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Canadian Biomass Reserves for Biorefining

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Abstract

A lignocellulosic-based biorefining strategy may be supported by biomass reserves, created initially with residues from wood product processing or agriculture. Biomass reserves might be expanded using innovative management techniques that reduce vulnerability of feedstock in the forest products or agricultural supply chain. Forest-harvest residue removal, disturbance isolation, and precommercial thinnings might produce 20–33 × 10^6 mt/yr of feedstock for Canadian biorefineries. Energy plantations on marginal Canadian farmland might produce another 9–20 mt. Biomass reserves should be used to support first-generation biorefining installations for bioethanol production, development of which will lead to the creation of future high-value coproducts. Suggestions for Canadian policy reform to support biomass reserves are provided.

Index Entries: Biorefining; lignocellulosic biomass; forestry; agriculture; energy plantations; policy reform.

Introduction

Biomass reserves may be created to supply inexpensive and secure feedstocks to the biorefinery, allowing the substitution of renewable biomass for fossil petroleum in the production of energy, fuels, and chemical or material products. In the literature, the term "biomass reserve" is applied to natural biomass accumulations in both terrestrial and marine ecosystems *(1,2)*, and to human-designated zones used in the management of terrestrial and marine biomass resources *(3)*. The latter type of reserve may be created using policy instruments, and is often associated with resource protection. A good example of a legislated biomass reserve is the farmland under the Conservation Reserve Program in the United States, a voluntary program designed to encourage land-owners for farming land that is prone to erosion or that represents rare or declining habitat.

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Although biomass reserves for biorefining operations have not been discussed specifically in the literature, the concept of reserves dedicated to supplying energy needs has been referred to by a number of authors. There are two distinct approaches to creating these reserves. Some articles refer to an area-based approach in which dedicated crops or trees are grown on a landbase that is unsuitable for traditional agriculture or forestry *(3–8)*. Other authors *(9–11)* have considered a volume-based approach in which agricultural (herbaceous) and forest (woody) residues are recovered from existing operations—in practice, an intensification of current activities. These approaches may be considered as complimentary, as each serves a valuable role in supplying biomass and thereby increasing energy independence and national security. The choice of approach will be largely determined by resource availability, moreover, it is also controlled by desired energy-substitution levels, which vary nation-wise, and is a matter of policy.

There is some consensus that initial biomass-for-energy reserves will be volume-based and will take advantage of residue availability *(5,10,12)*, whereas future reserves might use either area- or volume-based approaches, or a combination of the two. In countries that have large populations, large amounts of biomass are required to affect significant levels of energy substitution, and area-based approaches are favored. Studies in the United States and Europe have concentrated on identifying agricultural land that might be dedicated to energy production *(4,5)*. A recent study by the International Institute for Applied Systems Analysis (IIASA) examining 22 nations in Eastern Europe and North-Central Asia has identified 33.8×10^6 ha of land that might be used for energy crops or plantations, supplying approx 12% of total per capita energy demand *(8)*. Conservative estimates for the United States indicate that *(15–17)* $\times 10^6$ ha of marginal farmland might be used for energy crop purposes *(7)*, potentially replacing a large portion of transportation fuel demand *(5)*. In part, the area-based approach is dictated in these countries by the assumption that a large portion of energy demand might be met with biomass-based energy.

An area-based approach for the United States exploits the fact that growing seasons and agricultural advances favor short-rotation crops in many of the US states, and recognizes that converting existing forest land to energy crop production has a negative environmental impact *(13)*. It also takes advantage of the available marginal land. Significant areas of such land are registered in the Conservation Reserve Program, which controls approx 14.6×10^6 ha for the purpose of watershed and habitat protection. Other federal programs may contribute up to 10×10^6 ha of additional farmland depending on the year *(5)*. Using these lands for energy crops or plantations may have additional benefits for the United States, in addition to increased energy security. It has been predicted that switchgrass crops for energy has the potential to provide higher profits than conventional crops on 16.9×10^6 ha *(14)*. In addition, Murray and Best *(6)* showed that a switchgrass biomass program in the West America could create new habitat for grassland birds.

Few articles have explored biomass reserve strategies for Canada, where a lower population, lower total energy demands, shorter growing season, and an abundance of natural forest resources dictate a different approach. In Canada, a biomass reserve strategy will likely include elements of the area- and volume-based approaches, and might include short-rotation bioenergy plantations as well as forest residues. A strategy with similar elements is defined by Van Belle et al. as a three-tier system involving small, medium, and large-scale logging operations working within softwood and hardwood forests *(11)*.

It is not proposed that biomass reserves be created to meet Canada's total energy, fuel, or material demand. Rather, this strategy is suggested as a means of overcoming barriers to developing bio-based processes and products. Fischer et al. *(8)* identified two such barriers including the low cost of competing fossil energy sources and the high cost of land suitable for high-yield production of biomass. In order to address these barriers in the long term, the biorefining strategy must focus on creating value-added products in addition to energy or fuels. This article postulates that biomass reserves could be used to support the first generation of biorefineries, allowing for continued research and development at the demonstration and commercial scales into these types of products. Using biomass reserves, biomass-to-energy capacity may be developed in advance of energy demand, with the assumption that fossil-based energy will continue to rise in cost. A biomass reserve strategy will not necessarily going to reduce the cost of biomass under current market value, but it will serve to guarantee long-term access to the resource, a necessary step in securing funding and investor support. Development of a product mix with higher value will eventually ensure greater access to biomass resources in the longer term.

Biorefineries

Biorefineries can offer many environmental, economic, and security-related benefits to global society, and particularly to Canada. For instance, energy, fuels, and chemicals made from renewable biomass are characterized by reduced carbon dioxide emissions when compared with petroleum use, and thus can play a role in meeting the challenges of climate change *(15,16)*. Canada can use biorefinery products in order to fulfill national obligations under the Kyoto Protocol, an agreement scheduled to come into force in February 2005 after Russia formally ratified the pact on November 18, 2004. The processing facilities required to convert biomass into value-added products create direct and indirect jobs, provide regional economic development, and can increase farm and forestry incomes, particularly in rural areas *(17,18)*. In some cases, substituting sustainable biomass for fossil resources may serve to increase the security of energy, fuel, and chemical supplies *(19)*. With this technology, a biomass-rich nation such as Canada might be able to reduce its reliance on foreign-owned oil supplies, which are subject to political uncertainty and conflict epitomized by the current conflict in Iraq. The argument for developing renewable substitutes for petroleum products is particularly compelling as current reserves of fossil oil are being consumed at an increasing rate, whereas the discovery of new reserves is in decline *(20)*.

There are several available technological approaches or platforms that may be applied in a biorefinery in order to separate different products from the biomass feedstock. In this paper, the bioconversion platform is considered. This platform differs from others such as pyrolysis or gasification in that it is designed to recover intermediate products from biomass. Instead of thermal degradation, bioconversion uses acid or enzymatic hydrolysis to release complex chemical compounds, such as sugars, which are contained in many sources of biomass. Existing biorefining operations built on the bioconversion platform utilize agricultural crops and food processing residues that have high starch contents and are relatively homogenous in composition *(21)*. Starch is ideal for bioconversion because it comprises a single sugar (glucose), which simplifies process design and complexity *(22)*. Examples of existing operations include the Archer Daniels Midland facility in Decatur, Illinois, which utilizes corn grain and fiber removed during the processing of corn.

The bioconversion platform may also be applied to inedible biological materials, including the structural components of agricultural (herbaceous) and forest (woody) biomass. These structural components are largely composed of lignocellulosic materials, a matrix that blends α-cellulose, hemicellulose, and lignin *(23,24)*. Implementing a biorefining system utilizing lignocellulosic feedstocks is more challenging than processing starch-based materials, as it requires a separation of carbohydrates from aromatic compounds and the subsequent hydrolysis of a range of carbohydrates, including glucose, galactose, mannose, xylose, and arabinose *(22,24)*. This means that lignocellulosic-based bioconversion is more difficult and therefore more expensive than starch-based operations. The bioconversion process has evolved to include several stages that can separate and recover the various structural and chemical components of lignocellulosic biomass, including fiber, carbohydrates, and aromatic compounds from the lignin and extractives. This creates the potential for additional chemical outputs that can serve as coproducts from the biorefinery. Several new facilities, each utilizing variations on the lignocellulosic-based bioconversion platform, are currently in existence or are under development, indicating that this process is approaching commercialization. These facilities include the Etek Etanolteknik pilot facility in Sweden, the Abengoa demonstration plant in Spain, and the Iogen demonstration plant in Canada.

Current Lignocellulosic Biomass Availability in Canada

Initial lignocellulosic biomass reserves should be created using biomass that is easy to access and relatively centralized. The most likely immediate feedstocks for bioconversion operations in Canada are residues from wood product processing facilities, and from agricultural harvesting operations. Wood product residues have the advantage of being collected at the mill site, whereas agricultural residues are readily accessible through existing permanent road networks. In 2003, approx 86×10^6 m^3 of chips and particles were generated in Canadian primary wood product processing, but 78×10^6 m^3 of this material was subsequently used in the manufacture of secondary wood products, such as pulp and paper *(25–29)*. Only 8×10^6 m^3, or approx 4–5 × 10^6 mt, could be considered surplus for biorefinery operations, given average wood densities for Canadian tree species *(30)*. Furthermore, this surplus of material has been shown to be rapidly diminishing. A recent report by McCloy *(31)* indicates that new ventures, such as wood pelletization for energy generation, will have claimed approx 1 mt/yr of this material in British Columbia alone by 2005.

Lignocellulosic residues from agricultural harvesting operations include wheat straw and corn stover. Statistics indicate that approx 37 mt of residues from cereal and oilseed crops were produced in Canada in 2003, much of which is left on the field *(27,32)*. Given that a portion of this material must be set aside for soil conservation and nutrient recovery, estimates of surplus lignocellulosic residues for Canada range from 5.3 to 14.1 mt/yr *(26,33–35)*. To use this material, the biorefining industry must be willing to pay for the retrieval and transport of this material.

The data indicate that 9–19 mt of lignocellulosic material might be easily accessible in Canada. By comparison, the US starch-based ethanol industry processes approx 25 mt/yr of corn. It is clear that for the Canadian biorefining industry to compete in the global marketplace, additional sources of lignocellulosic biomass must be considered, and ways in which costs might be reduced must be considered. A means of creating new sources of inexpensive biomass could be innovative management strategies that harvest lignocellulosic material that is inappropriate for existing forestry or agricultural operations. It is theoretized that these strategies may be applied in order to reduce the impact of disturbances, including insects, disease, fire, and drought, on total biomass supply, which could entail savings (in terms of avoided expenditures) to both sectors of the economy.

Insects, Disease, and Fire

Disturbances including insects, disease, and fire can reduce biomass production in both agricultural and forest operations. These disturbances often occur in a linked progression, with insects infesting a field or stand of wood and introducing disease, leading to mortality in standing timber which then dries and becomes highly flammable. In agricultural systems, diseases carried by insect hosts are estimated to cause up to 20% of the world's crop failures *(36)*.

In North America, a number of preventative measures, including insect control and the development of disease-resistant crops, has a limited the impact of insects and disease on crop production. However, insects and fire have been identified as the primary modes of disturbance within North American forest ecosystems *(37)*. In any given forest stand, the combination of species composition, local climate, and management practices will determine the frequency of individual insect or fire outbreaks. In some ecosystems, such as the interior forests of British Columbia, bark beetle outbreaks may be seen as often as every 5 yr, and may persist from 2 to 4 yr *(38)*. In the western United States, western spruce budworm outbreaks occurred every 20–33 yr and lasted approx 11 yr *(39)*. The longest outbreaks coincide with dryer ecosystems and periods of drought *(38)*. In a sedimentary record in Western Canada, peak fire events were found to occur 1–3 times per century, with extreme fires occurring approximately every 200 yr *(40)*.

The impacts of insects, disease, and fire can be significant, but insects tend to prove the most damaging to timber stocks. In 1952, approx 8.6×10^9 board feet of timber was estimated to be lost per year to insects in the United States, along with 4.3×10^9 board feet lost to disease, and 1.2×10^9 board feet lost to fire *(41)*. In four beetle outbreaks in western Oregon and Washington, occurring between 1950 and 1969, 7.4×10^9 board feet of timber were killed *(38)*. In Canada, the worst insect outbreak in modern times is the ongoing mountain-pine-beetle outbreak centered in British Columbia. This disturbance has been underway since 1994, and has claimed 173.5×10^6 m^3 of timber cumulatively, affecting 65.8×10^6 m^3 (4×10^6 ha) in 2003 alone *(25,42)*. By comparison, approx 482,000 ha of timberland has been damaged or destroyed by fire in British Columbia over the same timeframe *(43)*. The cost of the mountain-pine-beetle epidemic to date is approx \$18 $\times 10^9$ in lost revenue from forest products, whereas the cost of fighting forest fires over the same period is approx \$1.1 $\times 10^9$, as well as the loss of potential products from the damaged or destroyed timber resource *(42,43)*.

Climate change may play a role in increasing the frequency and range of insect outbreaks and fire in the forest. The frequency and severity of extreme weather events is likely to increase owing to global warming *(44,45)*. Climate change is also expected to lengthen the forest-fire season parts of Canada owing to longer growing seasons and increased summer temperatures. The link between climate change and insect outbreaks is less certain. The synchrony between host species and insect pest will likely be altered, particularly in the spring and autumn. The predicted temperature rise should generally, but not always, favor insect growth and reduce winter mortality. Recent outbreaks of budworm in the American west may be related to climate change, although they may also be related to changes in forest structure owing to increased silvicultural management *(39)*. Deforested areas and highly stocked, second-growth forests have been shown to be more flammable than primary growth forests *(44)*. The trends for most of these disturbances seem to be increasing, and it is likely that in the future, more forest biomass will be lost to natural disturbances such as fire, storms, and insect outbreaks *(46)*.

Drought

Biomass production is highly dependent on water availability, and even short droughts have the potential to cause significant interruptions in feedstock supply to the biorefinery. Agricultural operations are particularly sensitive to drought, and can be affected by relatively short disturbances that occur over weeks or months in the growing season. Long-term drought may also increase mortality in forests, as well as increasing the risk of other disturbances including insect outbreaks and fire within forest ecosystems. By studying tree rings, freshwater and marine sediments, and ice-core records, the cyclical nature of drought in North America has been well documented *(40,47,48)*. These environmental records show that drought and other climatic phenomena recur on a regular basis, and it is reasonable to expect that they will affect biomass supply in the future.

The frequency of drought varies with location. The central Plains/Prairie region of the North American continent, including the southern reaches of Alberta, Saskatchewan, and Manitoba, are relatively prone to periods of aridity *(47)*. In two independent studies carried out in New Mexico and in the foothill region of Alberta, respectively, tree ring analysis indicates that less than average rainfall occurred about half the time between 1700 and 2000 *(48,49)*. These analyses further reveal that significant, extended drought periods may recur about once every half-century, and that these disturbances may last for over a decade. Some periods of drought have been especially severe; for instance, the Grissino-Mayer data indicate that a catastrophic, 50-yr drought was experienced in early 1700s, and Cook et al. *(50)* reported a period of aridity that extended from 900 to 1300. In other regions of North America, drought cycles occur at a lower frequency. In the interior forests of British Columbia, lake sediment analyses indicate that two significant droughts have occurred since 1700, each lasting for extended periods of 10–20 yr *(40)*. Data show that a new drought cycle has begun in the western regions of Canada and the United States *(40,50)*.

In agricultural systems, even a short drought may tremendously reduce the productivity of crops. During one extended drought event in 1950s, it is estimated that total production of corn in South Dakota was diminished by up to 60%/yr *(47)*. In 2003, severe droughts in Europe reduced wheat production by 10% and corn production by 20% under 2002 figures *(51)*. In a drought year, the agricultural economy of the Canadian

Prairies may lose millions or billions of dollars *(52)*. In 2002 alone, ongoing drought conditions in the Prairies was estimated to have cost the regional economy $\$2.774 \times 10^9$, on approx 23×10^6 ha of land *(53)*.

Tree species tend to be more resilient to drought than herbaceous crops, although droughts can reduce forest productivity, and over longer periods increase the risk of other disturbances. In British Columbia, interior forests experienced exceptionally hot and dry summers between 2001 and 2004 *(54)*. As a result, lake levels in this region were the lowest since records were set in 1920s *(55)*. Elevated temperatures during this dry period increased evaporation from lakes and transpiration from forests and soils, which further reduced the water table. The extreme aridity across the province created forest-fire threats, raised concerns about drinking water quality, and adversely affected fisheries *(56)*.

Although historical drought is characterized by cyclical, repeating events, future patterns may not be so easy to predict. A rise in greenhouse gases within the atmosphere owing to industrial activities will likely exacerbate the severity and duration of drought events. In the Great Plains region of the United States, for instance, models suggest that doubling the concentration of CO_2 in the atmosphere will result in a marked increase in the occurrence of extreme droughts *(57)*. Thus, prudent policy for biomass generation should promote systems that are highly resistant to this phenomenon.

Innovative Management Strategies for Forest Ecosystems

Some management strategies proposed to reduce forest ecosystem vulnerability to insects, disease, and fire disturbances involve biomass removal *(58,59)*. These strategies are volume-based, and involve reducing and controlling stand densities, effectively reducing their vulnerability to disturbance by limiting habitat for insects or fuel loading for fire.

One strategy is to remove biomass from the growing stand via commercial or precommercial thinning activities. Precommercial thinnings are ideal for the biorefining strategy, as this removes stems that are of little value to the forest product industry. High-intensity thinning treatments, leaving relatively few stems per hectare, have been shown to be most effective in reducing the vulnerability of stands to mountain-pine-beetle infestations and fire *(58,60,61)*, and provide a range of ancillary benefits to the mature stand. In a British Columbia study examining paper birch (*Betula papyrifera* Marsh.), high-intensity precommercial thinnings in 5-yr-old stands were shown to reduce mortality in young stands and to significantly increase the size of remaining trees on the site as they matured *(62)*. Even low-intensity thinning treatments may lead to reduced fire risk, and provide maximum stand volumes in mature stands when compared with high-intensity treatments.

One disadvantage to the precommercial thinning strategy is that it entails additional harvest and transportation costs. Precommercial thinnings at any intensity yield relatively little material per hectare, which means that these costs are relatively high. In the study by Simard et al. (62), yields from precommercial thinnings varied from 8.5 to 13.3 m^3/ha (approx 2.7–4.3 t/ha, given average wood specific gravities of approx 0.325). Therefore, if 100,000 ha were thinned in Canada on an yearly basis, approx 0.3–0.4 mt of lignocellulosic biomass could be realized. The relatively low returns on a per-hectare basis means that this option may only be of interest in areas where disturbances may cause additional economic hardship, such as in forest-urban interface zones where residential housing exists. Dellasala (58) provided a conceptual framework that might be utilized to prioritize precommercial thinning treatments in the forest-urban interface zone, rather than in wild areas.

A second approach to reducing vulnerability in forest ecosystems is the removal of logging slash. Models indicate that slash reduction reduces the risk of fire and insect outbreaks (60). An advantage to utilizing slash is that the equipment is already present and the material is already harvested, meaning that the only additional costs are transportation to the processing facility. In 2003, approx 186×10^6 m^3 of forest biomass, in the form of industrial roundwood (approx 130×10^6 mt), was harvested in Canada (28,29). Forest-harvesting operations generally leave behind variable amounts of lignocellulosic residue, depending on forest type, stand composition, and site characteristics (63). Residue-generation rates range from 15% to 25% of the total above-ground forest harvest (10,64). Based on the typical residue-generation rates, it can be assumed that Canada generates 19.5–32.5 mmt of lignocellulosic residues on an yearly basis.

Total removal of forest-harvest residues may trigger erosion and nutrient deficiencies, which will increase the long-term cost of harvests and the difficulty associated with forest regeneration (65–67). The amount of forest residue that may be safely recovered for the biorefinery will thus be less than the total biomass available. Few studies are available that describe the impacts of forest-residue recovery on site characteristics, but two studies carried out within the Canadian boreal forest indicate that high levels of removal may be possible, within the boreal setting. One study by Brais et al. (68) suggested that slash removal alone has little impact on soil nitrogen, although the authors speculate that long-term use of harvesting techniques which increase slash removal may adversely reduce nitrogen levels. Similarly, decreased slash removal associated with whole-tree harvests was found to have little impact on the regeneration of black spruce (*Picea mariana* [Mill.] BSP) (69). On sites prone to erosion, safe residue recovery may be reduced or curtailed.

These strategies would have little impact on existing biomass supplies to forest operations, but have the potential to reduce forestry losses during periods of high insect and fire risk. The decade-long mountain-pine-beetle disturbance in British Columbia had cost approx $\$18 \times 10^9$ in lost revenue from forest products, and fire management had cost an additional $\$1.1 \times 10^9$ over the same period. This means that, if innovative management techniques had reduced the occurrence of these disturbances by 10%, up to $19 $\times 10^7$/yr could have been saved in British Columbia alone.

Innovative Management Strategies for Agricultural Systems

In Canada, farming operations have become increasingly concentrated on the most productive soil types over the past 50 yr, with a corresponding decline in use of less productive areas. This has led to a decline in the total amount of farmland in use in Canada from approx 70 $\times 10^6$ ha in 1951 to 67 $\times 10^6$ ha in 1991 *(70)*, with the greatest areas of marginal land being freed in Ontario, Quebec, New Brunswick, and Nova Scotia *(71)*. Of the remaining arable farmland, approx 25 $\times 10^6$ ha is considered to be only marginally viable with severe restrictions on its use, under the Canadian Land Inventory *(70,71)*. The location of a significant proportion of this marginal farmland corresponds to the "dry belt" region of the Palliser triangle—a part of Alberta and Saskatchewan, known to be subject to relatively frequent and extended drought activity *(72)*. If 10% of the most vulnerable farmland in the Prairies, or approx 2.3 $\times 10^6$ ha, was removed from agricultural service and turned over to energy plantations, it may be estimated that at least $277 $\times 10^6$ in losses might be avoided during a drought year *(53)*. Innovative management strategies might provide incentives to replace marginal farmland in drought-prone areas with forest cover that is more drought resistant.

On marginal farmland, alternatives to herbaceous crops might be considered. With much longer periods of growth, trees may weather short droughts with less resulting impact on total biomass accumulation. Some tree species are naturally more drought tolerant than others, including species of pine as well as rocky mountain or interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) *(73,74)*. Other species may be modified to be more drought resistant, including loblolly pine (*Pinus taeda* L.) and specific genotypes of hybrid poplar (*Populus spp.*) *(75)*. Simulation models have shown that adaptive forest management strategies that utilize drought-tolerant tree species may mitigate the impact of drought on biomass production *(76)*.

The potential of agroforestry plantations on marginal farmland to contribute biomass to the biorefinery strategy is difficult to estimate, as growth rates will change depending on year-to-year conditions, species considered, and initial soil conditions. Relatively conservative yield estimates for fast-growing hybrid poplar in Canada range from 10 to 12 m^3/ha/yr, given 20-yr rotations. More ambitious models suggest that yields of up to 20 m^3/ha/yr might be possible in the same rotation *(77)*. Given average wood densities for poplar, this translates approximately to yields ranging from 3 to 6.5 mt/ha/yr *(30)*. If the 3 $\times 10^6$ ha already removed from active farming in eastern Canada were combined with 10% of vulnerable Prairie farmland,

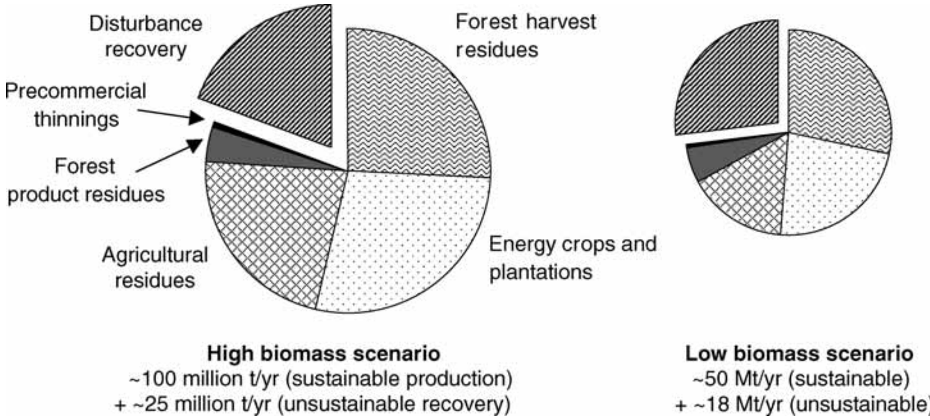

Fig. 1. Two scenarios of lignocellulosic biomass residue availability in Canada.

5.3×10^6 ha could be completely given over to biomass production through energy plantations. This could generate 9–19.5 mmt/yr of feedstock for biorefining operations.

Potential Bioethanol Production

The current levels of availability of six sources of lignocellulosic residues in Canada have been discussed, including sustainable contributions from precommercial thinnings, wood processing residues, agricultural residues, energy crops and plantations, forest-harvest residues, and recovery from natural disturbances. Using the high and low potentials discussed earlier, the contribution of each of these sources to total lignocellulosic biomass availability is shown in Fig. 1.

A calculation of potential bioethanol production from lignocellulosic sources was created based on previous work in the literature. According to Gregg et al. *(78)*, hydrolysis of C_6 sugars can result in yields of 0.5–0.75 g/g cellulose, for softwoods and hardwoods, respectively; fermentation of these sugars can result in ethanol yields of 95%, or 0.48–0.72 g/g cellulose *(78)*. In another study, it was demonstrated that variations in subprocess design have a large impact on total yields. The bioconversion of C_6 sugars through separate hydrolysis and fermentation, and simultaneous saccharification and fermentation yielded 0.61 and 0.86 g/g cellulose, respectively *(79)*. Finally, it has been shown that process ethanol yields from hydrolyzed feedstock containing both C_6 and C_5 sugars (i.e., both cellulose and hemicellulose) can range from 0.32–0.47 g/g for agricultural residues to 0.48–0.50 g/g for hardwood residues *(80,81)*. These yields are based on the fermentation of a hydrolyzed feedstock using recombinant *Zymomonas* yeast, which is capable of hydrolyzing both glucose and xylose effectively. When the chemical characteristics of lignocellulosic residues are considered, it may be estimated that ethanol yields will range from 0.12 to 0.32 L/kg of undried feedstock. In Table 1, two

Table 1
Scenarios of Lignocellulosic Biomass Availability and Potential Ethanol Production

Feedstock availability by scenario (10^6 mt, undried)			Yield scenarios (10^9 L ethanol/yr)			
			Feedstock low (0.12 L/kg EtOH)	Feedstock low (0.32 L/kg EtOH)	Feedstock high (0.12 L/kg EtOH)	Feedstock high (0.32 L/kg EtOH)
Forest residues	Low (mt)	19.5				
	High (mt)	32.5	2.34	6.24	3.90	10.40
Energy plantations	Low (mt)	15.9				
	High (mt)	34.5	1.91	5.09	4.14	11.04
Agricultural residues	Low (mt)	5.3				
	High (mt)	14.1	1.27	3.39	3.38	9.02
Wood product residues	Low (mt)	4				
	High (mt)	5	0.48	1.28	0.60	1.60
Precommercial thinnings	Low (mt)	0.3				
	High (mt)	0.4	0.03	0.09	0.05	0.14
Disturbances	Low (mt)	18.5				
	High (mt)	24.5	2.22	5.92	2.94	7.84

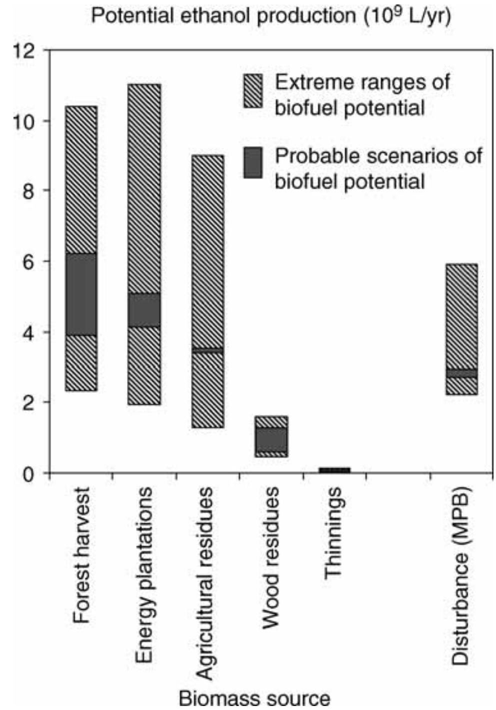

Fig. 2. Scenarios of potential ethanol production associated with lignocellulosic biomass sources.

scenarios of biomass availability are combined with the high and low ethanol yield limits in order to create four scenarios of lignocellulosic-based ethanol availability in Canada.

Figure 2 illustrates the wide variation in potential fuel production from lignocellulosics, ranging from low bioethanol yield and low feedstock availability to high yield and high availability for each category of material. The data indicate that, even at low yields and availability, sustainable biomass reserves in Canada could be significant. By harvesting agricultural residues, (1.3–9) $\times 10^9$ L of bioethanol per year might be provided. Energy plantations on marginal farmland could generate an additional 1.9–11 $\times 10^9$ L/yr of bioethanol. Given current levels of residue generation from the wood processing industry, the amount of bioethanol that could be produced on an yearly basis ranges from 480 to 1.6 $\times 10^9$ L of fuel. Forest residues could be converted to (2.3–10.4) $\times 10^9$ L of bioethanol every year. In addition to sustainable biomass reserves, unsustainable, opportunistic supplies might also be accessed. Disturbances including fire and insect-kill would provide a highly variable amount of wood annually. The ongoing mountain-pine-beetle outbreak in British Columbia and Alberta, for example, could provide (2.9–7.8) $\times 10^9$ L/yr of bioethanol at the anticipated height of the outbreak, which is predicted to occur in 2012.

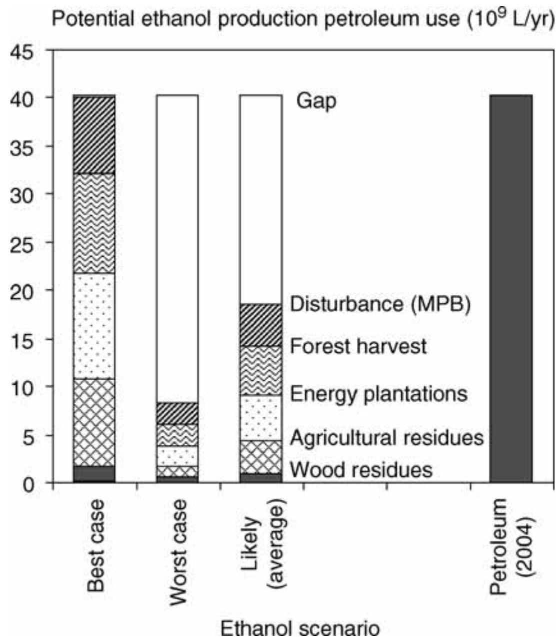

Fig. 3. Scenarios of potential ethanol production compared with Canadian petroleum use.

In Fig. 3, the cumulative potential biofuel production from each scenario is shown and compared with current levels of gasoline consumption. It is clear from this figure that no single biomass option can source Canadian demand for biofuels, but that available biomass sources a significant amount of fuel requirements. At the extreme positive range of these scenarios, almost all fuel consumption in Canada could be substituted with lignocellulosic-based ethanol without impacting agriculture or forestry operations significantly. A biomass reserve might then be an effective strategy for increasing environmental performance and energy security, in addition to providing opportunities for economic growth.

Conclusions and Suggestions for Policy Reform

Canada has an excess of 400×10^6 ha of forested land, approx 93% of which is publicly owned, and 77% of which is controlled by various Provincial Governments *(25)*. Rights to harvest or manage these public resources are allocated by the Provincial Government to private parties in the form of "timber tenures" also referred to as the tenure system *(82)*. A portion of the biomass reserve might access volumes of forest residues, which would require that some revisions to the tenure system must be contemplated. A major challenge is that, although most forests are controlled by Provincial Governments, policy related to the Kyoto Protocol is controlled by the Federal Government. Thus, a national biorefining strategy must seek consensus from the provinces, which is never easy to achieve.

In British Columbia, forest harvests are controlled licenses that regulate either area harvested or volume removed. The area-based tree farm licence and the volume-based forest licence account for over 80% of the timber volume harvested from British Columbia's public lands *(82)*. However, the even flow of wood generated by the tenure system has proven to be insufficient at insulating resource-based communities from boom and bust cycles. From 1979 to 1997, three complete cycles of boom and bust were recorded owing to fluctuations in the international demand for forest products, resulting in temporary and permanent job loss and mill closures *(83)*. A biorefining strategy may be useful in reducing the effect of boom and bust cycles in resource-dependent communities.

One possible reform that would encourage innovative management techniques and create supply for the biorefinery would be to exempt a predetermined volume of biomass used as feedstock for the biorefinery from annual allowable cut quotas. This would support Canada's commitment to the Kyoto Protocol, and would fall within the mandate of Provincial Governments, which is not only to manage the timber supply to generate revenue and jobs, but also to develop policies that address the environmental concerns and socioeconomic values of multiple forest stakeholders *(84)*. Determining the volumes to be exempt would be a challenge; land tenure reform is a hotly contested issue at the time of writing, with advocates spanning all facets of the forestry industry. Supporters of changes to the forest tenure system include royal commissions, existing tenure holders, and smaller timber companies that are out-competed by larger, established firms *(84)*. Change to the existing land tenure systems should include a consideration of a wider range of nontimber uses for the forest. Some have suggested that new tenures should contain incentives for the production of value-added and higher-value products *(84,85)*, an approach that is synergistic with a biorefining strategy.

Agricultural residue availability in Canada is relatively limited, particularly compared with the United States, where large amounts of corn stover and wheat straw may be accessed. Additional biomass production could be achieved if areas of marginal farmland in the Prairie provinces could be set aside and utilized for biomass production. This type of area-based approach is already seen in existing programs that promote plantations on marginal farmland, such as the Saskatchewan Forest Carbon Sequestration Project, which are beginning to address needs beyond shelterbelt or windbreak creation toward the provision of environmental services *(86)*. Perhaps the most significant of these projects is Agriculture and Agri-Food Canada's Prairie Farm Rehabilitation Administration (PFRA). This 60-yr-old project works to ensure sustainable use of the Prairie's soil and water resources, and promotes environmentally responsible use of the land. The Shelterbelt Centre of the PFRA provides seedlings at no cost (save shipping) to eligible farmers, which can be used in afforestation activities on marginal land. As part of Canada's Action Plan 2000 on

Climate Change, the PFRA has launched the Shelterbelt Enhancement Program, which is designed to increase afforestation activities in order to increase greenhouse gas sequestration in the Prairie provinces (87). This program could easily be expanded and linked to biorefinery operations, which could provide farmers with revenue from plantation operations in addition to further contributing to Canada's Kyoto obligations. This type of program would also be useful in parts of the United States where no suitable crop residues are available.

The policy reforms suggested have the potential to be interpreted as a negative force by forestry companies and farmers. However, each has the potential of reducing the vulnerability of ecosystems to disturbance, which reduces costs to the tenure holder or land owner in the long term. As shown in this article, the costs of disturbance can be extremely significant, and avoiding even 1% of these costs would mean tremendous savings for operators. In pursuing this strategy, it is essential that a mechanism should be created that transfers some of the benefit of avoided costs to the companies and individuals who hold stewardship over the land, in order to win public support for the biomass reserve strategy. Potentially, a biomass reserve strategy could also utilize some of these savings as a tool to reduce the cost of biomass to the operators and promote the biorefining sector.

It is clear from the data that no single biomass option can source Canadian demand for biofuels, and that different feedstocks will require significantly different policy approaches. A volume-based policy reform that would create supply for the biorefinery would be to exempt biomass used as feedstock for the biorefinery from annual allowable cut quotas. An area-based approach would identify marginal farmland for energy plantations. Together, these approaches could provide a secure and sustainable biomass source to support first-generation biorefining operations, allowing technological advancement and the development of future value-added products. This approach would contribute to Canada's biofuel requirements in the short term, and support economic growth and environmental sustainability over a long period.

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