TROTTIER ENERGY FUTURES PROJECT

Working Paper

BIOMASS FEEDSTOCKS

FINAL COPY

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Introduction

Canada's current biofuel production is almost completely sourced from four agricultural crops: corn and wheat, which support ethanol production to meet the Canada's mandate of 5% renewable content in gasoline (2.1 billion litres currently required), and soybean and canola, which support biodiesel production to the 2% renewable content requirement in diesel fuel (translating to 585 million litres of demand) (Evans 2013, Mabee, McFarlane, and Saddler 2011).

There is a small but significant biomass-to-energy sector in Canada in addition to biofuels. As of 2012, there were 39 cogeneration plants in pulp and paper mills and sawmills across Canada, with estimated generation capacity of 1,349 megawatts (MW) (electricity) and 5,331 MW (thermal). While impressive, the total number of cogeneration facilities declined by 20 between 2005 and 2012 due to the slowdown in the forest sector. There are also 16 independent biomass-to-electricity facilities in Canada capable of producing about 465 MW of electricity, and an unknown amount of thermal power. Finally, there are 8 community-based wood-to-heat plants in Canada, with capacity about 10 MW (thermal (CANBIO 2012). Production of heat and power from wood in Canada represents about 2% of Canada's total primary energy supply in 2009, down from about 4% in 2007 (UNECE/FAO 2009).

Canada's feedstock potential is primarily comprised of lignocellulosic biomass from forests, agriculture, and waste management. The forest and agricultural biomass sectors are considered in depth in the second section of this working paper. Other forms of biomass – notably as found in waste streams including solid waste, wastewater, and manure – are given more cursory treatment. The greatest challenge with the latter group of feedstocks is that few places in Canada have sufficient population densities to ensure the creation of large amounts of these feedstocks in an accessible fashion. An arbitrary cut-off of municipalities with 1 million + in population was selected for the analysis.

Emerging feedstocks, including plantation-style forests, energy crops, and algae are each given attention in the third section, and the fourth section identifies potential ranges of feedstock availability.

The working paper explores the potential use of biomass for both biofuel and bioelectricity generation, and shows that some options (i.e. wholesale replacement of diesel fuel, or substitution of non-renewable electricity generation) are feasible at high conversion efficiency and high biomass availability. This suggests that significant steps towards the project goal of 80% GHG reductions could be met through biomass use.

Section 1: Biomass sector descriptions

Canadian biomass that could be available for energy production are predominantly from forests, farms, and waste streams (both in urban and rural settings). Most of the research in the area of Canadian biomass feedstocks focuses on agricultural feedstocks (e.g. (Stephen, Mabee, and Saddler 2010, Mupondwa et al. 2012, Ebadian et al. 2011)) and forest feedstocks ((Alam et al. 2012, Kumar, Cameron, and Flynn 2003, Kumar et al. 2012, Upadhyay et al. 2012)). These types represent significant potential supply but are found on an extensive basis across very large areas.

When comparing biomass from forests and agriculture, important considerations include chemistry and energy content. The most widely distributed commercial tree species in Canada is pine, which is represented primarily by lodgepole pine (*Pinus contorta* Douglas var*. latifolia* (Engelm.) Critchfield) in British Columbia, and by Jack pine (*Pinus banksiana* Lamb.) across the boreal forest landscape (from northern British Columbia to Newfoundland and Labrador). When comparing Jack pine wood grown in Saskatchewan to a number of agricultural biomass sources, including wheat, barley, and flax straw as well as timothy grass, a recent report suggested that pine wood has very high calorific value (approximately 19.6 ± 0.2 gigajoules per dry tonne), compared to grasses and straws which might have between 16-18 GJ/dt (Naik et al. 2010). Pine wood is also found to have the highest cellulose and hemicellulose content and low ash content compared to grasses (Naik et al. 2010). For the purpose of this working paper, energy contents of 18 GJ/dt for wood and 17 GJ/dt for perennial grasses/straw are used.

Far less work has been done on waste streams including solid waste, wastewater, and manure. Solid wastes - including residential and industrial streams - are generally viewed as a source for thermal energy and a number of studies have examined the human health (Ollson, Knopper, et al. 2014) and ecological implications (Ollson, Aslund, et al. 2014, Abedini, Atwater, and Fu 2012) of using these materials in this way. Industrial wastewater as a source for methane production has been considered (Saha, Eskicioglu, and Marin 2011, Rapport et al. 2011), as has manure (Morin et al. 2010).

All of the biomass streams that are considered in this paper are extremely widely distributed over the geography of the country. Dealing with extensively distributed feedstocks may require biomass densification at an early stage of the process, to reduce transport costs and potentially increase conversion yields (Stephen, Mabee, and Saddler 2010). The most likely form of densified biomass is pellets, which currently are only made commercially with wood residues; accordingly, a section on wood pellets is included in the working paper Some researchers have focused on alternative transport mechanisms such as pipelines to reduce overall delivery costs (Kumar, Cameron, and Flynn 2004). These alternative forms of transport seem unlikely to be used and are not explored in detail.

Section 2: Base Year Sector Data for existing feedstocks

Forest biomass

Canada has approximately 396.9 million ha of forests and other wooded land, representing more than 1/3 of Canada's total area (Canadian Council of Forest Ministers 2014). Of this, approximately 259 million ha are used for forest operations. Approximately 579,000 ha were harvested in 2012 (Canadian Council of Forest Ministers 2014), which is approximately 0.2% of the commercial forest estate. Canada experiences a small amount of deforestation: since 1990, about 1 million ha of forest has been lost. Currently, about 19,000 ha per year is lost through conversion to agriculture, and 11,100 ha per year is lost to resource extraction (oil and gas exploration and production) (Environment Canada 2013).

The Canadian forest products industry harvested and processed in excess of 150 million m^3 of wood in 2012 (FAOStat 2013), or about 259 m^3 per ha harvested. This represents a rise of almost 40 million m^3 in total volumes harvested since the industry hit a low in 2009, but is still significantly lower than peak production levels in 2004-5, which exceeded 200 million m^3 annually (see Figure 1). Peak volumes in those years predated the worst of the mountain pine beetle outbreak and were carried out using sustainable forest management practices, and thus those peaks might be seen as a theoretical 'maximum' sustainable output from the natural forest systems. This suggests that approximately 50 million m^3 of wood that might be sustainably harvested remains uncut in Canada's forests each year.

With an average density (specific gravity) of 0.4 (Panshin and de Zeeuw 1980), Canada is currently harvesting approximately 60 million dry tonnes (Mdt) of wood per year. This is about 10 Mdt lower than the average harvest since 1990, and 20 Mdt lower than peak harvests during this period, suggesting that a large amount of sustainable biomass is available in the forest.

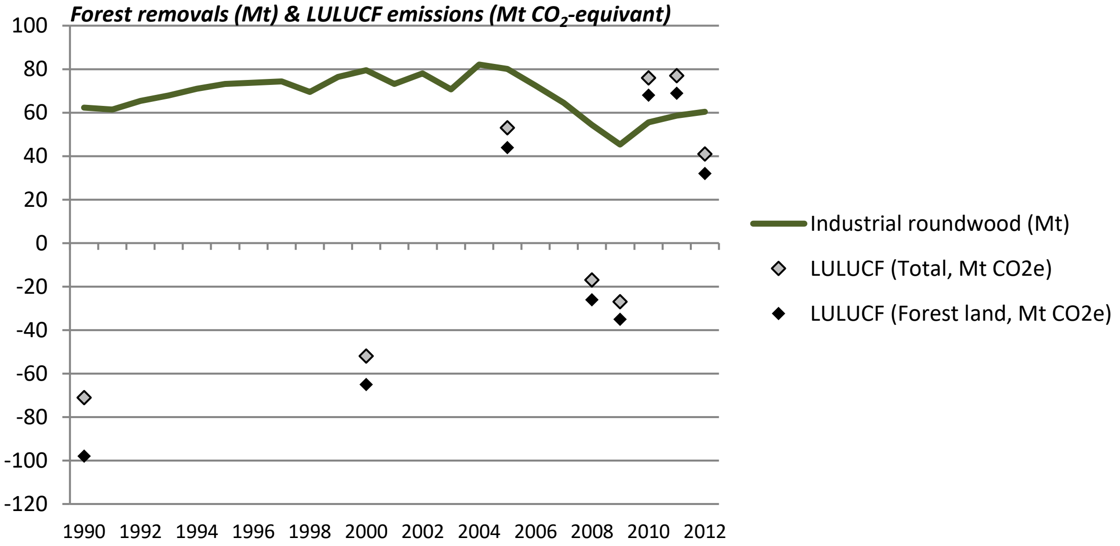


Figure 1 - Harvest levels and LULUCF figures for Canada's forest sector (Environment Canada 2013, FAOStat 2013)

LULUCF: In addition to harvested wood, Figure 1 also illustrates the carbon emissions or sequestration associated with LULUCF (land use, land use change and forestry). Most of the carbon equivalent emitted or sequestered across Canada is related to forest activity. In good years, where fires and insect disturbances are minimal, this can result in significant rates of sequestration - in 1990, almost 100 Mt of CO_2-e was sequestered on forest land, with total LULUCF at just over 70 Mt CO_2-e sequestered. Since 2004, several years have seen large emissions, driven by forest activity; in 2012, the net flux was 32 Mt CO_2-e from forests (Environment Canada 2013). This unpredictability, and the sheer size and impact that Canada's forests have on LULUCF numbers, is one of the reasons that carbon associated with LULUCF was not include in early emissions trends reports from Canada.

As of spring 2012, Canada indicated to the UNFCCC that it intended to include LULUCF excluding the emissions resulting from natural disturbances (Environment Canada 2012). By 2020, the government anticipates that 25 Mt of CO_2-e will be sequestered, primarily through improved forest management. Part of this projection is the anticipation that harvest levels would remain at the same historic level as seen between 1990 and 2009, or about 70 Mdt of roundwood harvested per year. The Canadian government sees the inclusion of LULUCF in the long term as a significant step towards meeting GHG reduction goals.

Energy use Emissions: The forest and agricultural sector are combined when reporting energy-related emissions. In 1990, the combined sectors emitted 2.39 Mt of CO_2-e; this rose to 3.54 Mt of CO_2-e in 2012 (Environment Canada 2013). The forest sector harvested about 61 Mt of biomass in 1990 and 60 Mt in 2012. The agricultural sector harvested 59 Mt of cereals, oilseeds and pulses in 1990 compared to about 61 Mt of these crops in 2012 (FAOStat 2013). This suggests that the energy intensity of both forestry and agricultural has increased, from about 19.9 kg CO_2-e/Mt biomass to about 29.5 kg CO_2-e/Mt biomass. This likely reflects increased mechanization of both agricultural and forest practices, but it should be noted that the equal weighting of the two sectors is arbitrary and that actual emissions may be different.

Harvest residues & disturbance wood: Wood that is harvested and taken to the mill is only a portion of the amount of wood that is cut overall; much wood is cut and left in the forest or at the roadside (usually referred to as 'slash'), and in some years a large amount of wood can be killed through fire or insect damage. The amount of forest harvest residues varies greatly; when expressed as a weight-based percentage of total roundwood removals, these residues range from a high of almost 100% to a low of just 0.08% (FAOStat 2013, Bull, Mabee, and Scharpenberg 1998). A model to estimate residues from forest harvest operations suggested that more than 20 Mdt/year might be available, with the greatest concentrations on an area basis found in British Columbia (Dymond et al. 2010). Other studies confirm that western residues are likely to be found at increased concentrations, which improves harvest and transport logistics (Shinners, Digman, and Runge 2011). Much more wood might be available from natural disturbance, such as beetle infestation or fire; the model suggests up to 51 Mdt/year might be available in the future (Dymond et al. 2010, Kurz et al. 2008). These figures represent anywhere between 28-100% of the removals from Canada's forests over the past twenty years.

Not all of this wood should be removed; there are restrictions on the amount of harvest residue that can ultimately be retrieved from a forest system while maintaining ecosystem services such as biodiversity conservation and soil and water protection (Skog and Rosen 1997). In order to be truly renewable, the removal of forest biomass must be carried out in a fashion that limits impacts on local ecosystems, in accordance with the principles of sustainable forest management. Thus recovery rates will vary from location to location. The sustainable recovery rate for forest harvest residues in temperate northern countries has been estimated at about 12% of harvest levels - this is a conservative estimate based on 40% recovery of minimal residues (Mabee, McFarlane, and Saddler 2011). This figure suggests that between 6 and 9.6 Mdt of biomass might be sourced from harvest residues annually. Disturbance wood amounts will vary depending upon the year; it should be noted that they are intrinsically unsustainable but represent an interesting opportunistic feedstock.

Processing residues: Wood harvested in Canada is processed in a couple of ways. The Canadian pulp and paper sector operates about 100 mills, with a total capacity of about 64,000 tonnes per day of output (Pulp & Paper Canada 2012), which can be translated into approximately 23 Mdt per year of capacity (FAOStat 2013) on inputs of about 30 Mdt feedstock (both logs and chips). Current sawmill capacity is harder to gauge but is likely around 38.9 million m^3/year (Sawmill Database 2013), the equivalent of 15.6 Mdt/year of lumber product in 2011 (Mabee 2013), again on inputs of approximately 30 Mdt. A detailed study of sawmill residue production suggests that residues have declined from 21 Mdt/year in 2004 to perhaps 7.3 Mdt/year in 2009 (based on relative decline in the outputs of the industry) (Krigstin et al. 2012). This means that the rate of residue generation has dropped from about 86% to about 56% based on lumber recovery; this suggests that processing residue generation rates would range between 7.2 and 11.2 Mdt per year based on the current mix of sawnwood and pulpwood.

Biomass price: One estimate suggests that price will determine how much uncut wood might be accessed; at C$100/dry tonne, 43 million dry tonnes of forest and mill residues is potentially available across Canada on annual basis, but at a price of C$50/dt, only 25% of this amount would be accessible by the emerging biorefinery industry (Kumarappan, Joshi, and MacLean 2009).

Summary of forest biomass availability

Forest biomass	**Low estimate (Mdt/year)**	**High estimate (Mdt/year)**
Trees harvested	80	50
Sawnwood/Pulpwood ratio	50/50	50/50
Estimated biomass available		
Harvest residues	9.6	6
Processing residues	11.2	7.2
Unharvested biomass	0	30
Disturbance wood (unsustainable)	0	51
TOTAL	**20.8**	**43.2 + 51**
Energy equivalent (gross) (PJ)	*374 PJ*	*778-1694 PJ*
*Approximate GHG emissions of inputs**	*0.61 Mt CO$_2$-e*	*1.27 Mt CO$_2$-e*

Wood pellets

Canada had 40 operational wood pellet plants with capacity of 3,396,000 tonnes per year by the beginning of 2013 (Biomass Magazine 2013). A number of other facilities are in the planning phase - potentially adding as much capacity as 2 million tonnes per year in the next few years (Wood Pellet Association of Canada 2012). Pellets have approximately the same energy content as wood (17.2 GJ/t), but are less bulky and thus easier to transport. The evolution of wood pellet production and capacity development is shown in Figure 2 below.

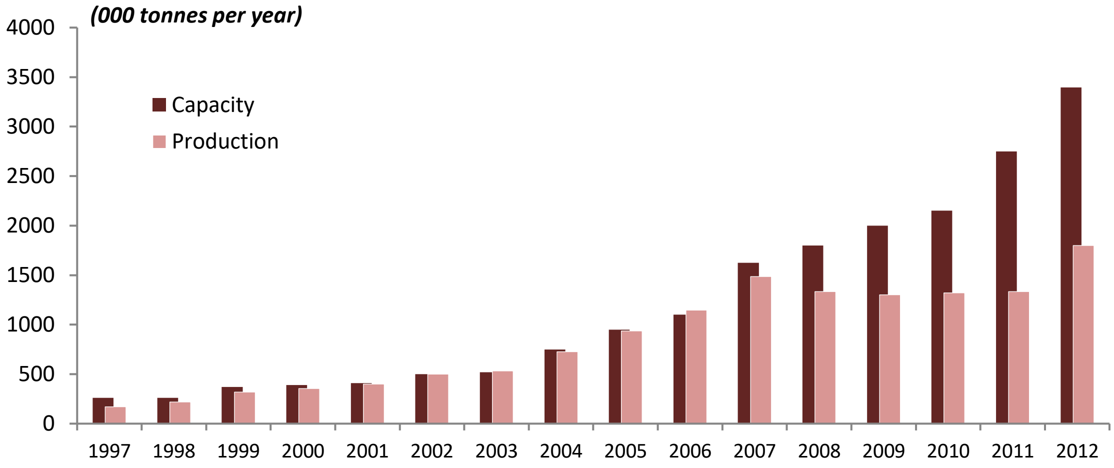


Figure 2 - Wood pellet capacity and production, 1997-2012 (Wood Pellet Association of Canada 2012, CANBIO 2012)

It can be seen from the figure that while Canadian capacity to produce wood pellets has grown steadily, the actual production of pellets still lags behind capacity (Wood Pellet Association of Canada 2013). In part this is because exports to the USA have fallen dramatically in recent years, a loss of market which has not been recouped in domestic or overseas sales (see Figure 3). In 2012, exports of wood pellets from Canada were reported at 1.4 million tonnes, with a worth of C$ 208 million (Statistics Canada 2013a). Major importing countries include the United Kingdom, the Netherlands, Japan, and Italy. As previously mentioned, while the US remains an important importer of Canadian pellets, the size of that market has shrunk largely due to new pellet production capacity coming online in that country. In 2012-13, Canadian exports to Europe were reported to climb by 25% year-over-year from 2011-2012 (Canadian Biomass 2013).

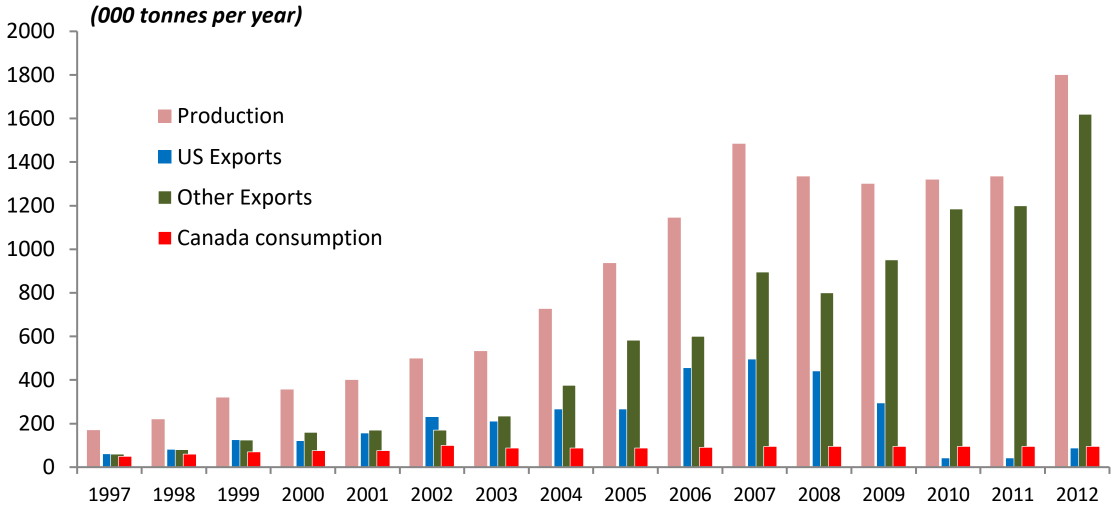


Figure 3 - Wood pellet consumption and exports, 1997-2012 (CANBIO 2012, Wood Pellet Association of Canada 2012)

Summary of wood pellet availability

Pellet biomass	**Low estimate** (Mdt/year)	**High estimate** (Mdt/year)
Pellet capacity	3.4	3.4
Pellet production	1.8	3.4
Pellet exports (total)	1.4	1.4
Estimated biomass available		
Domestic pellets	0.4	2.0
TOTAL	**0.4**	**2.0**
Energy equivalent (gross) (PJ)	*6.9 PJ*	*34.4 PJ*
*Approximate GHG emissions of inputs**	*0.01 Mt CO_2-e*	*0.06 Mt CO_2-e*

**energy inputs only – excluding combustion and transport*

Agricultural biomass

As of 2011, Canada had approximately 35.3 million ha of land under crops, with an additional 2 million ha of summerfallow land, 5.5 million ha of tame or seeded pasture, 14.7 million ha of natural land for pasture, 4.9 million ha in forested agricultural land (including Christmas tree farms), and finally about 2.2 million ha of other land (Statistics Canada 2011a). Total farmland is therefore about 64.6 million ha, compared to 67.6 million ha reported in 2006 and 67.5 million ha reported in 2001 (Statistics Canada 2006). The government of Canada reports that approximately 315,000 ha of farmland was lost to urban sprawl during the period between 2001-2011 (Statistics Canada 2013f), with the majority of these losses occurring in southern Ontario. This suggests, however, that a great deal of land (2.7 million ha) has been taken out of agricultural practice and not yet consumed by urbanization.

In 2012, Canada harvested about 50 million tonnes of cereal crops, of which wheat and corn accounted for 54% and 23%, respectively. Oilseed production reached about 21 million tonnes, of which canola or rapeseed accounted for 73% and soybeans 23%. Finally, Canada harvested about 4.7 million tonnes of pulses (including beans, peas and lentils) (FAOStat 2013). Analysis of production trends (Figure 4) indicates that maize or corn production is rising, as is canola; wheat and soybean production has been relatively stable since 1990, with wheat harvest fluctuating by as much as 10 million tonnes per year depending on weather and markets. Based on the areas of cropland currently being used in Canada, this translates to an average production of 1.17 Mt/ha/year.

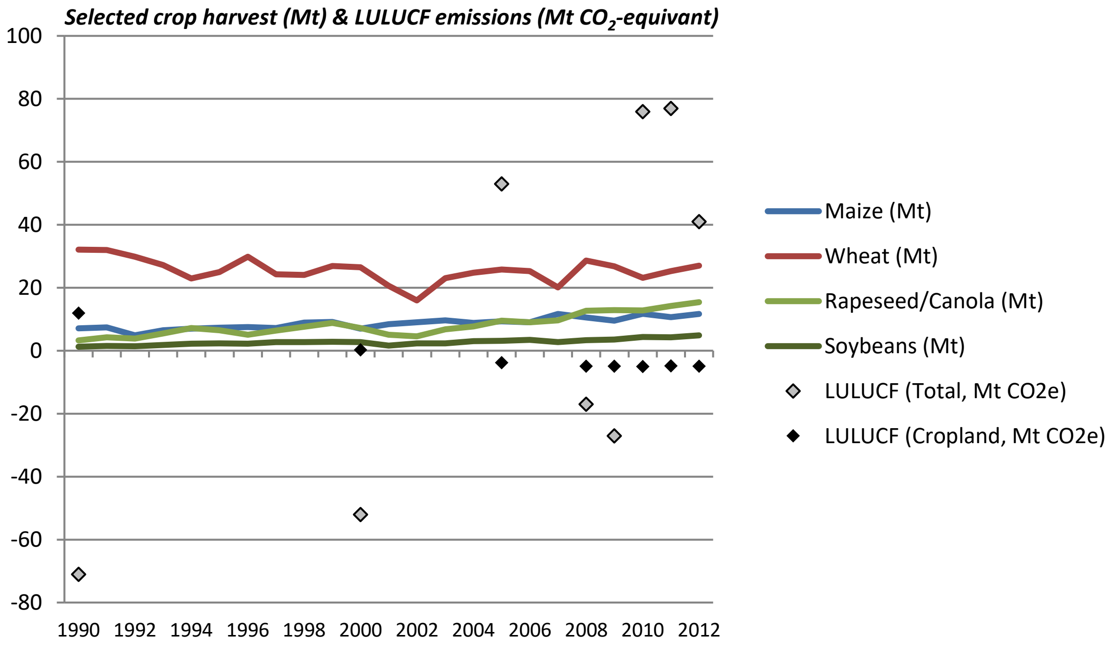


Figure 4 - Select crop harvest and LULUCF emissions for Canada's agricultural sector (FAOStat 2013, Environment Canada 2013)

LULUCF: It is interesting to note that LULUCF emissions associated with cropland have improved over the past two decades, and that agricultural lands are providing small but significant amounts of carbon sequestration over time due to the introduction of no-till and lower-impact farming (Environment Canada 2013).

Emissions: As discussed in the previous section, the energy intensity of both forestry and agricultural has increased, from about 19.9 kg CO_2-e/Mt biomass to about 29.5 kg CO_2-e/Mt biomass. This likely reflects increased mechanization of both agricultural and forest practices, but it should be noted that the equal weighting of the two sectors is arbitrary and that actual emissions may be different.

Emissions associated with farming also include emissions from livestock (methane from plant digestion, and both methane and N_2O from manure management) as well as fertilizer application for improved crop production. Since 2008, emissions associated with livestock have declined while fertilizer emissions increased. A breakdown of agricultural emissions (not including energy use) for 2012 is shown in Figure 5; total emissions in that year were 56 Mt of CO_2-e.

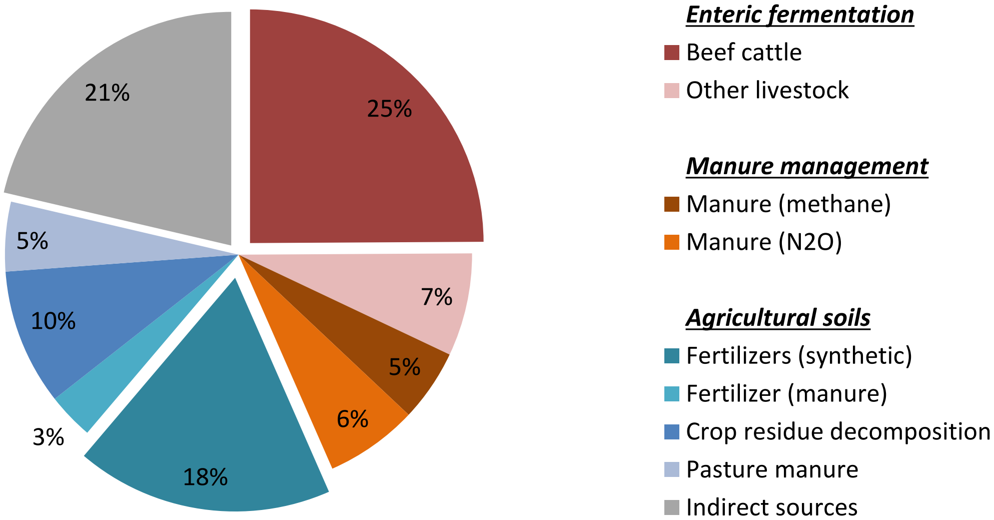


Figure 5 - Total agricultural emissions in Canada, 2012 by source (Environment Canada 2013)

It can be seen from Figure 5 that the three most dominant sources of emissions in Canada's agricultural system are linked to enteric fermentation in beef cattle (25% of agricultural emissions, CH_4); synthetic fertilizer applications (18% of emissions, NH_3 and NO_x) and finally 'indirect' soil emissions (21%, as NH_3 and NO_x), which includes volatization of nitrogen from synthetic fertilizers and manure, and leaching and runoff of fertilizer, manure, and crop residue (Environment Canada 2013).

In total, 970 kt of methane (20 Mt CO_2-e) and 100 kt of N_2O (40 Mt of CO_2-e) were reported in 2012, with total emissions (after accounting for overlap between the two systems and rounding) of 56 Mt CO_2-e. Emissions associated with fertilizer are most often associated with crop production, and thus based on current land under crop the average emissions per ha was about 1.58 Mt CO_2-e, with approximately 2/3 of these emissions consisting of N_2O and the remainder methane. Average emissions per ha of cropland were slightly higher in 2006 (1.62 Mt CO_2-e/ha) but lower in 2001 (1.54 Mt CO_2-e/ha) (Statistics Canada 2006, Environment Canada 2013). Based on average production figures, this translates to emissions of 0.74 Mt CO_2-e/tonne of food product. It should be noted, however, that this is the entire emission associated with the system; residues collected in addition to food would only be assigned a fraction of these emissions.

Harvest residues: Agricultural residues are abundant across Canada, and the potential availability of this resource has been explored widely in the literature. The most comprehensive study in recent years was carried out by Li et al., which used 10-year production data to estimate that between 24.5 and 48 Mdt per year of agricultural residues might be available across Canada, depending on growing conditions and the presence or absence of drought (Li et al. 2012). Li et al. considered all of the primary crops grown in Canada, including cereal crops, oilseeds (including soybeans, canola, and flax) as well as pulses (peas). The estimates of agricultural residue availability determined by Li et al. exceeds those found in other studies, including Mabee et al. (9-19 Mdt/year) and Wood and Layzell (17 Mdt/year) (Wood and Layzell 2003, Mabee and Saddler 2010).

The amount of residue available from any given agricultural operation will vary by location and by crop. One recent study looked at the Peace River region in Alberta for biomass production and found that between 50,000 and 500,000 tonnes of agricultural biomass might be available annually (Stephen et al. 2010). A significant part of the variation presented in these figures represents the limits placed upon the system by sustainability concerns. Similarly, many studies have been conducted on the amount of residue or straw left behind in typical cereal crop production. It has been noted that the crop under consideration will dictate the total amount of residue left behind, with average residues for wheat, barley, and oats, on the order of 1.3, 1.0 and 1.2 t/ha respectively (Wedlin and Klopfenstein 1985, Bowyer and Stockmann 2001). Further study on wheat straw residues shows that variation in amounts between 1.37 and 8.46 t/ha may be expected, depending upon the harvest method employed (Bowyer and Stockmann 2001).

In most cases, conservative estimates of biomass generation are used to respect sustainability concerns. It can be assumed that soil conservation requirements will account for 50% or more of the total residues in many areas, and some older studies indicate that particularly dry conditions could result in mandating that 100% of residues remain on the field (Johnson et al. 2001, Lindstrom 1986, Lindstrom et al. 1981). Furthermore, a proportion of cereal straw will generally be utilized by farmers for livestock feed. Finally, variation in year-to-year crop yields will result in a reduction in residue production (Russell 1996). After accounting for the factors of soil conservation, livestock feed and season variation, Bowyer and Stockmann (2001) suggested that between 15-40% of the total residue production would be available on average for industrial purposes. Concerns over the sustainability of removing agricultural residues from the field continue to be investigated in Canada (Huggins et al. 2011). One study considered the removal of 22% of wheat residue in southern Saskatchewan over a 50-year period, and found that this level of removal did not significantly reduce soil carbon availability, although higher levels of removal were anticipated to be detrimental to soil carbon levels (Lemke et al. 2010).

Biomass price: As noted previously, the price associated with biomass is important, with one study suggesting that C$50/dt would provide about 10.5 Mdt/year of residues across Canada, while C$100/dt would provide 42 Mdt/year (Kumarappan, Joshi, and MacLean 2009).

Summary of agricultural biomass availability

Agricultural biomass	**Low estimate (Mdt/year) (year)**	**High estimate (Mdt/year) (year)**
Selected crops harvested	25.4	64.1
Maize	*4.88 (1992)*	*11.72 (2010)*
Wheat	*15.96 (2002)*	*32.10 (1990)*
Rapeseed/Canola	*3.27 (1990)*	*15.41 (2012)*
Soybeans	*1.26 (1990)*	*4.87 (2012)*
Available biomass		
Harvest residues (estimated)	9	48
Harvest residues (% of crop harvest)	*35.5%*	*74.9%*
TOTAL	**9**	**48**
Energy equivalent (gross) (PJ)	*153 PJ*	*816 PJ*
*Approximate GHG emissions of inputs**	*0.266 Mt CO_2-e*	*1.416 Mt CO_2-e*
Approx. GHG emissions (crop total)	*18.77 Mt CO_2-e*	*47.43 Mt CO_2-e*
Approx. GHG emissions (residues only)	*6.66 Mt CO_2-e*	*35.52 Mt CO_2-e*

**Energy only – not including chemicals, fertilizers, combustion or transport*

Solid waste

A source of biomass that is often discussed is included in waste from residences and industrial facilities. Canadian households produced about 13 Mdt of waste in 2008, of which 8.5 Mdt was sent to landfill or incinerated and the remainder was captured by recycling programs (Statistics Canada 2013b, c). Industry produced about 21 Mdt of waste in 2008, of which 17 Mdt were sent to landfill or incinerated (Statistics Canada 2013c, b). On a per capita basis, this translates to waste generation rates in 2008 of approximately 0.77 dt/person/year (not including recycled materials). It is worth noting that this approximately the same rate as observed in 2002. If it is assumed that disposal rates have remained approximately the same since 2008, it might be suggested that between 25.8-26.8 Mdt of waste is available (not recycled) across Canada today. From these streams, it has been estimated that up to 7 million dt/year of municipal solid waste might be suitable for energy purposes (Kumarappan, Joshi, and MacLean 2009). The availability of municipal solid waste as a feedstock for biorefining activity is highly limited by Canada's relatively small population and by the wide geographic distribution of that population; only six census metropolitan areas in Canada exceed 1 million individuals, with likely waste generation rates ranging between approximately 0.90 Mdt/year and 4.31 Mdt/year (based on 2011 populations and per capita generation rates) (Statistics Canada 2011b). Based on suitable components of the waste streams, these large centres could provide a cumulative 3.09-3.21 Mdt/year of feedstock for energy purposes, equivalent to approximately 62-66 PJ of energy. In 2012, solid waste disposal and decomposition in landfills accounted for 19 Mt of CO_2-e emissions in Canada, with an additional 0.67 Mt CO_2-e associated with incineration (Environment Canada 2013).

Wastewater

Good statistics on municipal wastewater generation in Canada are difficult to find; the average production per person in 2004 was about 243,000 litres per year, but rates of wastewater generation vary by region (Sierra Legal Defense Fund 2004). Given a current population of 35 million (Statistics Canada 2011b), it may be assumed that national production of wastewater is about 8.5 trillion litres per year. Wastewater effluents are very widely distributed across a very large area; only a fraction would be available in such volumes to be useful as a feedstock for energy production. The amount of energy per unit of wastewater also varies depending upon the treatment type. In the United States, the Greater Lawrence Sanitary District in Massachusetts, generates approximately 75.2 m^3 CH_4/million litres wastewater treated (Massachusetts Department of Environmental Protection 2013), and 1 m^3 of CH_4 can deliver 9.67 kWh. Using these figures, and assuming that 50-100% of wastewater could be captured for the six census metropolitan areas in Canada, it can be estimated that the potential electricity generation from anaerobic digestion of wastewater could range between 102 GWh for the smallest city at 50% recovery to 986 GWh at 100% recovery in the largest – equivalent to a total of 4.9-9.7 PJ across Canada's largest metropolitan areas. Wastewater treatment generated 1 Mt CO_2-e in 2012.

Anaerobic digestion of manure

The potential to produce methane from manure ranges between 210 and 240 m^3 CH_4/t solids, with beef cattle providing higher values and dairy cattle or pigs providing lower values (Pugesgaard et al. 2014). Canada produced 181 Mt of manure in 2006, up from 156 Mt in 1981 (Statistics Canada 2013d); beef cattle supplied 38% of this manure, followed by milk cows at 12%. Given an average electricity generation rate of 9.67 kWh/m^3, and presuming an arbitrary recovery rate of 10%, it can be estimated that between 37,000 GWh and 42,000 GWh of electricity (133.2-151.2 PJ) might be generated from this resource - the equivalent of the Bruce Nuclear generation facility. Like wastewater, however, manure is geographically dispersed across most of southern Canada. While it is true that certain regions, such as southern Alberta or south-central Ontario, have higher concentrations of beef farms and thus might be able to more easily collect manure for central generation, the vast majority of this resource remains far-flung and difficult to access. It is clear, however, that this is a very significant potential feedstock for future development. Manure management contributed 6.4 Mt of CO_2-e emissions in 2012, up from 5.7 Mt in 1990 but down from a high of 7.5 Mt in 2005 (Environment Canada 2013).

Summary of other biomass availability

Other biomass	Low estimate	High estimate
Solid waste (Mt/year)	3.09	3.21
Solid waste (gross energy) (PJ/year)	62	66
Wastewater-to-biogas (PJ/year)	4.9	9.7
Manure-to-biogas (PJ/year)	133.2	151.2
TOTAL	**200.1**	**226.9**

Section 3: Sector Data for new Technologies

Fast-growing tree species

The development of new forest and agricultural feedstocks for energy feedstocks continues to be an area of interest for Canadian researchers, as fast-grown species grown in plantation style (i.e. intensive, short-rotation) is seen as a viable means of reducing the logistical costs of harvest and transport, particularly when compared to existing forestry and agricultural production (Yemshanov and McKenney 2008). Poplar (*Populus* spp.) and willow (*Salix* spp.) are the two fast-growing tree species most commonly considered for application in Canada; they are both native to this climate. Trees of these species may be grown in coppice style, where the young trees are cut back after the first year of growth, allowing multiple shoots to grow from the remaining roots, which in turn are harvested while still in shrub form on a 2-4 year cycle. Trees may also be grown in a plantation form where trees are allowed to reach more significant size and where cut cycles are considerably longer (generally between 7 and 20 years) (Ribeiro and Betters 1995).

***Poplar**:* Tests have been conducted on hybrid poplar species across Canada. For example, a range of clonal varieties were grown in non-coppiced plots over an 8-year period in eastern Canada. This study demonstrated that site conditions tend to have a stronger impact on biomass yield than clonal type (although clonal type is also important). On high quality sites in eastern Canada - usually abandoned agricultural land - biomass accumulation of approximately 8.9-16.9 dt/ha per year was observed, while poor sites yielded only 0.4-2.4 dt/ha per year. On average, hybrid poplar can produce relatively high yields (above 4 dt/ha per year) on fertile sites (Truax et al. 2012, Fortier et al. 2010). Similar studies at the Indian Head site in southern Saskatchewan reported average yields of approximately 3.9 dt/ha per year (Amichev, Johnston, and Van Rees 2010).

Willow: In southern Ontario, coppiced willow grown in agroforestry plots had observed yields of 3.0 dt/ha by the second year of growth and as much as 5.0 dt/ha after the third year, with gains in productivity being strongly correlated to increased soil moisture (Clinch et al. 2009). One study considered the physical fibre potential of coppice willow (*Salix viminalis*) grown in Quebec and found that pulp yields ranged between 29-34% for one-three year-old crops, with mechanical properties similar to hardwood pulps (Lavoie, Capek-Menard, and Chornet 2010). This suggests that even in coppiced energy plantations, a significant amount of fibre might be recovered for physical applications including paper or board products. Short rotation coppice willow plantations harvested over a long period in the Prairie ecozone produced about 5.5 dt per ha per year, which is about 20% more C sequestration than observed in willow plantations situated in the Boreal plains ecosystem (Amichev et al. 2012). This study reinforces the idea that future biorefining feedstocks be developed on underused agricultural lands across Canada.

Energy crops

Switchgrass: Switchgrass (*Panicum virgatum* L.) is one species that is considered to have high potential, particularly in Eastern Canada. Growth of switchgrass has been tested near Montreal, PQ, achieving between 10.6 and 12.2 tonnes/ha in production after a single season (Madakadze et al. 1999). Switchgrass grown in western Canada was identified as being highly suitable for biofuel production, along with other warm season grasses including big and little bluestem, with total carbohydrate concentrations ranging between 536 and 731 g per kg dry biomass (Jefferson et al. 2004). The potential of using switchgrass as a biomass feedstock for anaerobic digestion has also been considered due to the higher potential of energy recovery when all organic components can be converted to methane; detailed suggestions on planting and harvesting switchgrass for methane production are provided by (Masse et al. 2010). The cost of growing switchgrass has been estimated at $241/ha, although it is suggested that slightly lower costs could be realized in western Canada (Liu et al. 2012). It is interesting to note that most Canadian research on perennial grasses for energy builds on US or European examples, and thus focus on warm-season grasses. Little research in Canada focuses on the use of perennial cool-season grasses for energy purposes, although fundamental research on these crops is ongoing (e.g. (Shay and Kubien 2013)). This may suggest a lack of strategy in terms of developing a purely Canadian energy crop solution.

Triticale/wheat: A range of annual cool-season plants are being considered for use in Canada. Goyal et al. considered the adaptability of Triticale (x *Triticosecale Wittmack*) to local ecosystems in southern and central Alberta. In this study, triticale consistently produced higher grain and biomass over comparators such as hard red spring wheat, and ultimately one genotype considered over the course of the study was recommended for registration (Goyal et al. 2011). Various wheat strains, including Sunrise soft red winter wheat (Fowler 2012), Accipiter hard red winter wheat (Fowler 2011), Peregrine hard red winter wheat (Fowler 2010b), and CDC Ptarmigan soft white winter wheat (Fowler 2010a) have been designed to meet high energy demands in livestock feed as well as biofuels.

Camelina: Camelina (*Camelina saliva* L. Crantz) is another crop of interest in both Canada and the USA, particularly as an oil source for renewable jet fuels. Data from a number of trials carried out in the United States suggests that the crop grows well across a range of climate, with advantages in ‘drier’ ecozones (in this case characterized as between 175-475 mm per crop-year (Schillinger et al. 2012), a range observed through much of southern Saskatchewan and Manitoba). Currently, there is no good data on yields associated with this species.

Common issues

Siting: Some studies suggest that deployment of fast-growing trees and energy crops should be on abandoned or underperforming agricultural land in Canada, rather than in existing boreal regions where soil characteristics will not support high yields (Fortier et al. 2012). One author has specified that hybrid poplar as a species should be prioritized for planting on these type of lands, intermixed with or adjacent to intensive agriculture (Fortier et al. 2012). As energy crops and fast-growing trees can be grown in a more intensive pattern and because agricultural lands tend to be well-serviced with roads and other infrastructure, the costs associated with logistics of harvest and transport can be reduced, although a range of conditions - including presence of government support to get plantations and crops established, and the presence of an active market to take up the biomass once produced - are required to ensure success of these operations (El Kasmioui and Ceulemans 2012). Overall, productivity of fast-growing species tends to be lower in previously forested regions than on abandoned agricultural sites, which reflects the realities of poorer forest soils (Nelson et al. 2012). Using the Canada Land Inventory as a starting point, one study suggests that up to 9.48 million ha of abandoned or underused agricultural land could be identified as available for energy cropping in Canada (Liu et al. 2012). Since 2006, at least 2.7 million ha has been taken out of agriculture but not absorbed by urban sprawl (as previously discussed). Of these lands, one might assume that 10-20% would be suitable for energy crops such as switchgrass, while the remainder might be better suited for fast-growing trees.

Pests: Dangers associated with tree plantations and agricultural energy crops include new disease and pest infestations, which have been observed in both willow and poplar plantations (Royle and Ostry 1995); some research suggests that certain clones will be more resistant to these types of disturbance (Labrecque and Teodorescu 2005). As with existing feedstocks, managing this risk will involve diversification of feedstock sources. Indeed, the ideal biorefinery configuration, if not feedstock agnostic, might be one that can manage a reasonable number of feedstocks over a relatively broad range of growing conditions (and therefore geographies), which in turn would insulate operations from shocks to a single feedstock stream which might interrupt supply. Increasing the number of feedstocks being grown would result in increased logistical challenges associated with managing harvest and transport operations (Sokhansanj and Hess 2009).

Emissions: A recent study examined an ethanol production system using a biochemical pathway and generating wood pellets as a coproduct for use as a coal replacement in electricity generation; this study suggests that a facility producing biomass-based electricity, steam, and ethanol could achieve the greatest GHG mitigation (-174% relative to gasoline) (McKechnie et al. 2011). Similarly, it is estimated that increased canola production in Western Canada to support increasing amounts of biodiesel use would increase GHG emissions in terms of direct land use impacts, but that GHG reductions compared to petroleum-based fuel use could be up to 2.6 tonnes of CO_2-e/ha (Dyer et al. 2010), which translates to 0.06-0.09 t CO_2-e reductions per GJ of canola oil produced . By comparison, life cycle emissions for oilsands range between approximately 0.085 t CO_2-equivalent/GJ (conventional oil) to 94.8 g CO_2-e/MJ (oilsands-mining) and 0.105 t CO_2-e/GJ (oilsands-in situ removal) (Yeh et al. 2010).

Price: One study suggested a break-even cost for poplar plantations starting at C$76.4-C$95.5/dt, depending upon location across the country (Yemshanov and McKenney 2008). Introducing a carbon price of C$5/t could reduce these figures by as much as C$20/dt, depending upon location. Lowering plantation establishment costs has been recognized as a major requirement to accelerate uptake of biomass-to-energy plantations (McKenney et al. 2006). Price signals can help establish biomass supply - one study estimates that up to 30 million dt per year of feedstock might be available if the price of this biomass ranged from $70-100/dt (Kumarappan, Joshi, and MacLean 2009). Much of this cost might be associated with the relatively high cost of establishing fields (Liu et al. 2012). It is important to note that none of the existing studies predict low costs for fast-grown feedstocks.

Algae: While solid biomass sources have been a dominant area of research across Canada, there is increasing interest in the development of non-lignocellulosic sources. Development of microalgae production in wastewater treatment ponds has been explored in Saskatchewan. Secondary municipal wastewater was shown to support algae production providing biomass accumulation rates ranging between 21 and 33 mg per litre per day. When cultivated mixotrophically (i.e., when acetate was provided to the cultures as an additional energy and carbon source), the strains considered in this study showed increases in both biomass accumulation and oleic acid yield (Park et al. 2012). This study further reports total fatty acid/methyl ester production of between 81 and 117 mg per g biomass (Park et al. 2012). It has been suggested that microalgae could also be recovered in tailings ponds associated with diamond mining, and some testing has been carried out using at the Diavik Diamond mine site in the Northwest Territories (Power et al. 2011). At the current time, however, there are no significant algae operations in Canada. Most of the existing research is focused on indoor, artificially-lit algae production as Canada’s climate is not conducive to year-round algae production in out-of-doors systems.

Summary of fast-growing trees, energy crops, and other biomass sources

Biomass type	**Low estimate**	**High estimate**
Marginal farmland available (M ha)	2.7	9.48
Plantations/energy crops ratio	90/10	80/20
Plantations (dt/ha/year)		
Poplar	*3.95*	*8.9*
Willow	*3*	*5*
Subtotal (Mdt/year)	7.3 - 9.6	37.9 - 67.5
Energy crops (dt/ha/year)		
Switchgrass	*10.6*	*12.2*
Subtotal (Mdt/year)	2.9	23.1
TOTAL (Mdt/year)	**10.2 - 12.5**	**61.1 - 90.6**

Section 4: Demand projection rationale

Biomass used for biofuel production

In previous sections the potential for different biomass sources has been described. These are summarized below.

Biomass type	Low estimate (Mdt/year)	High estimate (Mdt/year)
Forest harvest residues	9.6	6
Processing residues	11.2	7.2
Unharvested biomass	0	30
Disturbance wood (unsustainable)	0	51
Wood pellets	0.4	2.0
Agricultural harvest residues	9	48
Solid waste (Mt/year)	3.09	3.21
Fast growing trees/Energy crops (low)	10.2	61.1
Fast growing trees/Energy crops (high)	12.5	90.6
TOTAL (Mdt/year)	**56**	**299**
Energy equivalent (gross) (PJ)	*995*	*5331*

Previously published work has determined biofuel yields per tonne of feedstock (Mabee, McFarlane, and Saddler 2011); these figures are shown below.

Process	Lower Yields (m^3 per tonne feedstock)*	Higher Yields (m^3 per tonne feedstock)*	Energy Content (LHV, GJ per tonne fuel)	Lower Yields (GJ per tonne feedstock)*	Higher Yields (GJ per tonne feedstock)*
Bioconversion:					
Lignocellulose-to-ethanol, Agricultural residues	*0.11*	*0.27*	*21.1*	*2.29*	*5.70*
Lignocellulose-to-ethanol, Forest residues	*0.12*	*0.30*	*21.1*	*2.61*	*6.39*
Thermochemical:					
Syngas-to-Fischer-Tropsch	*0.08*	*0.20*	*34.4*	*2.87*	*7.60*
Syngas-to-ethanol	*0.15*		*21.1*	*3.06*	

Using these yields and biomass sources, a range of biofuel potentials can be determined as shown in Figure 6 (next page). On the same figure, 2012 sales of gasoline (42 billion litres, 1,471 PJ) and diesel (17 billion litres, 635 PJ) provide a benchmark for current fuel use (Statistics Canada 2013e).

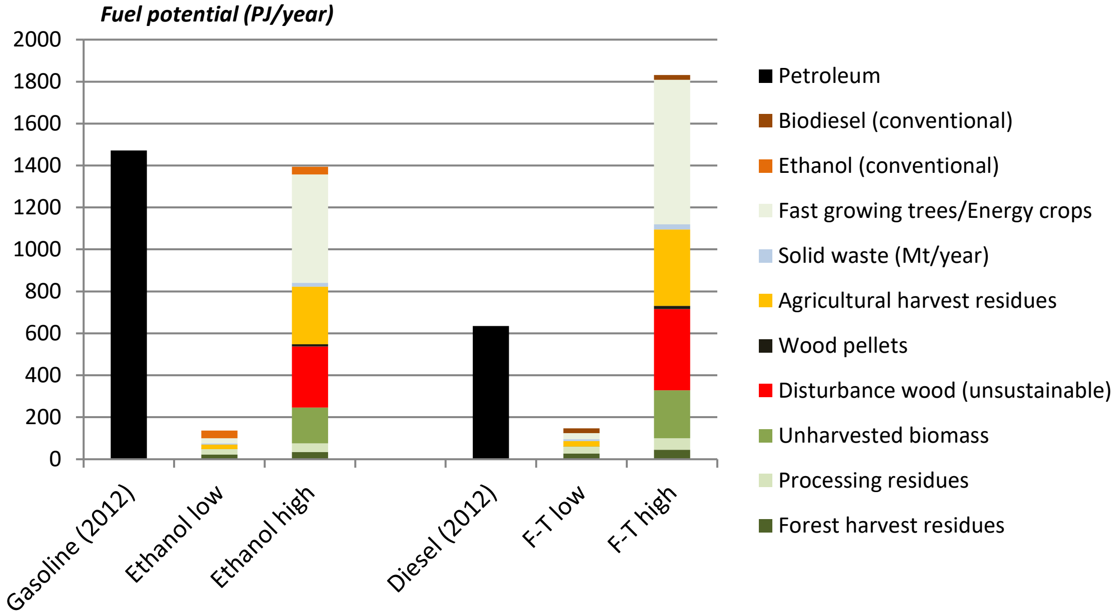


Figure 6 - potential biofuel production, low and high scenarios

Figure 6 includes several important lessons. First, that it is important that biofuel conversion yields must be at the higher end of the potential range to ensure that biomass is efficiently converted to fuel. At the low yields, the ability of ethanol to substitute for gasoline or for Fischer-Tropsch fuels to substitute for diesel is highly limited. Second, even at high yields and high availability, the contribution of some biomass feedstocks is highly limited. Forest harvest residues, processing residues, wood pellets, and solid waste are not available in large enough quantities to meet demand for biofuels (as determined by petroleum use). The most important future contributions to biomass availability can be made by fast growing trees and energy crops on a large landbase (approaching 10 million ha), by aggressive recovery of agricultural harvest residues, by the use of currently unharvested wood from the forest, and by the occasional (but not sustainable) use of disturbance wood.

If biofuel yields remain low and biomass availability remains at the lower estimate, the total production of ethanol (including conventional) could meet 9% of Canada’s 2012 gasoline use; the production of Fischer-Tropsch fuels could meet 20% of Canada’s 2012 diesel use. At high biofuel yields and high biomass availability (including the uptake of disturbance wood), ethanol could meet 95% of current gasoline consumption, while Fischer-Tropsch fuels could provide 2.85x the current level of diesel consumption.

Biomass used for electricity production

When converted to biofuels, the amount of energy that is recovered from the biomass (assuming that biofuel facilities use some of the biomass for self-generation but no electricity sales) ranges between 100-125 PJ (low estimates) to 1357-1809 PJ (high estimates). This is equivalent to between 10-13% (low estimate) to 26-34% (high estimates) of the total amount of potential energy in the biomass. It is well known that conversion to electricity can provide at least 30% energy recovery (using a steam turbine and without heat recovery); combined heat and power facilities using modern gasification technology, assuming that they can find a use for the heat, can achieve 80% efficiency or better (Mabee and Mirck 2011). Thus the total

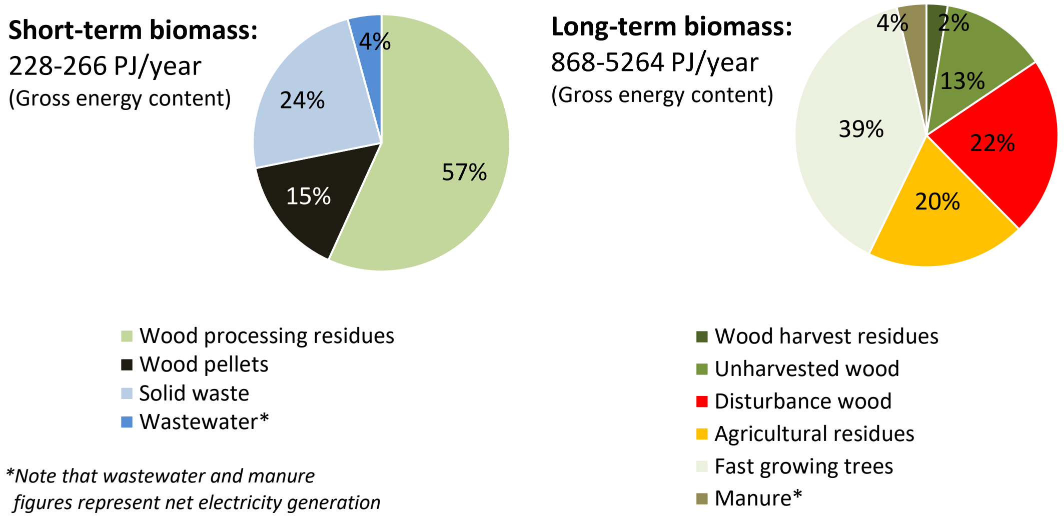
Biomass resource	Electricity (PJ/year)	Electricity (PJ/year)
Steam generation (30% recovery)	298.5	
Combined heat and power (80% recovery)*		2132.4
Wastewater-to-biogas	4.9	9.7
Manure-to-biogas	133.2	151.2
TOTAL	**436.6**	**2293.3**

**Assuming 50% electricity and 50% thermal output*

According to the IEA, Canada generated 2293 PJ of electricity in 2011, of which 38% (863 PJ) was sourced from non-renewables (gas, coal, and oil) as well as nuclear power (IEA Statistics 2011). This suggests that even at low estimates of biomass availability and using low energy recovery, half of the electricity currently sourced from non-renewable resources could be replaced with biomass-to-electricity. At high conversion rates, more than 2.6x as much power as is currently generated from non-renewables could be produced through biomass-to-electricity, allowing the application of electricity to be expanded in other energy use sectors such as transport or heating.

Section 5: Recommendations

Canadian biomass production is primarily linked to forestry and agricultural activities, and additional biomass can be sourced from waste collection. Some of these feedstocks can be accessed in the short term, while some must be developed and accessed over the longer term. The availability of these feedstocks is shown below in Figure 7.



**Note that wastewater and manure figures represent net electricity generation*

Figure 7 - Overall availability of short- and long-term biomass feedstock sources

Several important opportunities have been identified in this analysis:

1. In the short term, biomass that may be available for energy purposes is largely found in wood processing residues or municipal solid waste, with a significant amount of pellets. To access this biomass:
   a. Focus attention on the forest products sector and identify policy mechanisms to ensure that processing residues are collected and made available for energy generation.
   b. Develop a strategy to access solid waste from the six major municipalities in Canada (Toronto, Montreal, Vancouver, Ottawa, Calgary, Edmonton) to ensure that industrial and residential waste is made available for energy generation.
   c. Compare efficiency of conversion of each feedstock for biofuels and/or electricity, and link production to local energy requirements. While rough estimates are provided in this paper, this is an area that warrants more attention.
2. Agricultural residues and unharvested wood also represent a significant, sustainable source of biomass in the future. To ensure that this feedstock becomes available:
   a. Develop guidelines to ensure that residue removal does not exceed sustainable limits.
   b. Consider short-term forest tenures to access biomass from underutilized tress.
3. In the long-term, the largest likely source of biomass will be energy crops and fast-growing trees. In order to ensure that this biomass supply develops:
   a. Develop a policy incentive for landowners to begin biomass establishment on abandoned or underutilized agricultural land. The policy should encourage energy crops (such as switchgrass) on the most productive land or lands closest to markets; other lands could be put under fast-growing trees.
   b. Consider a government purchase mechanism to ensure that a market exists for the first biomass crops, to ensure that significant feedstock development occurs.

Section 6: Summary of perspectives

Key findings of this working paper:

1. There are significant amounts of biomass available across Canada, even in the short term, which could be used to develop more biofuel and bioenergy for consumption.
2. In the short term, the primary focus for developing biomass supply should be on forest products residues. In the longer term, the focus should be on agricultural residues, unharvested wood and harvest residues, and finally energy crops and plantation forests.
3. In the long term, biomass development and the implementation of Fischer-Tropsch fuels (or a similar substitute for diesel) could easily meet diesel consumption requirements across Canada (based on 2012 consumption figures). Even at very high biomass availability levels, however, biofuels could not meet the current level of gasoline consumption. It should be emphasized that the analysis was an either-or comparison, and that biomass - even at very high levels of availability - could not meet both transportation fuel requirements. This analysis did not include marine or aviation fuel consumption.
4. In the long term, biomass development and implementation of high-efficiency bioelectricity generation facilities could easily meet the requirement for non-renewable electricity in Canada (based on 2011 production figures). About 2.6x as much electricity could be generated from biomass as is currently generated from non-renewable and nuclear options. This means that the electricity generation capacity of the country could be extended significantly in a sustainable fashion. This, however, would mean that no biomass would be made available for biofuel development.
5. All biomass is expensive, save solid waste (which usually requires additional processing and cleaning before it can be used). Most of the analyses available suggest that biomass prices between C$ 50-100 per tonne can be expected, with more biomass available as the price rises. The review suggests that even purpose-grown crops will command prices that range between C$ 75-100 per tonne. This means that energy costs from biomass will likely only be competitive if carbon pricing is incorporated into fossil options, or if carbon credits are applied to bio-based energy costs.

Data gaps:

1. Little is known about the trade-off between bio-electricity and biofuel. The analysis in coming months should focus on developing a better sense of these tradeoffs.
2. Aviation biofuels have not yet been documented. The pathways for aviation biofuels are beginning to be better understood, and a subsequent version of this paper may include more details on this important area.

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