BIOMASS SUPPLY FOR BIOFUEL PRODUCTION: ESTIMATES FOR THE UNITED STATES AND CANADA

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The potential supply of biomass feedstocks in the US and Canada is estimated using a static supply function approach. Estimated total biomass available at a price of $100 per metric ton is 568 million metric tons in the US and 123 million tons in Canada, which together can displace 23-45 billion gallons of gasoline. Sufficient biomass, mainly agricultural and mill residues, will be available at prices of around $50/ton to meet the advanced biofuel mandates of the US Energy Independence and Security Act of 2007. The estimates of agricultural residue supply are very sensitive to the assumed fraction of residues that can be sustainably removed from the field, and the potential of municipal solid waste as a feedstock depends on which components can be economically converted into liquid biofuels.

Keywords: Biomass supply; Resource assessment, Lignocellulosic biomass

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INTRODUCTION

Alternative fuels, especially biofuels for transportation, have become the focus of intense policy debate and legislative action due to volatile oil prices, an unstable political/military environment in major oil production regions, rapidly increasing global demand and dwindling reserves of oil, and concerns over global warming. Promoting biofuel production is also viewed as means to reduce high agricultural program costs and to promote rural incomes in North America. While ethanol from grains is expected to account for most of the US/Canada biofuel production in the short run, ethanol from lignocellulosic biomass is considered to be more attractive from a long term sustainability perspective because of significantly lower life cycle greenhouse gas emissions compared to grain ethanol, widespread domestic feedstock availability, and the potential to ameliorate the conflict over food v/s fuel use of grains (Wang et al. 2007). Reflecting this view, the renewable fuel standards under the US Energy Independence and Security Act of 2007 (EISA) set forth a phase-in for renewable fuel volumes beginning with 9 billion US gallons (34 billion liters) in 2008 and growing to 36 billion gallons or 136 billion liters by 2022 (EISA 2007). The conventional starch-based biofuel volumes are limited to 15 billion gallons, and advanced biofuel volumes are mandated to be 21 billion gallons including 16 billion gallons of cellulosic ethanol by year 2022. Canada has enacted Bill-33 that mandates 5% bio-ethanol and 2% biodiesel use in the Canadian transport sector by 2010 and 2012 respectively (Bill C-33: Govt. of Canada, 2008). Although there are no specific mandates for cellulosic ethanol in Bill C-33, the final regulations supporting the mandate are still being drafted, which may potentially include cellulosic ethanol mandates (Ethanol Producer Magazine, 2009; Green Fuels, 2009). Achieving these cellulosic ethanol mandates critically depends on the availability of biomass in sufficient quantities at reasonable costs for conversion to liquid fuels.

Cellulosic feedstocks include agricultural residues, forest and mill residues, organic/lignocellulosic portion of municipal solid waste, and energy crops grown purposely for conversion to fuels. Over the last decade, a number of studies, assessing biomass potential at various regional, national, and global scales have been published. While few studies include all major feedstocks (e.g. Perlack et al. 2005), many focus on a single feedstock, such as agricultural residue assessments (e.g. Haq and Easterly 2006; Gallagher et al. 2003), and energy crop assessments (e.g. De La Torre Ugarte et al. 2003; Walsh et al. 2003). Comprehensive biomass feedstock assessments at the national level have been completed for the US and Canada (Wood and Layzell 2003; Milbrandt 2005; Perlack et al. 2005; Mabee et al. 2006). However, as Berndes et al. (2003) conclude from their review of 17 studies of biomass energy supply, the studies vary considerably in their assumptions, models, and methodologies employed, feedstocks covered, temporal and spatial scales, production technology projections, and policy scenarios.

Four general approaches have been taken in estimating biomass supply potential in these studies: (1) inventories of potential biomass sources with minimal attention to the economics of actual supply and prices at which these quantities will be available; (2) static supply curves which estimate quantities of biomass supplied at various exogenously determined prices assuming everything else remains constant; (3) projections of supply quantities in competition with other crops and uses, but under current productivity and policy conditions; and (4) dynamic projections of supply quantities in competition with other crops and uses, under projected/potential productivity and policy conditions, ethanol/gas prices and quantity mandates. In addition, some studies use a bottom-up approach where biomass potentials are assessed at local/regional level, which are then aggregated into national level estimates, while some other studies directly estimate national potentials based on national economic models. Published studies have used a mixture of these approaches and often within a single study, and the details of all the model and parameter assumptions are often not explicitly reported. As a result, estimates of bioenergy potential vary significantly across studies, and comparison and reconciliation of differences becomes difficult. A recent review of fifteen North American studies, carried out by Gronowska et al. (2009), also finds large variations in estimated potential biomass supply across those studies for these reasons.

In this study, supply quantities for various biomass feedstocks in the US and Canada are estimated using a bottom-up, static supply function approach. The relatively simple, but consistent approach will provide more realistic estimates of short term supply of biomass feedstocks. Such short-run estimates will be useful for assessing feasibility of proposed cellulosic ethanol facilities. While similar supply functions have been previously estimated for specific feedstocks or regions, a major contribution of this study is providing comprehensive estimates for both US and Canada, covering all major feedstocks.

METHODS

Estimates of biomass supply from agricultural residues, forest and mill residues, cellulosic portions of municipal solid waste (MSW), and energy crops were developed. The methods used for each feedstock are summarized below.

Agricultural Residues

For estimating the supply of agricultural residues a procedure similar to Gallagher et al. (2003) was followed. Agricultural residue supply functions were estimated at the individual county level for the US and at the census subdivision level for Canada. These supply functions were then aggregated to estimate national level supply functions. The steps in the estimation procedure are as follows.

The average crop output data for the years 2000-2002 was used to estimate the total quantity of residue generated, employing average residue factors, i.e. residue generated per ton of crop output. Assumed residue factors were 1.5, 1, 1, and 1.27 for barley, corn, rice, and wheat respectively (Heid 1984; Wyman 1996). Four major crops – corn, wheat, rice and barley – are considered for the US estimates. The crop output data are from National Agricultural Statistics Service (USDA - NASS 2008). How much of this total quantity of residue generated will be supplied to the market for conversion is a decision made by the farmers, which is governed by: regulatory restrictions on residue removal and soil cover to prevent soil erosion, residue harvesting, storage and transportation costs, opportunity cost of soil fertilization from leftover residues, animal feed value of the residue, and other opportunity costs. The residue that needs to be left on the field to prevent soil erosion depends on local topographic, soil, and wind conditions. It was assumed that recommended amounts of crop residues, which keep the soil erosion below the threshold levels, are left on the field as soil cover. Gallagher et al. (2003) estimate that for corn, 0.65 tons (t) per acre of chopped corn stover left in the fall fulfills soil erosion prevention requirements. Similarly for wheat and other small grains 0.32 t/acre of fall residues satisfy the requirement including the loss of residues during the winter (Wischmeier and Smith 1978). However, Gallagher et al. (2003) estimate the minimum residue requirement for winter wheat- fallow at 0.46t/acre. An average of these two estimates (0.39 t/acre) was used for wheat and barley, because detailed information on crop land under winter wheat/barley-fallow rotation was not available.

Next, the assumption was that if the price offered by ethanol conversion facilities is lower than the feed value of the residues, farmers will first sell the residues as cattle-feed until the local forage demand is met; however, at prices higher than the feed value, this additional quantity of residues will be supplied for conversion to ethanol. The estimates for the feed values are updated from Gallagher et al. (2003) and range from \$28.70/t (for wheat) to \$56.74/t (for corn) in 2008 dollars. The forage demand was estimated based on county livestock population and hay crop production using the relation: Forage demand = County Cattle Population * Daily Feed Requirements * (365 – Pasture feeding season length) – local hay production.

Excess residues after meeting soil conservation needs and the local animal feed requirements will be available for conversion to ethanol only if the price offered is high enough to compensate for the costs incurred for harvesting, storage and transporting the residues. Further, residues left on the field have some fertilizer value, which subsequently reduces fertilizer requirements for the next season. The price offered should also cover this lost fertilizer value. The harvesting and transportation costs and lost fertilizer values for different residues were estimated and it was assumed that farmers will supply remaining residues at a price equal to the sum of these costs. The main operations in harvesting include chopping, baling, and hauling. The chopping, baling and hauling (within the farm) expenses were updated using recent fuel prices and wage rates, from Gallagher et al (2003) which in turn were based on engineering estimates by Lazarus (1997). The estimated total costs were $25/acre on an average, which included chopping and baling costs estimated on per acre basis and hauling costs which were estimated on a per ton basis. These estimates however, assume that existing farm machinery for chopping and baling can be adapted for residue harvesting which may not always be the case. Fertilizer nutrient value of barley straw, corn stover, rice straw, and wheat straw were estimated at $14.20, $12.30, $10.30, and $9.50 per metric ton respectively (Gallagher et al. 2003).

The farm to factory gate transportation costs depend on the average transportation distance, which in turn depends on the density of crop residues and the size of the conversion plant. For a plant with an annual capacity of Q (in metric tons) of residues, the radius of the collection area (assuming a circular one) is $(Q/\pi d)^{0.5}$, where d is the density of residue availability in t/square mile. The average distance of collection is $0.67(Q/\pi d)^{0.5}$ (Gallagher et al. 2003). The county residue density d was calculated by dividing the total quantity of residue available after meeting soil conservation and cattle feed requirements, by the total land area of the county. Harvesting and transportation costs were calculated by using weighted average costs of different crops, where the proportion of the different crop residue available after meeting soil conservation requirement was used as a weighting factor. It was also assumed that the ethanol conversion plant had a processing capacity of 2000 metric tons per day (tpd) of residues and average transport costs were $0.40/ton mile in estimating transportation costs.

Similar procedures were employed to estimate agricultural residue supply functions for Canada. However, because Canada does not produce any rice, oats was considered instead of rice. A dataset at the Census Sub Division (CSD) level for Canada, similar to the county level dataset for the US was developed. Data on crop area harvested and cattle population were collected from 'Statistics Canada' publications. Average crop yield data (barley, corn, oats and wheat) for the years 1999-2003 are from Statistics Canada reports (Statistics Canada, 2006). The data are reported at the CSD level. Other parameters such as residue factors, feed value, fertilizer value, length of foraging season, etc., were assumed to be similar to those for the US. Because data on crop yields at the CSD level were not available, the average yield and residue density at the Canadian provincial level were assumed to be the same for all CSD within that province. The individual county/CSD supply functions were then aggregated to derive national level agricultural residues supply function for Canada.

Forest Residues

Forest residues comprise of logging residues that are generated during the harvesting operations, and mill residues that are generated in saw mills, paper mills, and other wood processing units. Logging residues are currently left at harvesting sites and hence need to be collected and transported from the forests, while mill residues are available at processing facilities and currently being used either as fuel or as raw material for other wood products.

Milbrandt (2005) reports the total quantities of logging residues and mill residues produced in various states of the US, which are based on the USDA Forest Service's Timber Product Output database for 2002. Logging residue quantities for Canada were computed from the total roundwood production reported at provincial level in Canadian national forestry database for the year 2006 (NFDP 2007). For Canada, it was assumed that logging residue production would be16% of the total roundwood production (Mabee 2006). In comparison, logging residue estimates for the US, vary between 4% and 28% of total roundwood production (Smith, et al., 2004). Data on the quantity of Canadian mill residues were drawn from Bradley (2006).

It was assumed that all the logging residues produced in a US state or Canadian province would be available at a price equal to the sum of grinding costs and transportation costs. Mill residues were assumed to be available for conversion if the price offered was greater than the opportunity cost of their current use as fiber, fuel, or other feedstocks. The US state level estimates of mill residues used as fiber, fuel, and other applications were from Milbrandt (2005). The opportunity costs for the various types of residues were estimated based on their current use: the mill residues used for fiber products (pulpwood) were valued at $36/dry ton (dt), the fuel use was valued at $23.65/dt (i.e. $1.25/million BTU based on coal price), and all other uses were valued at $16/dt. Fuel value was estimated using coal price because biomass is usually co-fired with coal in boilers for heat or power production. The remaining residues that are not currently used were assumed to be available for free (Petrolia 2006). It was assumed that logging residues were chopped and ground onsite, and hence were uniformly distributed in the timberland area of the region being considered and the average transport distance required to supply a 2000 tpd ethanol plant was calculated using similar methods as outlined above for agricultural residues. The logging residues from the forests were valued at their fuel use value ($23.65/dt), which would be their opportunity costs in heat and power production. The estimated average distance for collection of forest logging residues varied between 19 to 55 miles based on the state geographic area and density of forest residues. These distance estimates were combined with the transportation cost of $0.40 per ton-mile as in the previous case to compute the transportation costs. Since mill residues were readily available at the processing facilities (like paper and pulp mills) a transport cost of $5/t was assumed for mill residues. The estimated state/province level supply functions were then aggregated to estimate the national supply functions.

Municipal Solid Wastes

The USEPA and the *BioCycle* magazine annually estimate the total quantities of municipal solid waste (MSW) generated, recovered, and discarded in the US. The USEPA estimates are at an aggregate national level based on material flow analysis, while the *Biocycle* estimates are based on an annual survey of state level MSW officials. In Canada, Statistics Canada publishes biannual data on waste disposal and diversion at the provincial level. We use state level estimates of MSW generated from the 15th annual survey conducted by the BioCycle magazine and Earth Engineering Center of Columbia University (Simmons et al. 2006). It was assumed that 66% of the wastes were organic materials suitable for cellulosic ethanol production, based on estimates from USEPA (EPA, 2008). An average moisture content of 40% was assumed in deriving dry biomass equivalent of MSW feedstock, based on estimated moisture content of various constituents in MSW which can vary from 2 to 70% (Reinhart 2008).

Since a well established collection system for MSW is currently operating, and tipping fees are paid to dispose MSW, all the lignocellulosic portion of MSW is essentially available (albeit at the landfill) at a negative price equivalent to the current landfill tipping fee. The tipping fees in 2006 ranged from $21/t to $123/t in the US and from $40/t to $75/t in Canada (Chartwell Solid Waste Group 2007; City of Guelph 2008; City of Windsor 2008). The total quantity of MSW currently landfilled in a state/province was assumed to be available at a negative price equivalent to the average tipping fee for the particular US state or Canadian province. Because the cellulosic portion of MSW needs to be separated from other constituents before conversion to ethanol, estimated separation/sorting and transportation costs of $55/wet ton were added to the negative price to estimate the ethanol feedstock supply price. The processing cost estimate is based on an update of a previous estimate (BWPRR, 2004). The state (province) level quantity and price data were then combined to estimate the total quantity of MSW feedstock supplied at various prices at national level.

Energy Crops

The potential supply of energy crops when they are competing with conventional crops is a complex function of several factors. Farmers will switch to energy crops only if expected returns from the energy crops are higher than returns from growing conventional crops and/or keeping the land idle under conservation programs such as the US Conservation Reserve Program (CRP) and collecting rental payments as well as the government support payments. In addition to switching to energy crops, farmers will also be switching between conventional crops based on relative expected returns. These returns are governed by expected prices for different crops, yield, and production cost structure for energy crops compared to that of conventional crops. These costs and yields also differ by the geographical location. Hence, the estimation of potential supply of energy crops has to be carried out using an integrated model of agriculture that incorporates the inter-dependencies across individual commodity grain, livestock, dairy, consumption, and international sectors, as well as agricultural policy variables. Most of the current projections of energy crop supply in the US, are derived from an integrated comprehensive model of US agriculture, POLYSYS, developed and maintained by the Agricultural Policy Analysis Center (APAC), University of Tennessee, Knoxville (De La Torre Ugarte et al. 2000; McLaughlin 2002; De La Torre Ugarte et al. 2003; Walsh et al. 2003; De La Torre Ugarte 2004; Perlack et al. 2005; Walsh, 2008). In fact, most of the estimates of bioenergy crop supply published by the US Department of Energy (USDOE) and US Department of Agriculture (USDA) draw on the POLYSYS model estimates. For example, see Perlack et al. (2005) and De La Torre Ugarte et al. (2000, 2003). However, estimates of energy crop supply using the POLYSYS model vary significantly, depending on variations in the underlying production/supply constraints, and assumptions about energy crop productivity, relative profitability and policy variables.

To derive static supply curves for energy crops that were consistent with other biomass feedstock estimates, a relatively simple approach was used. It was assumed that farmers will potentially divert land from current traditional crops to energy crops (e.g. switchgrass) if the 'returns over variable costs' (ROVC) for switchgrass were more than the returns over variable costs for the traditional crops. Since the current ROVC were adequate enough to cover the fixed costs such as land value and opportunity costs of labor and overhead charges, and retain the land under production, a higher ROVC from energy crop production would make switching to energy crops attractive.

Using county level crop production data from USDA - ERS, gross revenues per acre for various crops namely – corn, soybeans, wheat, rice, barley, oats, and cotton at the county level, were calculated using state average commodity prices and variable costs of production (USDA - ERS, 2008). The variable costs of production included the costs of seeds, fertilizers, pesticides, energy for machinery operations, and custom work. The returns over variable costs (ROVC – which is an estimate of fixed costs of agricultural production that are being covered currently) were calculated by subtracting these variable costs from total revenues. Average ROVC for the period 2002-05 for all major crops in each US County along with harvested acreages were computed. Government payments were not included in ROVC estimates because these payments have been effectively decoupled from commodity production since the passage of Farm Bill 2002 (Ahearn et al. 2004).

Next, ROVC for growing switchgrass at various switchgrass prices were estimated at the county level. Counties in the eastern half of the US, including the Dakotas, Oklahoma, and Texas, where switchgrass can be grown under rain-fed conditions were considered. To account for differences in state level yields and costs of production, the states were divided into three regions: south, central, and north. In the southern region (AL, AR, FL, GA, KY, LA, MS, NC, OK, SC, TN, TX, VA, WV) the energy crop yield was assumed to be higher at 8 dt/acre at an average variable cost of \$259.56 per acre (Tiller 2008). In the central states (IL, IN, IA, KS, MO, NE, NY, OH, PA) the yield was assumed to be 4.45 dt/acre at an average variable cost of \$211.71/acre (Perrin et al. 2008). The northern states (CT, DE, ME, MD, MA, MI, MN, NJ, RI, SD,VT, WI) are located in much colder climates, and the yields were found to average only 2.79 dt/acre with variable costs of \$128.32 per acre (Vadas et al. 2008). The variable costs include seed costs, initial establishment costs, fertilizer costs, harvesting costs, and baling costs. It was assumed that once established, switchgrass can be harvested over a period of 10 years. These yield and production costs are based on realized values in pilot studies, and since energy crops are not yet grown widely in the US or Canada, the estimated ROVC from switchgrass should be considered indicative rather than definitive. Further improvements in switchgrass yields and production costs are also likely. Although other energy crops such as miscanthus and energy cane have been considered potentially attractive, the analysis is limited to switchgrass, to be consistent with previous analyses (De La Torre Ugarte et al. 2000; De La Torre Ugarte et al. 2003; Perlack et al. 2005).

The average annual ROVC of field crops were compared with ROVC from switchgrass at various switchgrass prices and it was assumed that 10% the land currently earning lower ROVC than that of switchgrass would be converted to energy crop production.[1] A variety of factors affect the crop-switching decision including subsequent changes in relative crop prices and returns as a result of crop switching, land characteristics, local weather/rainfall conditions, expectations, farmer expertise, and risk preferences. 10% land conversion was used as an indicative aggregate constraint resulting from all these considerations. The estimates using this simplification are consistent with the earlier work using POLYSYS models that estimated 5 to 14 per cent of crop land being converted into energy crops (English et al. 2006; Walsh 2008). Transportation costs from the farm to factory gate were estimated employing a similar approach as for agricultural residues.

Canadian energy crop supply

The Whole Farm Database managed by Statistics Canada reports harvested acres and total revenues for various crops at the Census Agricultural Region level (table series C) in Canada (Statistics Canada 2006). However the expenditure data are not available separately by individual crops but aggregate expenditure per acre for the portfolio of crops is available. Hence the average farm ROVC (dollars per acre) from the existing 'portfolio' of crops was compared with the potential returns from energy crops. The Canadian crop portfolios included the major crops such as wheat, oats, barley, rapeseed, soybeans, corn, small grains, and forage crops. The land area switching to energy crops at various energy crop prices was estimated using similar procedures outlined above for the US energy crops.

RESULTS

US Biomass Supply

Figure 1 and Table 1 summarize the biomass supply estimates for the US. The supply curves are shown only up to the price level of $100 per dry metric ton (dt), beyond which biomass use for ethanol conversion will likely be uncompetitive. The total biomass potentially available in the US, at a price of $100/dt is 568 million dt, comprising of about 250 million dt (44% of total supply) of agricultural residues, and 135 million dt (24%) of forest and mill residues. Under the assumption of planting a maximum of 10 per cent of crop land in the eastern half of US, energy crops such as switchgrass and miscanthus would approximately yield 107 million dt of biomass, of which about 85 million dt will be available at a price of $100/dt.

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[1] To illustrate, Baldwin County (FIPS code 1003) in Alabama had an average of 4,250 acres under corn, 10,167 acres under soybeans and 7,933 acres under wheat crop during 2002-05. The net returns over variable costs for those crops during those years were $140, $109 and $61 per acre respectively. If the energy crops were able to generate a return of $50 per acre, then none of the land under these crops would be diverted to energy crops. But if the ROVC from energy crops were $125 per acre, then we assume that 10% the soybeans and wheat acreage will be converted to energy crops as the latter is more profitable.

From Table 1, it can be seen that 384 million dt of this biomass will be available at price of $50 /dt in the US – primarily from agricultural residues and forest feedstocks. Compared to that the minimum price at which switchgrass starts becoming available is $67/dt. The reasons for higher prices for energy crops are two-fold: (i) the field crops that are displaced by energy crops generate higher returns, raising the break even prices of energy crops, and (ii) the yield of energy crops is currently low in temperate climates. In fact, some studies consider energy crops as future (third generation) biomass feedstock after corn grains and agricultural/forest residues (BRDB 2008). A total of 98 million dt of MSW is potentially available for cellulosic ethanol production; however only less than a third of MSW will be available at price of $50/dt, due to higher MSW processing costs.

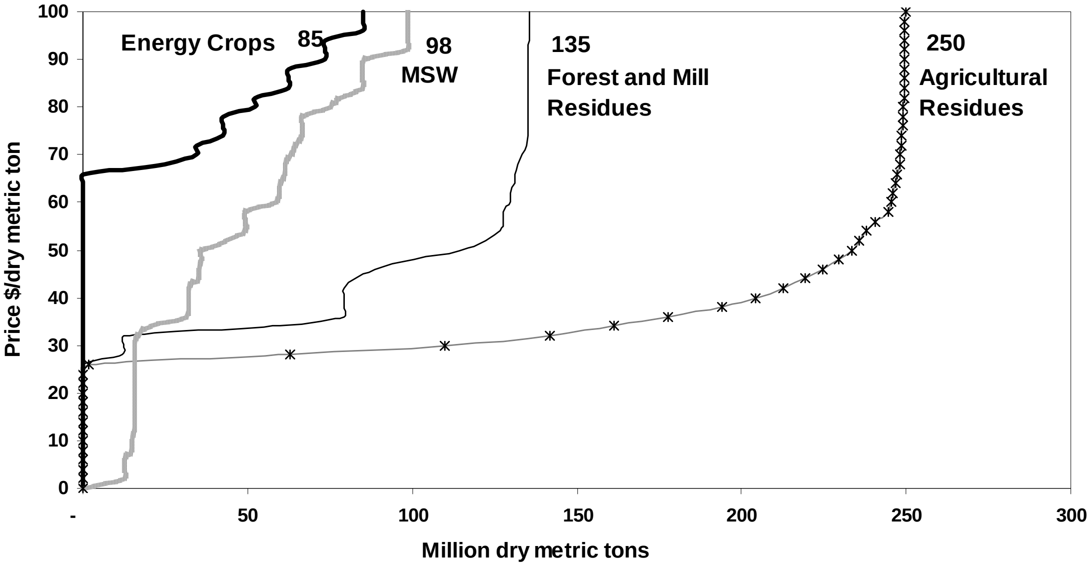

Fig. 1: Biomass supply curves for the US

Table 1. Biomass Supply Estimates for the US

Price at biorefinery gate ($/dt)	Quantity supplied million dry metric tons				
	MSW	Agricultural-residue	Forest and Mill residues	Energy crops	Total*
30[a]	15	110	12		137
40	32	204	80		315
50	36	234	114		384
60	58	245	130		434
70	63	248	133	35	480
80	75	249	135	52	512
90	86	250	135	73	544
100	98	250	135	85	568

[a] in 2008 US dollars

* Total quantities are different from the summed up values due to rounding

Canadian Biomass Supply

The potential total biomass supply in Canada is 123 million dt, with agricultural residues (42 million dt) and forest/mill residues (43 million dt) constituting 60 per cent of the supply. As shown in Table 2, the biomass in Canada is likely to be more expensive than in the US. At a price of $50/dt, only one-fourth of all potential biomass would become available in Canada, compared with nearly two-thirds in the US. The reasons are three fold: (i) the lower agricultural cropping density in Canada (due to cooler climate) leads to higher transportation costs; (ii) the yield of biomass is lower due to temperate climate, and (iii) the lower population result in lower MSW generation. Unlike in the US, agricultural residues are more expensive than forestry feedstocks in Canada; the main reason being increased transportation costs due to lower cropping density. MSW and energy crops are costlier in the Canadian case as well. Energy crop supplies are 31 million dt at $100/dt. However, if switching to energy crops occurs in 20% of all agricultural land with lower ROVC than switchgrass, then energy crop supply can nearly double to 61 million dt in Canada

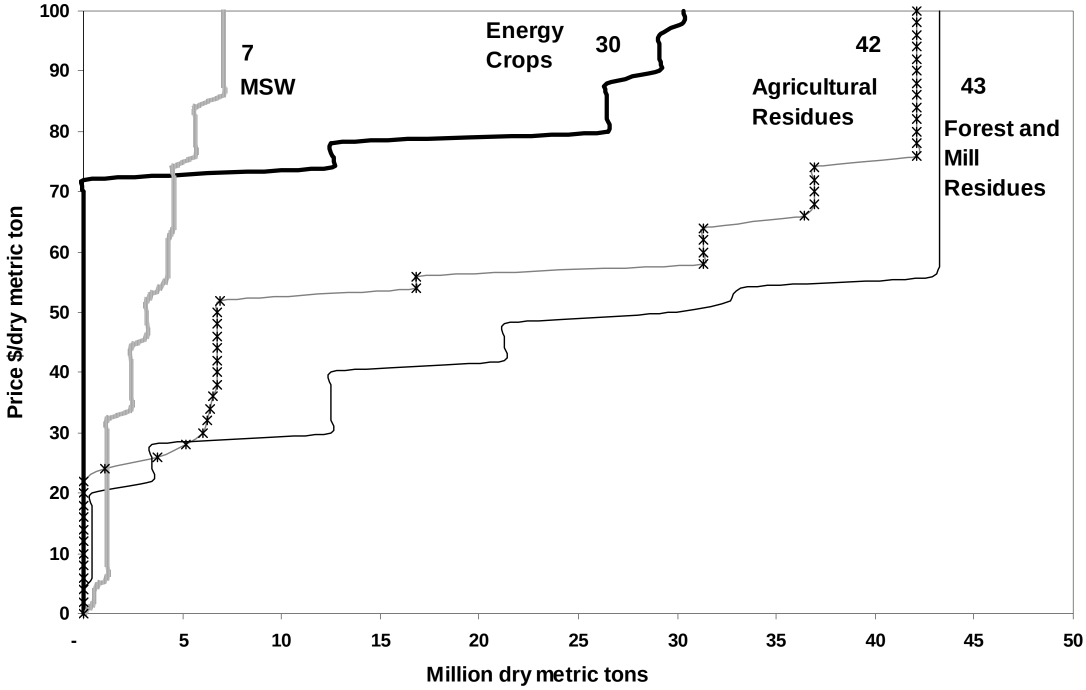

Fig. 2: Biomass supply curves for Canada

The renewable fuel standard provisions under the US Energy Independence and Security Act, 2007 mandate using 21 billion gallons of advanced biofuels for transportation by the year 2022, including 16 billion gallons of cellulosic ethanol (EISA, 2007). At a conversion rate of 70-100 gallons/dt the biomass requirement to supply 21 billion gallons is 210-300 million dt. These results suggest that this quantity of biomass (required by 2022) is readily available under current conditions at prices below $50/dt.

Table 2: Biomass Supply Estimates for Canada

Biomass Price $/dt*	Quantity Available (million dry metric tons)				
	MSW	Agricultural residue	Forest and Mill residues	Energy crops	Total**
30	1	6	12		20
40	2	7	12		22
50	3	7	30		40
60	4	31	43		79
70	5	37	43		85
80	6	42	43	26	117
90	7	42	43	30	121
100	7	42	43	31	123

* At biorefinery gate in 2008 US dollars
** Total quantities may differ from the summed up values due to rounding

Table 3 presents the amount of biomass required to produce 7, 14, and 21 billion gallons of cellulosic ethanol and estimated composition of biomass supplied to meet these requirements. Almost all (97%) of biomass required for meeting the advanced biofuel provisions of EISA 2007 is likely to be various types of residues, with agricultural residues accounting for 61%, followed by forest and mill residues (27%). Dedicated energy crops are likely to be a minor source.

Table 3: Biomass Feedstock Requirements and Expected Composition to meet Cellulosic Ethanol Production Targets in the US

Ethanol production target billion gal (at 70 gal/dt)	7	14	21
Required biomass (million dt)	100	200	300
Agricultural Residues	67.3	147.0	180.0
Energy crops	-	-	9.0
Forest and Mill Residues	12.0	22.0	80.0
MSW	20.7	31.0	31.0

Geographical Distribution

Table 4 shows the geographical distribution of feedstocks required to meet EISA 2007 mandates. The corn-belt states that supply agricultural residues account for the largest quantities of biomass for biofuel production, followed by states like Texas, Georgia, and Oregon supplying significant quantities of forest and mill residues. It should however be noted that the states near the bottom of Table 4 are unlikely to have cellulosic ethanol plants, due to low quantities of biomass available, which would not be adequate to exploit the significant economies of scale observed in biorefineries. Mill residues account for almost all of the 80 million dt of forest and mill residues supplied. Collecting logging residues was found to be uneconomical at prices below $50/dt. Energy crops are competitive with field crops in south-eastern states, Carolinas, Tennessee, Texas, and Oklahoma at prices around $50/dt.

Table 4: Geographical Composition of Feedstock Mix to meet EISA Mandates (Biomass Quantity Target: 300 million dt)

State	Agricultural Residues	Energy Crops	Forest and Mill Residues	MSW	Total
Illinois	34.79	-	0.33	5.91	41.02
Iowa	38.27	-	0.16	-	38.43
Minnesota	18.95	-	1.04	0.84	20.83
Nebraska	20.09	-	0.07	-	20.16
Indiana	16.06	-	0.65	-	16.71
Michigan	4.34	-	1.40	4.51	10.25
Washington	2.31	-	5.68	1.94	9.93
Ohio	8.70	-	0.91	-	9.61
Texas	3.21	3.36	2.23	-	8.80
Georgia	0.09	0.66	7.33	-	8.08
Oregon	0.06	-	6.54	0.87	7.47
Wisconsin	5.47	-	1.69	-	7.16
Florida	-	0.09	2.03	4.57	6.69
Idaho	2.18	-	4.42	-	6.60
Alabama	0.01	0.66	5.91	-	6.59
South Dakota	5.92	-	0.15	-	6.07
California	0.92	-	5.02	-	5.94
Missouri	4.63	-	1.11	-	5.73
Pennsylvania	0.08	-	1.49	3.52	5.08
North Carolina	0.18	0.85	4.02	-	5.04
Mississippi	0.39	0.07	4.58	-	5.04
Virginia	0.24	0.17	2.21	2.06	4.68
Louisiana	0.80	0.09	3.61	-	4.50
Kentucky	2.40	0.58	1.49	-	4.46
Arkansas	0.31	-	3.66	-	3.96
Kansas	3.25	-	0.05	-	3.30
Tennessee	0.83	0.58	1.63	-	3.04
South Carolina	-	0.51	2.51	-	3.02
Oklahoma	0.86	1.09	0.66	-	2.60
Montana	0.46	-	1.95	-	2.41
Maryland	0.65	-	0.17	1.36	2.18
New Jersey	-	-	0.08	1.98	2.06
West Virginia	-	0.46	0.82	0.58	1.86
Colorado	1.37	-	0.22	-	1.60
New Hampshire	-	-	0.94	0.39	1.33
New York	0.07	-	1.18	-	1.25
Massachusetts	-	-	0.17	0.98	1.14
North Dakota	1.01	-	0.01	-	1.01
Delaware	0.46	-	0.02	0.35	0.83
Other States	0.13	-	1.4	1.14	2.67
US Total*	**180.00**	**9.00**	**80.00**	**31.00**	**300.00**

* Sum of state biomass supply may not equal US totals due to rounding

Table 5 presents the geographical distribution of biomass supply at a price of $100/dt in Canada. Agricultural provinces of Saskatchewan, Alberta, and Ontario account for most of agricultural residues and energy crops, while forest and mill residues account for most supplies in British Columbia and Quebec. Compared to US, a larger proportion of crop land is expected to convert to switchgrass production on account of relatively lower profits from traditional row crop production Canada.

Table 5: Canada Geographic Distribution

	MSW	Agricultural residues	Forest residues	Mill residues	Energy crops
Saskatchewan	0.27	16.68	0.54	0.52	16.82
Alberta	0.86	13.27	2.73	2.63	7.17
British Columbia	0.67	-	8.70	8.40	0.14
Ontario	2.46	5.54	2.91	2.81	1.53
Manitoba	0.35	6.17	0.24	0.23	4.52
Quebec	2.06	-	4.55	4.40	0.14
Other Provinces	0.32	0.16	2.32	2.24	0.01
Canada Total*	**7.00**	**41.81**	**21.99**	**21.23**	**30.33**

* Sum of province biomass supply may not equal totals due to rounding

COMPARISON WITH RECENT ESTIMATES

Walsh (2008) estimates that a total of 283 million dry short tons (256 million dt) of biomass will be available at a price of $100/dry short ton ($110/dt) in 2010, consisting of 101 million dt of agricultural residues, 18 million dt of urban wastes, 54 million dt of forest residues, 52 million dt of mill residues, and 31 million dt of switchgrass. These estimates are substantially lower than our estimates. The reasons for the differences are discussed below. Walsh's study was chosen because its results are being used as inputs in USEPA's regulatory impact analysis of EISA, 2007 (EPA 2009), and for ongoing update of the US biomass inventory by Perlack et al. (2005), which itself was based on an earlier study by Walsh. Since comparable studies of Canadian biomass supply curves were not available, this comparative analysis is limited to the US.

Walsh estimates that 101 million dt of agricultural residues will be available by 2010 at a price of $110/dt, compared to our estimate of 250 million dt. The difference arises mainly from assumed percentage of available residues that are collected for ethanol conversion. Our analysis assumes that the recommended level of residues to reduce soil erosion below tolerable levels will be left on the field, which results in collection rate of 76% of available residues. In comparison, estimates by Walsh (2008) implicitly assume a collection of only 33-45% of available residues. Walsh estimates the amounts of residues that should be left on the field to maintain soil carbon and organic matter levels in addition to soil erosion control. Our estimates only include mandatory soil erosion control requirements, but incorporate opportunity costs of soil fertility maintenance. What is the sustainable residue removal rate is a subject of debate (Wilhelm et al. 2004; Andrews 2006). Our estimates are consistent with the 'Billion ton' study by Perlack et al. (2005), which assumes removal of 70-80% of residues from the fields. If the collection is limited to about 40% of available residues, our estimates are similar to those by Walsh (2008). Moreover, Walsh's estimates consider only corn-stover and wheat straw, while our estimates include residues from other crops, namely rice, barley, and oats.

For estimating urban wastes, Walsh only considers wood portions of urban wastes; but, in this study all organic components of MSW including paper, wood, yard trimmings, and food waste are included as potential feedstocks for ethanol conversion. Paper and food wastes accounted for 32.7% and 12.5%, respectively, of total MSW generated in the US, compared wood and yard trimmings, which accounted for 5.6% and 12.8% respectively (USEPA 2008). Technologies for converting all organic fractions of MSW into biofuels are reportedly available, e.g. gravity pressure vessel process from Genesyst Inc. (Kalogo et al. 2007; Genesyst 2009). Walsh further adjusts the wood waste quantities downward by 53% to account for contamination by paints, chemical treatment, adhesives, etc.

Our estimates of forest and mill residues consist of 55 million dt of logging residues and 80 million dt of mill residues. The logging residue estimates are very similar to those by Walsh. Walsh's assumption that 10% of mill residues are not usable because of too small particle size helps explain some of the difference in mill residue estimates. Additional differences may arise because Walsh's residue estimates are based on projected harvest rates for 2010, while our estimates are based on actual harvests in 2002. Enough details are not available to reconcile all the differences.

With regard to energy crops, Walsh projected 31 million dt by 2010 at a price of \$110/dt. Our estimate is 85 million dt of energy crops at \$100/dt. Her estimates are based on dynamic projections from the POLYSYS model. While POLYSYS model compares energy crop returns with field crop returns (similar to our approach), it also imposes various 'flexibility constraints.' For example, changes in acreages under different crops are limited to a maximum of 20% from the previous year, and conversion of pasture lands to energy crops is accompanied by corresponding increase in hay crop output to meet animal feed requirements. In comparison, we employ a much simpler and cruder assumption that 10% of all cropland with current economic returns lower than switchgrass returns will shift to switchgrass. Further, in POLYSYS crop prices are determined endogenously within the model and hence are likely to be higher in the future, which makes energy crops relatively unattractive. Our ROVC estimates are based on historical costs. As a result, our energy crop supply estimates are higher and represent more optimistic estimates. The above comparison also demonstrates the sensitivity of the estimates to underlying assumptions and modeling, which can lead to large variations in biomass supply estimates across studies as pointed by Berndes et al. (2003) and Gronowska et al. (2009).

CONCLUSIONS

The analysis suggests that more than 500 million dt of biomass is available at price of \$100/dt in the US, while Canadian supplies are limited to 123 million dt. Assuming ethanol yields of 70-95 gallons of ethanol/dt, the biomass quantity is sufficient to displace 27-37 billion gallons of gasoline in the US and 5.8-7.8 billion gallons of gasoline in Canada. Biomass quantities necessary to meet advanced biofuel provisions of EISA 2007 will be available at prices around $50/dt. Agricultural residues such as corn stover are the cheapest and most abundantly available sources of biomass, followed by mill residues. Forest residues and energy crops are likely to play minor role in meeting EISA 2007 mandates. At current productivity levels, energy crops are not competitive with conventional crops in the prime agricultural areas of the US. However in some southern states such as Texas, Oklahoma, and Tennessee, energy crops may be able to compete with conventional crops, and hence dedicated energy crop plantations are likely to appear first in these states. For example, a 1000 acre switchgrass plantation is being developed by Oklahoma Bioenergy Center, and University of Tennessee in contracting with farmers to grow switchgrass for the proposed Dupont-Danisco cellulosic ethanol plant (OBC 2008; UTK 2008). Energy crops may be more attractive in Canada because of relatively lower returns from traditional crops. Saskatchewan and Alberta will be major sources of both agricultural residues and energy crops, while British Columbia and Quebec will be major sources of forest and mill residues.

The estimates of agricultural residue supply are very sensitive to the assumed fraction of residues that can be sustainably removed from the field. Similarly, the potential of MSW as a feedstock depends on which components (e.g. food, paper, wood) can be economically converted into liquid biofuels. Yields of energy crops need to improve significantly from current levels to make them competitive with conventional crops. Hence future research is needed in these areas. Finally, the static supply function approach taken in this study, while is relatively simple and transparent, inadequately accounts for several factors that influence future biomass supplies, such as productivity gains, harvesting and conversion technology improvements, inter-temporal variations in yields, costs and returns, potential effects of indirect land use changes, policy interventions, and international trade effects. These limitations have to be kept in mind while interpreting and drawing policy conclusion from the reported results.

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