, district heating systems are currently not widely available. The best opportunity for using plantation-grown material for space heating would be to grow material for small- to medium-sized biomass combustion installations in rural areas. An example of the potential scale of this opportunity can be observed from Austria's development of this technology, which has 13,000 small- to medium-sized automatic wood chip furnaces (Grubl, 1995).

In Canada, typical medium-sized biomass heating systems are in the 5-15 MW range and are currently burning sawdust or bark from the wood processing industry. The company *KMW* of London, Ontario has been the major player in this market, with approximately 75 wood combustion systems installed and 8-10 new installations each year. Approximately 20 systems have been installed in institutions such as schools and hospitals.

Concerning smaller-scale biomass heating systems, Grovewood heat of Little York, Prince Edward Island, has installed approximately 150 wood chip heating systems in the 75-300 kW range for heating enterprises such as hog farms, fish farms, greenhouses, garages, motels, as well as smaller wood industries. Approximately 15 new combustion systems are being sold each year. The equipment typically consists of a wood chip hopper, combustion and boiler. Two combustion systems are often set up in tandem which allows the operator to run one burner at high capacity during periods of low heat demand such as the spring and fall shoulder heating seasons (*EOMF*, 1994). These types of units are ideal for farmers that could grow their own wood fuel for farm energy purposes. This would help reduce material transport costs to more distant facilities.

Biomass combustion systems must compete with conventional energy sources such as oil, natural gas and electricity. SRF willow plantations for fuel production can easily compete with these energy sources on a fuel cost basis, however, wood fuel burning systems have a higher capital cost and somewhat lower energy conversion efficiencies than those of conventional energy systems. An analysis of fuel costs for residential-delivered conventional energy sources for heating oil, natural gas and electricity was \$9.27, \$7.14 and \$16.61 gigajoule^{-1} (GJ^{-1}) respectively in Quebéc while SR willow was \$3.20 - \$4.82 GJ^{-1} delivered to a plant and \$2.82 - \$4.46 GJ^{-1} when used on site (Girouard et al., 1995). However automated biomass systems typically costs 2-4 times as much as oil burning systems for example, mainly because of the cost of the fuel storage and handling components of biomass systems (McCallum, 1993). These additional capital costs must be amortized by the savings achieved from the lower cost of biomass fuels.

With this market, the main problem for SR plantations is the low cost of wood residues for the heating systems currently available in most regions. For example, in Prince Edward Island, sawdust is sold for \$23 odt^{-1}, while wood chips are selling for \$40-\$52 odt^{-1}, with sawmill chips at the lower end of the range and whole tree chip prices at the upper end of this range (Court, 1999). However wood residue availability concerns are rising and it is reasonable to expect that SR willow plantations used on farms could compete with wood chips. The current cost of production of SR willow wood chips is \$58-\$85 odt^{-1} (Girouard et al., 1998). This cost is reduced to approximately \$49 -\$72 odt^{-1} if used on-site through reduced transportation costs.

Of all the biomass energy applications currently available, the direct combustion of green wood chips for space and process heat in small- to medium-sized commercial heating systems may be the most viable energy entry point for SR willow plantations. The advantages of this end use are the relatively low capital cost of the energy conversion systems and the proximity of the market for the material. The main barriers to this technology are the low cost of fossil fuels and the existing supply of lower cost wood residues. Nonetheless, this could be a promising strategy for GHG abatement in the future as fossil fuel prices increase and wood residue supplies diminish.

4.4. Pellet Fuel

The use of wood fuel pellets for home-heating purposes is slowly gaining in popularity both in North America and Europe. From 1995-96 to 1997-98, sales of bagged fuel pellets increased from 595,000 tonnes to 628,000 tonnes, in North America. Canada is expected to export approximately 100,000 tonnes of bulk pellets to European countries in 1999, which is seen as the main growth area over the next several years. Despite the competitiveness of the North American home fuel heating market, pellet stove sales still managed an 11% increase in sales in 1997-1998 after two years of declining sales (Pellet Fuels Institute, 1998). Wholesale pellet selling prices vary by region. In western Canada, pellet producers report prices of \$110-\$121 (CAN \$165-\$182) t^{-1}, while central and eastern Canadian producers report prices of \$121-\$138 (CAN \$182-\$207) t^{-1} for domestic sales. Prices for bagged pellets are higher in the U.S. with US\$ 110-\$129 (CAN 165-\$194) t^{-1}, US\$ 105-\$116 (CAN \$158-\$174) t^{-1}, and US\$ 99-\$105 (CAN \$149-158) t^{-1} in the northeast, northwest and mid-western U.S., respectively (Pellet Fuels Institute, 1998).

Sawdust and wood shavings are the main feedstocks for pellet production. As residues are becoming less available and more expensive, there is increased concern about the future competitiveness of the pellet fuel industry. Tree bark is seen by many as the upcoming raw material for pellet production, however, the increased ash content of this material causes slag formation in most pellet stoves that are currently on the market. The only pellet stove that can potentially handle bark burning has been recently developed by *Dell-Point Technologies* (Québec) in partnership with Natural Resources Canada. This close-coupled gasification technology pellet stove also has an overall efficiency of 81-87%, which compares favourably to more modest efficiencies of 35-70% attained by most stoves currently on the market (Samson et al., 1999).

In the short- to medium-term, wood pellets produced from SR tree species may likely be used as a substitute to other forest residues for stoves currently installed and incapable of handling higher ash content fuels, such as bark. In the long run, the likely increased use of new technology pellet stoves will improve the role of bark in the market and may limit the potential market value of SR tree species for pellet manufacturing. Bark is a widely available raw material and unless demand for this commodity increases substantially in the future, it will likely remain a fairly low-cost feedstock.

Recent development in pellets manufactured from a potential herbaceous energy crop, namely switchgrass (*Panicum virgatum*), suggests that this feedstock may also play a significant role in the future of the pellet industry. *REAP-Canada*, *Dell-Point Technologies* and Natural Resources Canada are currently optimizing the pellet production process for switchgrass and early results show that pelleting throughput can be increased by two- or three-fold compared with wood residues. In addition, drying of the material is unnecessary, further contributing to a reduction of energy and capital costs over wood residues and bark. Switchgrass is 40% less expensive to grow than SR tree species, such as willow (Girouard et al., 1995). Preliminary research on the pelleting of SRF willow indicates higher throughput rates compared with conventional hardwood materials. This may be a result of the relatively weak fibre properties of these species.

A survey involving U.S. wood pellet producers has indicated that the average cost of wood residues and drying for pellet manufacturing is \$46.29 odMg^{-1} (*Council of Great Lakes Governors*, 1995). Recent discussions with pellet manufacturers have indicated that some pellet manufacturers in the northeast U.S. are presently paying up to \$45 odMg^{-1}, prior to drying costs, to access forest residues. In eastern Canada, pellet manufacturers are apparently paying from \$20 to \$30 for forest residues. Although regional prices vary with supply and demand, a market price of \$30-\$50 odMg^{-1} for SR poplars and willows for sale to the pellet industry is used in this study. This range is thought to be applicable in the future since bark, and potentially switchgrass, will enter that market.

The fuel cost associated with heating a 2,000 square foot (ft^2) home in the Montréal region using wood pellets has been recently estimated (Samson et al., 1999). Table 4.3 indicates that current wood pellets burned in the newly released high efficiency *Dell-Point Technologies* pellet stove can compete, on a fuel cost basis, with electrical heating and heating oil in Québec, at 35 cents per litre (¢ L^{-1}). More details are found in Samson et al. (1999).

Overall, the attractive retail price of wood pellets indicates that this market could be an interesting high-value market for SRF willow. Ash content of SRF willows is about 1% - 1.5%, which is lower than switchgrass or bark.

Table 4.3. Estimated fuel cost of home heating with electricity, wood pellets or oil, in Québec.

	Electricity	Pellets	Heating Oil
Fuel Cost	5.97 ¢ kWh^{-1}	\$180 t^{-1}	35 ¢ L^{-1}
Raw Fuel Cost after taxes 7% GST,7.5% TVQ.	6.87 ¢ kWh^{-1}	\$207 t^{-1}	40.26 ¢ L^{-1}
Cost/GJ	\$19.24	\$10.45	\$10.53
Cost/GJ after conversion (95% electricity, 85% pellets, 85% oil)	\$20.25	\$12.29	\$12.39
Cost to heat a new, detached, 2,000 ft^2 home in Montréal	\$2025	\$1229	\$1239

Source: Samson et al. (1999).

Note 1. Pellets are assumed to have an energy content of 19.8 GJ t^{-1}, electricity 3.6 MJ kWh^{-1} and oil 38.2 MJ L^{-1} (Natural Resources Canada, 1997).

Note 2. The analysis does not include capital costs associated with equipment.

Note 3. Heat requirement of home is 100 GJ (Natural Resources Canada, 1997).

4.5. Cellulosic Ethanol

The production of fuel grade ethanol in North America mostly relies on grain corn as a source of sugar for fermentation. The process of converting corn, or other starch-based materials, into ethanol is a well-proven technology at the commercial level, but requires financial incentives from governments to compete on a cost basis with relatively inexpensive gasoline. Ethanol production nonetheless offers the benefits of diversifying the farm economy and replacing mostly imported fossil fuels. With proper corn cropping practices and state of the art conversion technology, corn ethanol can contribute to reducing greenhouse gas emissions (Wang et al., 1999).

Lignocellulosic materials such as wood and grasses have long been identified as lower cost feedstocks that could be used for ethanol production. Although converting these feedstocks into alcohol has been known to be feasible since the early 19th century, when it was discovered that wood cellulose could be dissolved in concentrated sulfuric acid and converted to sugars (Klass, 1998), large commercial production was never found to be economical, except in war times. Lignocellulosic materials are made of crystalline and amorphous cellulose, amorphous hemicellulose, and lignin binder. The difficulty encountered in maximizing ethanol yields from the cellulose component, and the difficulty of fermenting the sugars from the hemicellulose component, have contributed to non-economical ethanol yields from these feedstocks in the past several decades (Klass, 1998).

Research efforts initiated in the mid-1970's in Canada and the U.S. are nonetheless beginning to show promising signs by the upcoming construction of demonstration plants in several locations across North America. In Canada, *Iogen Corporation* in partnership with *Petro-Canada* and the Canadian government, are planning to begin construction of a 50 odMg day^{-1} capacity lignocellulosic-ethanol demonstration facility. The objective pursued by *Iogen Corporation* during its 25-year research and development program, is to develop a conversion process that is similar in cost to that of grain corn, but using raw materials delivered to conversion facilities for approximately one-third to one-half of the average market price of corn. Fuel grade ethanol could then eventually be produced at a cost-competitive price with gasoline, which is difficult to achieve with corn as the conversion technology has nearly reached full maturity.

Estimating a competitive market price for lignocellulosic feedstock destined to ethanol production is relatively difficult since no commercial operations have yet been constructed. Nonetheless, delivered price in the order of \$30-\$40 odMg^{-1} is often mentioned by *Iogen Corporation* as being in the relevant range. In the U.S., the goal of the U.S. Department of Energy is to achieve fermentation ethanol costs in nominal dollars of about US\$ 0.16 L^{-1} by the year 2020 with lignocellulosic feedstocks. This will require raw materials to be delivered at conversion facilities for approximately US\$ 30 odMg^{-1} (Klass, 1998). In Canadian dollars, the equivalent would be approximately \$45 odMg^{-1}. Based on these values, the competitive market price of SR tree species for the ethanol production market is estimated to vary between \$30-\$45 odMg^{-1}. Potential ethanol production and by-products for different raw materials available in Canada are presented in Table 4.4.

Table 4.4. Ethanol and by-product production from different raw materials		
Feedstock	**Ethanol Production ($L\ odMg^{-1}$)**	**By-Product Available for Sale**
Grain Corn	450[a]	Distilled dried grains: 390 kg $odMg^{-1}$
Wood/Herbaceous Biomass	340[b]	Electricity/Steam from lignin: 1.1 kWh L^{-1}

[a] Dry milling process; commercial production.

[b] Estimated production in commercial operations. Wood feedstocks may produce slightly less ethanol per tonne of raw material than herbaceous crops but greater quantities of by-product electricity/steam.

4.6. Pulp and Paper Production

The forest sector plays a significant role in the Canadian economy as forests cover 45% of Canada's land base. It contributed $20.6 billion to the Canadian Gross Domestic Product (GDP) in 1996, out of a total of $680.9 billion, and employed (directly or indirectly) 1 in 16 people (*Natural Resources Canada*, 1997). Moreover, Canada is the world's largest exporter of forest products. In 1996, forest product exports contributed $32 billion to Canada's balance of trade.

Maintenance of the forest sector's important role in the Canadian economy requires significant adjustments, some of which are already being implemented. For instance, there is general consensus that long-term growth of the sector would involve reduced reliance on the production and export of commodities (i.e. lumber, woodpulp, and newsprint); products that have price as the main determinant of sales. Rather, emphasis should be placed on the development of higher-value added products, such as panels and composite materials, that will generate greater economic activity (GDP, employment, etc.) per volume of harvested wood (*Natural Resources Canada*, 1997).

Similarly, the Canadian Pulp and Paper Sector, which contributed $9.85 billion to the national GDP in 1996, has historically relied on two main export commodities, namely newsprint and woodpulp. Traditional comparative advantages, such as the readily accessible, abundant, economical, high-quality forest resource and the low-cost electrical energy allowing Canada to be competitive in these markets, are presently on the decline (Doering, 1997). Several factors account for this industry's loss of competitiveness on the world market including the adoption of forest conservation policies, the long-term rising cost of wood, and the emergence of new low-cost suppliers of fibre and pulp, mostly from countries in the Southern Hemisphere. These countries enjoy more favourable growing conditions, which contributes to reducing the cost of growing the wood, especially when SR tree species such as eucalyptus are used. Moreover, many of these countries are now capable of providing the necessary socio-economic infrastructure for the pulp and paper industry to develop.

Several strategies are being implemented to ensure the long-term viability of the Canadian pulp and paper industry. One such strategy allows for better control of wood procurement costs, which may represent up to 45% of the pulp production cost (Doering, 1997). Other strategies considered are increased pulp yields, integration of sawmills to secure access to wood chips, and establishment of SR poplar plantations in areas experiencing wood supply shortages. Current hardwood chip prices are reasonably low (*c.* \$80 $odMg^{-1}$) (Robert, 1999) but reached peak levels only three years ago, in early 1996 (\$140 $odMg^{-1}$) (*International Woodfibre Report*, 1997).

The volatility of pulp and paper markets in addition to the confidential nature of wood procurement costs renders our task of establishing an average market price for hybrid poplar chips difficult. Nonetheless, following discussions with industry representatives, a procurement cost range of \$80-\$140 $odMg^{-1}$, with a reference scenario of \$100 $odMg^{-1}$, encompasses most situations, and is used in this study.

Finally, though the present demand for pulp and paper products is increasing rather slowly, it is anticipated that worldwide demand may double within the next 20 years. Similarly, demand for alternative wood chip sources established in close proximity to mills should also increase in Canada, over the same period. Estimates of growth demand in Canada, and by region, are beyond the scope of this study.

4.7. Solid Wood and Related Products

4.7.1. Particle Board, Medium Density Fibre Board and Oriented Strand Board

Poplar can be used to make excellent quality particle board, medium density fibre board, and flake board due to its low density, desirable colour, and suitable gluing characteristics (Geimer and Crist, 1980). Two drawbacks are its high moisture content and its susceptibility to rot (Baldwin and Yan, 1968; Balatinez, 1977). Particle board is a non-structural material that is frequently used for furniture and kitchen cabinets. U.S. and Canadian consumption of various grades of fibre board is approximately 7.5 billion square feet (BSF). (*RISI Wood Products Review*, 1993). Aspen and poplar are viewed as good potential raw materials for expanding this market. Fibre board can be made from sawdust, shavings, and wood chips, though the latter is used to a lessor extent because of higher prices.

Oriented strand board (OSB) is within a class of composition boards that are made from large flakes or wafers using a phenolic binder. It is a versatile product, primarily made from round wood, and competes with exterior plywood in several structural applications such as roof and wall sheathing, and subflooring (Balatinecz, 1977). Poplar grown in plantations for the OSB market requires similar production practices and commands the same price as that for the pulp and paper industry.

4.7.2. Solid Wood Products

Limited research has been directed towards growing hybrid poplar for longer rotations that would make them suitable for solid wood products. However, this market has good potential for development as the supply of high quality timber declines. Lumber demand in North America has leveled off at approximately 55 to 60 billion board feet (BBF). Poplar, cottonwood and aspen represented about 4% of Canada's annual production of 55 million m^3 of lumber in 1992 (*RISI*

Wood Products Review, 1993). There has been recent interest in the use of hybrid poplar for structural lumber. However, it is unlikely that hybrid poplar will become essential for such a market since it can be used in most other applications of the forest products industry, and its reputation has been that it is prone to warping and is relatively weak as construction lumber. Recent forest product laboratory studies in the U.S. have found hybrid poplar to produce visually graded material that is similar in properties and characteristics to current visually graded native aspen and cottonwood (Kretschmann et al., 1999). It has been found that 65% of the sawn material would fall into the visual grades of either standard or better or # 2 and better. To avoid excessive degradation as a result of warping during drying, the material should be dried in the flitch form. It has been suggested that this might render studding material suitable for interior walls (Kretschmann et al., 1999). Poplar is becoming a preferred species for interior trim-work in houses. It is well-received by carpenters as it works well with power nailguns, requires minimum filling and it stains and paints smoothly and rapidly (Becker, 1999).

4.7.3. Engineered Lumber

A growing use of poplar as a solid wood product will most likely be in engineered lumber applications. The growing development of engineered, high-strength wood products is likely to continue to grow as solid wood product prices continue to increase and new advances in research and consumer acceptance of these products grows. Such applications of poplar could have major impacts on replacing other traditional wood species in solid wood product markets. The situation may be similar to what has occurred with OSB substituting for plywood. Long, high-quality logs are becoming scarce and therefore expensive. However, new technologies are allowing the use of lower quality wood, such as poplar, to manufacture structural building materials with sufficient structural strength. These technologies include wood I-beam, laminated veneer lumber, gluam, parallel strand lumber and parallel chord trusses. Such industries are relatively new and on the rise. The demand for long structural material is rising, partly due to a trend for open living spaces in housing requiring 24 to 36 feet trusses. These building materials currently have similar or higher prices than solid wood trusses. However, technological advances as well as a rising price for wood trusses should increase engineered lumber's competitive advantage in the near future. Poplar would be widely used in many applications in this newly-evolving industry.

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Task 5: Economics of Carbon Sequestration

5.1. Introduction

One of the main issues to address when developing policies to mitigate greenhouse gas (GHG) emissions is the relative cost of each policy option that is required to achieve the desired objective. Carbon sequestration estimates in forests may vary substantially depending on biomass growth rates and soil carbon accumulation levels. The end use of the biomass, after harvest, also plays a key role on the total carbon emission mitigation effect, from forests as well as the associated carbon offset cost.

Estimated aboveground, belowground and potential soil organic carbon accumulation levels in SR hybrid poplars and willows are reviewed in Task 1. This section integrates the information in Task 1 with the costs of production and potential market returns for SR willow and poplar, in order to develop cost estimates of sequestering carbon in these plantations.

The main limitation of the analysis is the omission of carbon mitigation arising from the use of the harvested wood biomass. An analysis of the complete cycle is beyond the scope of this study.

5.2. Estimated Carbon Accumulation

5.2.1. Carbon in Aboveground Standing Tree Biomass

Estimated aboveground productivity ranges of each tree species for each region (developed in Task 1) are converted into their carbon productivity equivalent using a carbon to biomass ratio of 45%. Cumulative carbon accumulation as aboveground biomass is presented by harvest cycle (Table 5.1 and 5.2).

Table 5.1. Aboveground carbon accumulation per harvest cycle in willow plantations.

Region	**Average Yield odMg $ha^{-1}yr^{-1}$**	**Cycle 1 Cumulative Carbon Accumulation Mg C ha^{-1}**				**Cycles 2-5 Cumulative Carbon Accumulation Mg C ha^{-1}**			
		Yr 1	**Yr 2**	**Yr 3**	**Yr 4**	**Yr 1**	**Yr 2**	**Yr 3**	**Yr 4**
Atlantic Provinces	5	0.34	1.80	4.05	**6.30**	2.25	4.50	6.75	**9.00**
	10	0.68	3.60	8.10	**12.60**	4.50	9.00	13.50	**18.00**
Québec	7	0.47	2.52	5.67	**8.82**	3.15	6.30	9.45	**12.60**
	12	0.81	4.32	9.72	**15.12**	5.40	10.80	16.20	**21.60**
Ontario	7	0.47	2.52	5.67	**8.82**	3.15	6.30	9.45	**12.60**
	12	0.81	4.32	9.72	**15.12**	5.40	10.80	16.20	**21.60**
Prairie Provinces	2	0.14	0.72	1.62	**2.52**	0.90	1.80	2.70	**3.60**
	6	0.41	2.16	4.86	**7.56**	2.70	5.40	8.10	**10.80**
British	10	0.68	3.60	8.10	**12.60**	4.50	9.00	13.50	**18.00**

Columbia	15	1.01	5.40	12.15	**18.60**	6.75	13.50	20.25	**27.00**

Table 5.2. Aboveground carbon accumulation in a 12-year rotation of hybrid poplar.

Region	**Average Yield odMg ha^{-1} yr^{-1}**	**Cumulative Carbon Accumulation Mg ha^{-1}**											
		Year in Harvest Cycle											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Atlantic Provinces	2	0.14	0.72	1.62	2.52	3.42	4.32	5.22	6.12	7.02	7.92	8.82	**9.72**
	6	0.41	2.16	4.86	7.56	10.26	12.96	15.66	18.36	21.06	23.76	26.46	**29.16**
Québec	2.5	0.17	0.90	2.03	3.16	4.28	5.40	6.53	7.65	8.78	9.90	11.03	**12.15**
	7	0.47	2.52	5.67	8.82	11.97	15.12	18.27	21.42	24.57	27.72	30.87	**34.02**
Ontario	2.5	0.17	0.90	2.03	3.16	4.28	5.40	6.53	7.65	8.78	9.90	11.03	**12.15**
	7	0.47	2.52	5.67	8.82	11.97	15.12	18.27	21.42	24.57	27.72	30.87	**34.02**
Prairie Provinces	1	0.07	0.36	0.81	1.26	1.71	2.16	2.61	3.06	3.51	3.96	4.41	**4.86**
	5	0.34	1.80	4.05	6.30	8.55	10.80	13.05	15.30	17.55	19.80	22.05	**24.30**
British Columbia	10	0.61	3.24	7.29	11.34	15.39	19.44	23.49	27.54	31.59	35.64	36.69	**43.74**
	12	0.81	4.32	9.72	15.12	20.52	25.92	31.32	36.72	42.12	47.52	52.92	**58.32**

Over a 4-year harvest cycle, between 12 - 22 Mg ha^{-1} of carbon can be accumulated in the standing tree biomass of SR willow in most regions, with lower values in the Canadian Prairies and up to 27 Mg ha^{-1} of carbon in British Columbia. To behave as sinks, these trees would have to accumulate more carbon than that from the prior vegetation on the site. However, if forested or abandoned land covered with thick brush is converted to willow, this projected carbon sink may not occur. In the case of agricultural or abandoned land covered by herbaceous vegetation, carbon sequestration may occur at the beginning of year 2 in a harvest cycle. However, there will be no carbon sequestration occurring following the first harvest cycle, since the average aboveground carbon will subsequently stabilize at a new level. Assuming willow is grown in central Canada, on idle land consisting of herbaceous biomass and light brush estimated to accumulate 7 Mg ha^{-1} of carbon in its aboveground standing biomass (Zan, 1998), then willow may initially sequester between 5 and 15 Mg ha^{-1} of carbon in its aboveground biomass. A substantial portion of this sink will be removed after the first harvest, normally after 4 years. Therefore, the main impact of willow aboveground biomass on GHG mitigation should arise from carbon offsets as a result of biofuels displacing fossil fuels.

The relatively longer harvest cycles employed in hybrid poplar production give rise to greater amounts of carbon being accumulated in poplar aboveground biomass than in willow. For most regions, carbon accumulation in standing biomass over a 12-year harvest cycle is in the order of 12-34 Mg ha^{-1}. Longer harvest cycles in hybrid poplar are apt to result in carbon sinks of greater duration than those of willow plantations, this may have important policy implications. If SR poplar is established in central Canada on an idle field consisting mainly of herbaceous vegetation and light brush representing 7 Mg ha^{-1} of carbon in the aboveground biomass, between 2 and 27 Mg ha^{-1} of carbon could be sequestered up to year 12 of the first poplar harvest cycle. Beyond this period, this substantial carbon sink will be removed unless the carbon harvested is retained in long-lasting materials such as those used for construction, or if the biomass is used for biofuel production. This issue is just beginning to be addressed in a systematic way (e.g. Marland et al., 1996).

5.2.2. Carbon in Belowground Biomass

Belowground biomass carbon accumulation within hybrid poplar and willow plantations is largely dependent upon root mass and level of living organisms. Carbon accumulation in roots and stumps of poplar and willow is presented in Task 1. Using these values, an average carbon stock is estimated for both tree species (Table 5.3). Over the 20-year life span of the plantation, willow is estimated to maintain an average belowground carbon stock of 4.03 Mg ha^{-1}. Similarly, over the 12-year life span of a poplar plantation, an average of 4.39 Mg ha^{-1} of carbon will be maintained as a belowground carbon stock. These estimates are based on root biomass levels eventually attaining a steady-state, a rather simplistic assumption that is necessary at present given the poor understanding of root production dynamics in SR tree systems.

Table 5.3. Estimated belowground biomass and corresponding carbon content.

	Biomass	Carbon	Biomass	Carbon	Biomass	Carbon
	odMg ha^{-1}	Mg ha^{-1}	odMg ha^{-1}	Mg ha^{-1}	odMg ha^{-1}	Mg ha^{-1}
Willow	**Year 1-3**		**Year 4-20**		**Weighted Average**	
	3	1.35	10	4.5	8.95	4.03
Poplar	**Year 1-3**		**Year 4-12**		**Weighted Average**	
	3	1.35	12	5.4	9.75	4.39

To constitute a carbon sink, belowground biomass carbon stock levels must be greater than levels present on the site prior to the establishment of the SRF crop. Since belowground carbon levels are relatively low (in the 4 Mg ha^{-1} range), it is assumed that the belowground biomass carbon stock will not be considered as a carbon sink for the remainder of Task 5. Therefore, carbon sequestration resulting from root production is assumed to be incorporated within the soil organic carbon pool.

5.2.3. Soil Organic Carbon Pool

The discussion in Task 1 focussing on potential increases in soil organic carbon levels from the adoption of hybrid poplar and willow plantations emphasizes the need to obtain more soil data in SRF systems, especially under varying field conditions and crop management regimes. The possibility of soil organic carbon losses in the years following the establishment of SR trees has also been highlighted. For the analysis presented in this section, three possible scenarios are investigated: (1) no soil organic carbon accumulation, (2) a carbon accretion rate of 1.5 Mg ha^{-1}yr^{-1} and (3) a carbon accretion rate of 3.0 Mg ha^{-1}yr^{-1}. These totals are assumed to be averages over the life span of the plantations, whereby carbon may be lost in some years and replaced in others. Table 5.4 presents the absolute change in soil organic carbon for hybrid poplar and willow for each scenario.

Table 5.4. Change in soil carbon stock for different rates of soil organic carbon (SOC) accumulation.

	Hybrid Poplar Change in SOC Level over 12 Years Mg ha^{-1}			**Willow Change in SOC Level over 20 Years Mg ha^{-1}**		
Annual Accumulation	0	1.5	3.0	0	1.5	3.0
Total Accumulation	0	18	36	0	30	60

5.3. Cost Estimates of Carbon Sequestration

Estimating the cost of sequestering carbon in hybrid poplar and willow plantations is performed using a number of simplifying assumptions, and aims at providing order of magnitudes of the potential costs. More detailed studies are required to develop specific estimates.

5.3.1. Cost of Sequestering Soil Organic Carbon

5.3.1.1 Scenario 1: Entire Plantation Life Span

An evaluation of the economics of carbon sequestration involves two main features: the amount of carbon sequestered and the costs involved in performing the operation. Scenario 1 uses the estimated cost of growing SR trees along with the soil organic carbon accumulation scenarios presented in Table 5.4, to develop the cost per Mg of CO_2 sequestered. Short rotation trees were assumed to be planted in the spring of 2001, with an expected lifespan of 12 and 20 years for hybrid poplar and willow, respectively[1]. Hybrid poplar is harvested in year 2012 while willow is harvested every four years beginning in year 2004 and ending in year 2020.

The annual cost per ha associated with growing, harvesting, and transporting chips to conversion plants are estimated in Task 3. The present value of these costs, using a 10% discount rate, is estimated for each respective plantation lifespan, and the results are divided by the cumulative soil organic carbon sequestered over the corresponding period. Carbon values are not discounted in this analysis, and all costs are expressed in 1995 dollars, which is the base year used in the *BIOCOST* softwares. Task 3 estimates annual costs of production on both a variable and full economic cost basis. In order to reduce the number of simulations to be performed in Task 5, the cost of production is averaged over the full economic cost and variable cost. For specific values, refer to Appendix 2. Estimated costs of carbon sequestered for Scenario 1 are summarized in Table 5.5. All values are expressed in Mg of CO_2[†].

Table 5.5. Scenario 1 – Estimated cost of soil organic carbon sequestration over SR tree plantation lifespan.

Region	**Expected Annual Harvestable Biomass Yield Range by Region (odMg $ha^{-1}yr^{-1}$)**		**SOC Accumulation Rate**			
			1.5 Mg $ha^{-1}yr^{-1}$		**3.0 Mg $ha^{-1}yr^{-1}$**	
			Harvestable Biomass Yield in a Region			
			Minimum	**Maximum**	**Minimum**	**Maximum**
			Estimated Discounted Cost of Carbon Sequestered (\$ Mg^{-1} CO_2)			
Hybrid Poplars – 12 year lifespan						
Atlantic Provinces	2	6	33	42	17	21
Québec	2.5	7	34	43	17	22
Ontario	2.5	7	34	43	17	22
Prairie Provinces	1	5	31	40	16	20
British Columbia	9	12	49	54	24	27
SR Willows – 20 year lifespan						
Atlantic Provinces	5	10	35	42	18	21
Québec	7	12	38	45	19	22
Ontario	7	12	38	45	19	22
Prairie Provinces	2	6	32	37	16	18
British Columbia	10	15	42	49	21	24

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[1] Site preparation would be performed during the year 2000.

[†] To convert Mg of carbon to Mg of CO_2, multiply carbon values by 44/12.

The cost associated with sequestering carbon in soil is similar for both crops. For example, at a soil organic carbon average annual accumulation rate of 1.5 Mg, hybrid poplar and willow may sequester carbon for \$31-\$54 Mg^{-1} CO_2 and \$32-\$49 Mg^{-1} CO_2, respectively, in Canada. A doubling of soil organic carbon accumulation rate will reduce the cost of carbon sequestered by half (i.e. 16-\$27 Mg^{-1} CO_2 for hybrid poplar; \$16-\$24 Mg^{-1} CO_2 for willow). The main limitation to the approach employed in Scenario 1 is that cost of CO_2 sequestered increases with increases in harvestable yield as a result of higher harvest and transportation costs per hectare.

5.3.1.2 Scenario 2: Commitment Period 2008-2012 Only

The first commitment period under the Kyoto Protocol runs from the year 2008 to 2012. In Scenario 2, the present value of costs incurred over the lifespan of SR hybrid poplar and willow plantations are associated to the soil organic carbon sequestered over the period 2008-2012 to determine the cost of carbon sequestered. In other words, Scenario 2 assumes that the present value of cost is attributed solely to carbon sequestered over the first commitment period, as opposed to over the entire plantations lifespan (i.e. Scenario 1). The results are presented in Table 5.6.

Table 5.6. Scenario 2 – Estimated cost of soil organic carbon sequestration in SR tree plantations over 2008-2012.

Region	Expected Annual Harvestable Biomass Yield Range by Region (od Mg $ha^{-1}yr^{-1}$)		SOC Accumulation Rate			
			1.5 Mg $ha^{-1}yr^{-1}$		3.0 Mg $ha^{-1}yr^{-1}$	
			Harvestable Biomass Yield in a Region			
			Minimum	Maximum	Minimum	Maximum
			Estimated Discounted Cost of Carbon Sequestered (\$ Mg^{-1} CO_2)			
Hybrid Poplars – 12 year lifespan						
Atlantic Provinces	2	6	80	100	40	50
Quebec	2.5	7	82	104	41	52
Ontario	2.5	7	82	104	41	52
Prairie Provinces	1	5	75	96	37	48
British Columbia	9	12	116	131	58	65
SR Willows – 20 year lifespan						
Atlantic Provinces	5	10	142	168	71	84
Quebec	7	12	152	179	76	89
Ontario	7	12	152	179	76	89
Prairie Provinces	2	6	126	147	63	74
British Columbia	10	15	168	194	64	97

Under Scenario 2, the cost associated with soil organic carbon sequestration is much higher than in Scenario 1. For instance, at a soil organic carbon accumulation rate of 1.5 Mg $ha^{-1}yr^{-1}$, carbon sequestration in hybrid poplar and willow will cost between \$75-131 Mg^{-1} CO_2 and \$126-\$194 Mg^{-1} CO_2, respectively.

5.3.2. Cost of Sequestering Carbon in Soil and Aboveground Biomass

5.3.2.1 Scenario 3: Entire Plantation Life Span

The growing of hybrid poplar and willow under short harvest cycles can lead to increases in average annual biomass production compared with natural stands, and can provide faster returns on investment. As discussed previously, however, shorter harvest cycles experienced in these systems can limit the effectiveness of aboveground standing biomass to develop carbon sinks. In Scenario 3, the estimated aboveground carbon sequestration over production from an abandoned field (i.e. 7.0 Mg C ha^{-1} developed in section 5.2.1), is added to the soil organic carbon accumulation scenarios used in Table 5.5. The cost associated with sequestering carbon over the entire lifespan of each respective tree species is then computed using the same present value of costs as in Scenarios 1 and 2. Results are presented in Table 5.7.

Table 5.7. Scenario 3 – Estimated cost of sequestering soil organic carbon and carbon in standing tree biomass over SR tree plantation lifespan.

Region	Expected Annual Harvestable Biomass Yield Range by Region (od Mg ha^{-1}yr^{-1})		SOC Accumulation Rate			
			1.5 Mg ha^{-1}yr^{-1}		3.0 Mg ha^{-1}yr^{-1}	
			Harvestable Biomass Yield in a Region			
			Minimum	Maximum	Minimum	Maximum
			Estimated Discounted Cost of Carbon Sequestered ($ Mg^{-1} CO_2)			
Hybrid Poplars – 12 year lifespan						
Atlantic Provinces	2	6	29	19	15	13
Quebec	2.5	7	27	17	15	12
Ontario	2.5	7	27	17	15	12
Prairie Provinces	1	5	35	20	17	13
British Columbia	9	12	16	14	12	11
SR Willows – 20 year lifespan						
Atlantic Provinces	5	10	33	31	17	18
Quebec	7	12	32	30	17	18
Ontario	7	12	32	30	17	18
Prairie Provinces	2	6	36	33	17	17
British Columbia	10	15	31	29	18	18

When carbon sequestered in the aboveground biomass is included with the carbon sequestered in the soil, costs associated with carbon sequestration are be reduced to \$14-\$35 Mg^{-1} CO_2 and \$26-\$36 Mg^{-1} CO_2 in hybrid poplar and willow, respectively, at a soil organic carbon accretion rate of 1.5 Mg ha^{-1}yr^{-1}. Compared with values developed in Scenario 1, these represent an average reduction in cost of 42% for SR hybrid poplar and a 20% in SR willow.

5.3.2.2 Scenario 4: Commitment Period 2008-2012 Only

Similarly to Scenario 2, Scenario 4 investigates the cost of sequestering carbon over the period of 2008-2012, but with the inclusion of carbon sequestered in aboveground standing biomass. The present costs are similar to those employed in the previous scenarios. For hybrid poplar, the cumulative aboveground biomass carbon stock at the end of 2007 is, in most cases, approximately equal to, or superior to, the benchmark value used to compute aboveground carbon sequestration in this study (i.e. 7.0 Mg ha^{-1} of carbon). Therefore, aboveground carbon accumulated in hybrid poplar from 2008-2012 is assumed to act as a carbon sink. Short rotation willow established in 2001 will complete their second harvest cycle by the end of 2008. By then, average aboveground carbon levels will have stabilized to a new level, indicating no further carbon sink compared with the previous land-use. It is therefore assumed that no carbon sequestration in willow aboveground biomass will occur during the period of 2008-2012.

Table 5.8. Scenario 4 – Estimated cost of soil organic carbon sequestration in SR tree plantations over 2008-2012.

Region	**Expected Annual Harvestable Biomass Yield Range by Region (odMg $ha^{-1}yr^{-1}$)**		**SOC Accumulation Rate**			
			1.5 Mg $ha^{-1}yr^{-1}$		**3.0 Mg $ha^{-1}yr^{-1}$**	
			Harvestable Biomass Yield in a Region			
			Minimum	**Maximum**	**Minimum**	**Maximum**
			Estimated Discounted Cost of Carbon Sequestered (\$ Mg^{-1} CO_2)			
Hybrid Poplars – 12 year lifespan						
Atlantic Provinces	2	6	50	36	31	26
Quebec	2.5	7	47	34	30	25
Ontario	2.5	7	47	34	30	25
Prairie Provinces	1	5	57	38	32	27
British Columbia	9	12	31	28	25	23
SR Willows – 20 year lifespan						
Atlantic Provinces	5	10	---	---	---	---
Quebec	7	12	---	---	---	---
Ontario	7	12	---	---	---	---
Prairie Provinces	2	6	---	---	---	---
British Columbia	10	15	---	---	---	---

Results form Scenario 4 indicate that the cost of carbon sequestration in SR hybrid poplar from the period of 2008-2012 would be \$28-\$57 Mg^{-1} CO_2, for a soil organic accretion rate of 1.5 Mg C $ha^{-1}yr^{-1}$. This represents an average cost reduction of approximately 55% compared to values estimated in Scenario 2.

5.3.3 Scenario 5: Cost of Carbon Sequestration Including Market Revenues for the Biomass Produced

Scenarios 1 to 4 have estimated the cost of carbon sequestration based on the costs of growing hybrid poplar and willow. Provided there is a profitable market for the biomass produced from each of these crops, carbon sequestration could occur concomitantly to the commercial activities, with no real cost associated with carbon sequestration. In the event that private landowners do not engage in SR tree activities as a result of a lack of profitability, monetary credits for carbon sequestered could provide the necessary incentive to landowners. Scenario 5 investigates the effect of two different market prices ($50 and $100 odMg^{-1}) for the biomass produced on the net present value (NPV) of SR tree plantations. In the event that the NPV is negative, incentives are required to engage landowners into SR tree cropping. The value of the incentives required, provided through credits for carbon sequestration, is estimated by dividing the value of the NPV by the cumulative carbon sequestered. In this scenario, carbon sequestration is based on a soil organic carbon accretion rate of 1.5 Mg ha^{-1}yr^{-1} over the lifespan of hybrid poplar and willow plantations.

Table 5.9: Scenario 5 – Effect of Biomass Market Price on the NPV of SR Tree Species Expressed per Mg of Carbon Sequestered

Region	Expected Annual Harvestable Biomass Yield Range by Region (od Mg ha^{-1}yr^{-1})		Biomass Market Price			
			$50 odMg^{-1}		$100 odMg^{-1}	
			Harvestable Biomass Yield in a Region			
			Minimum	Maximum	Minimum	Maximum
			Estimated NPV per Mg Carbon Sequestered ($ Mg^{-1} CO_2)			
Hybrid Poplars – 12 year lifespan						
Atlantic Provinces	2	6	-28	-26	-23	-10
Quebec	2.5	7	-28	-25	-21	-7
Ontario	2.5	7	-28	-25	-21	-7
Prairie Provinces	1	5	-28	-27	-26	-14
British Columbia	9	12	-25	-23	-2	8
SR Willows – 20 year lifespan						
Atlantic Provinces	5	10	-21	-12	-6	17
Quebec	7	12	-17	-9	3	26
Ontario	7	12	-17	-9	3	26
Prairie Provinces	2	6	-26	-19	-20	-1
British Columbia	10	15	-12	-4	17	40

Note: SOC accumulation rate = 1.5 Mg C ha^{-1}yr^{-1}

Negative values presented in Table 5.9 indicate that the present value of revenues generated over the life span of the plantation is not sufficient to cover the present value of the flow of expenses. If SR tree biomass is selling at $50 odMg^{-1} throughout the lifespan of the plantation, soil organic carbon sequestered in hybrid poplar must sell for $23-$28 Mg^{-1} CO_2 to return the NPV to zero. Similarly, soil organic carbon under willow plantations will have to sell for $4-$26 Mg^{-1} CO_2. The short term and more regular revenues in SR willow production improves the NPV of SR willow compared with SR hybrid poplar. If SR tree biomass is selling for $100 odMg^{-1}, carbon may be sequestered in hybrid poplar for $2-$26 Mg^{-1} CO_2, and at no cost in most cases for willow. Unfortunately, a selling price of $100 odMg^{-1} for willow chips does not appear to be realistic, as the crop is currently targeted mostly for energy applications.

5.4. Conclusion

The main objective pursued in Task 5 was to develop estimates of the cost associated with carbon sequestration in hybrid poplar and willow plantations. Most scenarios including a soil organic carbon accretion rate of 1.5 Mg C $ha^{-1}yr^{-1}$ led to estimates between \$14 and \$54 Mg^{-1} of CO_2 sequestered for hybrid poplar and \$4 to \$49 Mg^{-1} CO_2 for willow.

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Task 6: Potential Land Base for Short-Rotation Tree Production in Canada

Potential markets suited for hybrid poplar and willow are briefly reviewed in Task 4 by region, and potential regions best suited for afforestation programs are discussed in Task 7. This section provides information on potential land base availability for afforestation programs.

Although the precise definition of afforestation within the Kyoto Protocol is currently being reviewed, afforestation usually encompasses the establishment of forest vegetation on land that has not previously been forested or has not been forested in a long time (Sedjo et al., 1998). Therefore, within the context of this definition, afforestation programs that qualify under the Kyoto Protocol make particular use of agricultural land.

Soil types most suitable for poplar and willow production generally exhibit moderate to high levels of soil fertility and sufficient soil moisture during the growing season to sustain high tree productivity thus resulting in positive economics. Also, tile drained land in British Columbia and eastern Canada will not be planted to poplars or willows because of problems with the tree crops plugging drains. In the Canadian Land Inventory (CLI) classification system of agricultural land suitability, mineral soils are grouped into seven classes according to their potential to sustain agricultural production (*Environment Canada*, 1976). Classes 1 to 3 are considered capable of sustained annual production of common agricultural crops and therefore usually not considered for SR tree production (e.g. *Threshold Technologies Company*, 1995; Wamsley and Standish, 1996). Conversely, when land is classified as class 7, it is unsuitable for agricultural use. Thus, afforestation programs are typically developed on soils having capability classes 4 to 6 as described below:

- **Class 4:** land having severe limitations restricting crop range or requiring special conservation practices;
- **Class 5:** land having very severe limitations restricting their capability to produce perennial forage crops;
- **Class 6:** land capable of producing only perennial forage crops.

Given the soil fertility requirements of hybrid poplar and willow, economically viable production will mostly occur on soil classes 4 and 5. Experience acquired with poplar production in eastern Ontario suggests that the use of “poor” marginal land is not economically viable. Rather, the rule of thumb now appears to be the use of so-called “good” marginal lands, which probably encompasses land classes 4 and 5 that have sufficient moisture levels and adequate drainage. In a preliminary feasibility study evaluating agroforestry opportunities in Manitoba, *Threshold Technologies Company* (1995) also did not consider soils having soil capability classes 1-3 for hybrid poplar production, and identified classes 4 and 5 as most promising. The land base within these two soil classes was further evaluated to estimate the area that would have been graded higher for agricultural crop production were it not for the presence of excessive soil moisture at some time during the growing season. Although some of this land may be too wet for poplar or aspen production, much of it could provide an environment for near-optimal growth of poplar according to *Threshold Technologies Company* (1995).

It is beyond the scope of this study to develop a soil suitability matrix for poplar and willow production and treat this information with existing GIS technology in order to estimate agricultural land rated as good, fair, and poor for these production systems as well as those areas potentially available given current land use patterns. The approach followed in this study is rather to focus the analysis on areas across Canada rated within soil classes 4 and 5 and develop potential scenarios for their suitability within SR tree production systems.

Land base availability for energy crop production in Canada was estimated by Seecharan (1984) in a working paper prepared for Agriculture Canada. The study was performed for the production of corn, wheat, soybean, kochia and jerusalem artichoke grown for energy production on marginal land, that is, land in soil capability classes 4 to 6. Land base availability estimates for classes 4 and 5 computed in this study are presented in Table 6.1.

Table 6.1. Total and estimated usable area of class 4 and 5 agricultural land for energy crop production by province and CLI class.

	Land Class					
	4		5		Total of Class 4 & 5 Lands	
Province	**Total**	**Usable for energy Crops[a,b]**	**Total**	**Usable for energy Crops[a,b]**	**Total**	**Usable for energy Crops[a,b]**
British Columbia	1,701,678	n/a	6,671,675	n/a	8,373,353	n/a
Alberta	9,279,579	3,478,578	11,093,057	4,208,315	20,372,636	7,686,893
Saskatchewan	3,893,109	1,317,136	8,736,287	4,147,384	12,629,396	5,464,520
Manitoba	2,394,118	383,232	2,323,786	403,666	4,717,904	786,898
Ontario	2,624,648	495,263	1,915,301	310,666	4,539,949	805,929
Québec	2,580,503	1,031,444	1,658,600	517,707	4,239,103	1,549,151
New Brunswick	2,032,089	345,558	1,700,253	158,965	3,732,342	504,523
Nova Scotia	424,410	115,756	82,215	29,908	506,625	145,664
Prince Edward Island	49,776	17,321	76,064	19,943	125,840	37,264
Newfoundland[c]	16,613	n/a	91,517	n/a	108,130	n/a
TOTAL	**24,996,520**	**7,184,288**	**34,348,755**	**9,795,964**	**59,345,275**	**16,980,252**

Adapted from Seecharan (1984)

n/a not available

[a] consists mainly of non-productive woodland, improved pasture, rough grazing and rangeland

[b] energy crops included corn, wheat, soybean, kochia and jerusalem artichoke in the study

[c] includes areas of Newfoundland within a 161 km radius of St. John.

Canada accounts for 25 and 34 million ha of land in classes 4 and 5, respectively (Table 6.1). In further processing these data to restrict the area of each soil class to land use consisting mainly of non-productive woodland, improved pasture, rough grazing and rangeland, Seecharan (1984) estimated that 7.1 million ha of soil capability class 4 and 9.8 million hectares of soil capability class 5 could be available for energy crop production, that is nearly 17 million ha. The subset of this area not only capable of supporting economically viable poplar and willow plantations but actually available, still remains to be defined. However, assuming that 25% to 75% could be potentially used, then 4.25 to 12.75 million ha of land could be afforested in Canada. However much of this marginal land could also be used for production of perennial grasses for fibre and energy markets. Given that farmers tend to prefer the production of herbaceous biomass crops over tree plantations (Campbell et al. 1986), difficulties may be encountered when convincing farmers to tie up their lands for extended periods, given that alternative farming systems may be available.

Data for British Columbia were not available from Seecharan's (1984) study, however a recent study estimated that 1.5 to 4 million ha of the Agricultural Land Reserve could be available for forestry uses. Based on Statistics Canada census data, approximately 940,000 ha of private farmland is potentially available as well (*Nawitka Renewable Resource Consultants Ltd*, 1996). Nonetheless, the area actually suitable for hybrid poplar is likely much smaller, only an additional 10,000 ha was foreseen to be available to be planted in the lower mainland of British Columbia (See Task 7).

In their preliminary feasibility study on agroforestry opportunities in Manitoba*, Threshold Technologies Company* (1995) indicated that as much as 0.4 million ha of class 4 land and another 0.6 million ha of class 5 land may be suitable for hybrid poplar, slightly more than what is estimated in Table 6.1.

In terms of land base availability, Alberta and Saskatchewan would be the most promising areas to establish a substantial afforestation program. Nonetheless, as discussed in Task 1 and later in Task 7, the climatic conditions and soil moisture limitations prevailing in these regions are major concerns. Based on preliminary results from *Threshold Technologies Company* (1995), Manitoba could prove to be a promising region, especially since current wood resources are limiting the future expansion of fibre industries in the region.

Land base availability for afforestation in eastern located programs appears, at first glance, to be more limited, but more favourable growing conditions in the region will improve productivity and very likely the overall cost competitiveness of the plantations. The main deterrent to the economics of tree plantations in Québec and Ontario may be the higher opportunity cost of land targeted for afforestation than in the Prairie and Atlantic regions. Provided afforestation occurs on idle land, there obviously will be no effect, but if afforestation migrates towards higher value land, the more intensive nature of agricultural cropping in the region (higher net returns per ha) may dictate higher opportunity cost to access the land.

In summary, land appears to be available in Canada to develop an afforestation program using short rotation hybrid poplars and willows, possibly in the order of 4.25 to 12.75 million ha. Some of this land base will likely be more suitable for other types of energy crops, such as perennial grasses. These crops are better adapted to regions with low rainfall, soils of low water holding capacity and have a lower cost of production per od Mg of biomass produced (Girouard et al., 1995). Given that the main carbon offset benefits derived from SR tree crops are most likely to be from the displacement of fossil fuel products, it may be warranted to estimate the carbon offset cost incurred with these alternative crops concomitantly to evaluating the benefits of afforestation.

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Task. 7 Afforestation Programs

7.1. Introduction

Experience in growing SR trees within afforestation programs implemented in northern regions of North America has almost exclusively been limited to hybrid poplar. The work demonstrates three common features to be singled out as key components to a successful program:

1. **Perceived Need:** A strong demand for fibre in the area is necessary to encourage plantings, and to have strong market prices. Areas with existing wood deficits or forecast shortages are the best target areas.

2. **Requisite Talent:** It is of primary importance to have a certain amount of experienced scientists and silviculturalists in the region, specializing in fast growing trees and who have developed adept germplasm. Ideally, a fast growing tree breeding program should be in place to provide regionally adapted material for the program.

3. **Suitable Land Base:** A large land base of underutilized agricultural land that is capable of achieving productive growth rates is ideal.

The Canadian and U.S. experiences with fast growing trees are relatively similar. In both countries, industry-led programs have been essential to scaling up plantations.

7.2 Experience in the U.S.

7.2.1. <u>The Pacific Northwest</u>

The largest afforestation program using fast growing poplar or willow occurring to date is the hybrid poplar program of the Pacific Northwest. In 1996, there were 26,900 ha of hybrid poplar in this region (Wright and Tuskan, 1997). Tree plantation locations are approximately equally split between the fertigated east, and the non-irrigated west sites of the Cascade Mountains. Operational field yields have been reported by contractors of the U.S. Department of Energy to be between 11 and 22 odMg $ha^{-1}yr^{-1}$ (Wright and Tuskan, 1997) and managed on 6-9 year rotations.

The program has been successful due to various factors. The region has relatively high fibre prices since much of the fibre is imported into pulp mills within the region (in part due to new environmental restrictions on logging). Moreover, the west side of the mountain range receives abundant rainfall, furthermore, due to a favourable growing season, rotation cycles are relatively rapid compared with other regions. In addition, a research and development consortium was established between industry and university scientists to develop improved plant materials. Breeding programs are now led by individual companies. Drawbacks to the plantation program in the Pacific Northwest are the limited land base and high demand and costs of water for the irrigation on the east side. The program has achieved much success largely due to a strong emphasis placed on tree improvement through germplasm collection and evaluation, as well as plant breeding. Approximately 20-30 operational clones exist in the region, which is 3 to 4 times higher than the average for other regions.

7.2.2 The North Central Region

Minnesota, the most recent region with larger scale hybrid poplar plantings in the U.S., is the state with highest poplar research activity. The main reason for this has been the growing realization of an impending fibre crisis in the region as a result of the ongoing depletion of hardwood resources by the oriented strand board and pulp and paper industries.

Historically, Minnesota has had a strong hybrid poplar research effort with thirty years of research on poplar production, physiology, and breeding, performed by the University of Minnesota and the U.S. Forest Service. The main reason being the strong support it has received from the U.S. Department of Energy. The scale up program consisting of two projects was established primarily in the mid-1990. One project, funded by the U.S. Department of Energy, involved a scale up of an 800 ha area of Alexandria, Minnesota. The second project was the *Oklee Tree Project* established in Northwestern Minnesota. The latter project provides a good example of how to initiate tree planting in a region. The project involved a cooperative effort between the Agricultural Utilization Research Institute (AURI), University of Minnesota-Crookston, Natural Resources Research Institute (NRRI), Minnesota Power (MP) and local, state, as well as federal agencies. The goal was to plant 1,200 ha of poplars within a 50-km radius of Oklee, Minnesota, initiated in the spring of 1995. The project determined the economic feasibility of planting hybrid poplars as an alternative cash crop, and to provide an opportunity for the future development of a biomass energy facility. Trees that were planted on Conservation Reserve Program (CRP) land were eligible to receive: 5-year contract extensions, cost sharing for establishment from an Agricultural Stabilization and Conservation Service (ASCS), US\$ 85 acre^{-1} (CAN\$ 315 ha^{-1}) for establishment from a grant from the Legislative Commission of Minnesota Resources to AURI, and 30-year contracts from MP (which include guaranteed purchase contracts for wood and yearly payments to growers). Planting areas were selected based on number of available acres, suitable soil types and growing conditions, proximity of wood markets, high pressure gas and electric transmission lines, cooperation of local, state and federal agencies, and willingness of growers to consider hybrid poplars as an alternative crop. The program was initiated by letters outlining the plan, sent to all CRP contract holders in the area, and by conducting 3 local information meetings. Interested growers filled out and returned a form permitting access to their sites for measurements of pH, organic matter, slope, drainage, water holding capacity and depth to water table. Each site was rated for suitability of hybrid poplar growth, plantation size, and distance from Oklee. Growers determined when to plant poplars, grown at densities of 1,200-1,700 trees ha^{-1} and on rotations of 10-15 years, using similar cultural practices as in other regions.

To date, some shortcomings experienced include the cottonwood leaf beetle and septoria canker. Breeding efforts have been focussed on developing canker-resistant clones. No solution has yet been developed for the cottonwood leaf beetle. It became a nuisance to the majority of plantings in Minnesota, which were consequently sprayed with insecticide in 1998. Some plantings were sprayed on two occasions.

Commercial interest from the fibre industries now appears to be the driving force of the Minnesota poplar program. There are aspen wood deficit forecasts for the region within the next 20 years and the forest resource in Minnesota has reached its maximum allowable annual cut. The paper company *Champion* has been the industry leader, having announced plans to purchase or lease 6,900 ha for hybrid poplar plantings in the vicinity of its *Sartell* paper mill. Other wood fibre companies in the research and development phase with poplars are *Potlatch*, *Boise Cascade* and *Blandon*. Along with *Champion*, they have formed a research cooperative with the University of Minnesota, the U.S. Forest Service and the U.S. Department of Energy.

A new potential poplar user is the power generation industry. An announcement was made in late 1998 that *Northern State Power* would purchase power for a 25 MW (mega watt) facility to run on closed-loop biomass plantings of hybrid poplar. Several phases will be involved in the project, of which the first phase involves planting hybrid poplar. A Minnesota company, known as *Energy Performance Systems*, will build a whole tree burner to use the plantings. This will require an additional 10,000 ha of hybrid poplar plantings in the region. However, there is concern that the market value for wood for the fibre market will exceed its potential value for energy, and that the hybrid poplar plantings may not be used in an electrical energy end-use market.

7.2.3. Northeast

The main wood species currently undergoing scale up is hybrid willow managed in the form of the Swedish-style twin row system. High-density plantings (15,000 cph) are being managed on a 3-4 year coppice management system. The program is led by the State University of New York in a cooperative effort with U.S. Department of Energy, Electric Power Research Institute, several regional power companies, the cooperative extension agency, as well as other collaborators. The project planted 40 ha of willows in 1998 with four operational clones. Plans for another 80 ha and 125 ha in 1999 and 2000, respectively, are in progress. Farmers are being paid a 5-year land rent similar to existing commercial rents in the region, which range from US$ 25-40 acre^{-1} (CAN$ 93-148 ha^{-1}) Custom operators have been hired to perform the field work. Yields ranging from 5-10 Mg ha^{-1}yr^{-1} are anticipated on the heavy clay soils in northern New York. Maximum yields have attained 9 Mg ha^{-1}yr^{-1} in 1998. No insect or disease problems have been experienced to date.

Over the next 10 years, according to Wright and Tuskan (1997), commercialization of the SRF willow program appears to be a high risk as the only current market interest is from the electrical energy sector, provided production costs can be reduced to CAN$ 33 Mg^{-1}. The future of this afforestation program appears less promising than in other regions in the northern U.S., mainly because of its heavy reliance on the electrical energy industry, preventing a larger scale-up of acreage in New York, as the electrical market appears tenuous (Wright and Tuskan, 1997). This problem has been exacerbated by the recent change in ownership of *NY State Electric and Gas*, which has dropped out of the consortium, and the impending sale of *Niagara Mohawk* (which is focussing on electrical distribution and is accordingly in the process of selling its fossil-based generation capacity). (Fillhart, 1999). Other higher value energy markets, such as small commercial wood chip heating systems, or willow conversion into fuel pellets, may hold more potential for development of the afforestation program.

7.3. Experience in Canada

Currently, there are three important afforestation programs underway in Canada with fast growing trees. The earliest program to evolve was in southern British Columbia in the late 1950's by the *Scott Paper* company. This was followed by a program in eastern Ontario, by *Domtar Inc.* in the 1970's. The most recent interest in poplar plantings has been in northern Alberta, which has been led by *ALPAC*. A smaller afforestation program is also occurring in Québec, but requires more industry support such as that in the other three provinces. Elsewhere in Canada, very little commercial activity is underway.

7.3.1. Ontario

The government of Ontario funded a large research and development program for hybrid poplars in eastern Ontario from the early 1970's to the mid 1990's. The focus of the afforestation program was to establish abandoned and low quality farmland with poplar to supply *Domtar's* Cornwall pulp and paper mill. Currently the program consists of 1,000 ha of privately-leased lands and 1,200-1,500 ha of *Domtar*-owned lands, managed by the Ontario Ministry of Natural Resources. This arrangement is under review where control of all lands will likely be reverted to *Domtar*.

The program peaked in the 1980's, and was one of the leading programs in North America in the development of fast growing hybrid poplars. Much effort was placed into improving poplar silviculture techniques and improving poplar germplasm. The program was led by the fast growing forests group of the Ministry of Natural Resources in Brockville and received plant genetic material development support from the University of Toronto. The afforestation program experienced mixed success: some of the problems encountered included sites with poorly drained soils which proved unsuitable for poplar cultivation, and septoria canker caused mortality on a high number of clones particularly on the drier sites. The typical production scheme that evolved for pulp and paper production was to plant trees in a spacing of 3 m x 3 m (or 2.4 m x 3.6 m which facilitated inter-row cultivation with a larger tractor). Cuttings 25 cm long were hand planted in early spring at a density of 1,100 trees ha^{-1}. Plantations tended to be small as abandoned fields in eastern Ontario are typically 1-3 ha in size, with natural hedgerows between fields, therefore plantation sizes varied between 0.5 ha - 12 ha. The land was leased at \$27-30 $ha^{-1}yr^{-1}$ with an option to renew or opt out after the 12-13 year life-span of the stand.

Domtar has made many changes to the program over the past 5 years to improve poplar performance. Septoria resistant clones have been planted and slow-performing clones have been eliminated. Poplar plantings are being renewed on productive sites with soil conditions suitable for poplar cultivation, which include silty soils and flood plains. Dry sites are being improved for moisture holding capacity through the application of a biosolid stemming from the secondary waste treatment facility. Some coppicing is being conducted on the desirable poplar clones, however, it is generally too costly to thin regularly. During the harvesting process a new flail delimber has been introduced which reduces losses due to limbing, topping and debarking. Current yield estimates on moderately productive sites are in the range of 3.5-4.6 od Mg $ha^{-1}yr^{-1}$ delivered to the mill, or approximately 45-60 od Mg ha^{-1} on a 12-14 year rotation. Sites with natural regeneration (primarily ash, but also oak, maple, butternut and hickory) are not being replanted.

7.3.2. British Columbia

The southern mainland of British Columbia is home to Canada's fastest growing poplar trees. The earliest poplar planting program was initiated by *Scott* paper in the 1950's. The company currently has 2,000 ha of plantings mainly on provincial crown land and company owned land. On agricultural sites, densities of 800-900 stems per hectare are planted and harvested on 15 year rotations. The low density is used to facilitate the production of larger sized trees for ease of handling at their pulp facility. Cuttings of 45 cm length are used to encourage better early growth and to ease weed management problems. No serious pest problems have been experienced. Productivity on former agricultural sites is 6.6-10 od Mg $ha^{-1}yr^{-1}$ of merchantable timber.

However, the major scale up of the crop was then subsequently performed by *MacMillan Bloedel*. Research plantings were initiated by the company in the early 1980's with approximately 80% of the upscaling conducted over the past 4-5 years. The poplar planting program in British Columbia also received some technical support from the British Columbia Ministry of Agriculture. A total of 1,600 ha of plantings have been undertaken by *Macmillan Bloedel*'s subsidiary, *Poplar Farms Inc.*, in British Columbia and a further 2,300 ha on the coastal side of the Cascade Mountains of Washington State. In the U.S., the plantations are managed on a 9-year rotation and in Canada the rotation length is approximately 12 years due to the shorter growing season and less fertile soils. Rotations of 12 years or less qualify for a lowering of the tax status on the land for agricultural purposes. Density of the plantings was initially 1,000-1,200 stems ha^{-1}, however this has subsequently been increased to 1,300 stems ha^{-1}. In Canada merchantable fibre yields of 10-13 od Mg $ha^{-1}yr^{-1}$ are expected. The harvesting process which tops the trees, debranches and debarks, leaves 8-9% of this biomass as residual material on the site. Leases on rented land average approximately \$110 $ha^{-1}yr^{-1}$ (with a range of \$100-\$140). The primary commercial market for the material is a "high brights" paper chip product from *MacMillan Bloedel*'s pulp and paper mills. The afforestation program is currently in a state of flux as *Macmillan Bloedel* has recently divested from the pulp and paper industry, and *Poplar Farms Inc.* was sold along with the paper division to the paper company *Pacifica*. *Poplar Farms Inc.* is currently for sale by the new owners.

The major problem with the British Columbia afforestation program is the limited land base available in Southern British Columbia. No more than 10,000 ha of additional land is foreseen to be available for poplar plantings (Stenersen, 1999; Van Oosten, 1999).

7.3.3 Alberta

The most rapidly developing hybrid poplar program in Canada is occurring in Alberta. The program, led by *ALPAC*, in Boyle, has established 200 ha of operational and research trials since 1993. The company forecasts to plant 20,000-25,000 ha to supply 15%-25% of the 2.5 million m^3 annual supply required for its large single line pulp and paper mill in Boyle. Other forest product industries are also beginning trials. A Western Boreal Aspen cooperative has been formed which includes *ALPAC*, *Weyerhaeuser*, *Ainsworth Lumber*, *Daishowa-Marabini America*, *Slave Lake*, *Miller Western* and *Slocan*. Research on genetic improvement on hybrid poplars is being coordinated by the University of Alberta. Currently, the program is importing improved clone material and examining the possibility of establishing a breeding cooperative. The cooperative plans to evaluate both hybrid poplar and aspen, the latter species has achieved favourable yields of 15 m^3 ha^{-1} yr^{-1} (5 odt $ha^{-1}yr^{-1}$) in Sweden (Thomas 1999).

The major incentive for the development of the *ALPAC* program was the concern about fibre supply. The company forecasts a 25% loss of its land base during the next rotation due to oil and gas claims, land claims and fire. The company expects to average field growth of 12 m^3 $ha^{-1}yr^{-1}$ (4 Mg $ha^{-1}yr^{-1}$) over a 20-30 year life-span. The yield estimates are somewhat speculative as very limited field experience with hybrid poplars has occurred in this short growing season area with moderate rainfall. Planting of approximately 1,000-1,400 $ha^{-1}yr^{-1}$ are planned to take place in a 200-250 km radius of the Boyle pulp mill. Contracts will be carried out on a lease arrangement with local landowners or a potential joint venture agreement.

The company believes that plantations can help them control fibre costs for their mills in the future. *ALPAC's* current cost of fibre is \$30-35 m^{-3}, with an average cycle time (the time to bring wood to the mill and make the return run) of 9-10 hours with runs up to 15 hours. The wood price is expected to climb to \$41-45 m^{-3} over the next 20 years and plantation wood is expected to be below the lower range of this value and have cycle times of less than 5 hours.

7.4 Conclusion

Revisiting the three features required for successful plantings (perceived need, requisite talent, and suitable land base), none of the current Canadian regions are able to combine the level of suitability as that of the North Central region of the U.S.. British Columbia has a strong fibre demand, sufficient requisite talent (with support from the Pacific Northwest), however it lacks an adequate land base. Unquestionably, Alberta has a strong fibre demand, is building its human resource and genetic base, but is far from certain that relatively slow growing trees on 20-30 year rotations will prove to be a profitable venture. Eastern Ontario lacks a strong market demand due to the current surplus of hardwood fibre. It has a good land base availability, human resources available, as well as an existing germplasm base for scaling up, should a larger program be initiated. While Québec has no major afforestation program currently underway, it may present the best opportunity for SRF programs in Canada, at present. There is a stronger market demand than in Ontario, human resources and genetic material for developing the industry are present, and a relatively suitable agricultural land base is available. Market demand and land availability in Nova Scotia and Manitoba could also create opportunities for poplar plantings but there has been little previous experience with the crop in these regions. Finally, an analysis should be performed to assess the cost of fibre production in Canada versus fast growing trees in tropical countries to determine the viability of investing in plantations.

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General Conclusion

The emphasis of this analysis was on the carbon sequestering potential of fast growing trees. In particular, to summarize the knowledge in areas where little previous information is available. The analysis attempted to develop realistic estimates of fast growing forest species' growth potential in Canada, based on literature searches of existing published commercial and field plot data, as well as discussions with industry people, foresters and scientists. As well, a complete analysis of root biomass accumulation and impact of fast growing trees on soil carbon accumulation in temperate SR tree plantations was provided. An overview was also provided of the current status of the technology of fast growing trees, environmental issues and current afforestation programs. An assessment of the energy and fibre market opportunities was also undertaken. However, a thorough overview of these opportunities was not within the scope of the study. More emphasis was placed on the energy aspects of the material, not because this is where the greater commercial market opportunities are at present, but because this is where the greatest greenhouse gas abatement potential exists.

Overall, the study indicated that the least risky strategy to rapidly implement afforestation programs, for carbon sequestration in Canada, involved the production of SR hybrid poplars for fibre applications. Commercial risk with poplars is reduced compared to SR willow plantations, as SR poplars are already grown for fibre in North America and competitive market prices for the chips is approximately twice that for energy applications. This can be achieved, while at the same time incurring costs of carbon sequestration similar to those of willows. The main limitation of the study is that the carbon offset occurring over the complete life-cycle of the biomass produced from hybrid poplar and willow is not estimated. Willows are less expensive to grow than hybrid poplars, and from that standpoint, are closer to commercialization for energy applications. Since the greatest carbon offset benefit from SR tree species may be from fossil fuel displaced in the case of bioenergy production, life-cycle analysis should be performed for willow directed towards wood chip and wood pellet heating systems.