A REVIEW OF U.S. AND CANADIAN BIOMASS SUPPLY STUDIES

Magdalena Gronowska,[a] Satish Joshi,[b] and Heather L. MacLean[a,c*]

An improved understanding of lignocellulosic biomass availability is needed to support proposed expansion in biofuel production. Fifteen studies that estimate availability of lignocellulosic biomass quantities in in the U.S. and/or Canada are reviewed. Sources of differences in study methods and assumptions and resulting biomass quantities are elucidated. We differentiate between inventory studies, in which quantities of biomass potentially available are estimated without rigorous consideration of the costs of supply, versus economic studies, which take into consideration various opportunity costs and competition. The U.S. economic studies, which included reasonably comprehensive sets of biomass categories, estimate annual biomass availability to range from 6 million to 577 million dry metric tonnes (dry t), depending on offered price, while estimates from inventory studies range from 190 million to 3849 million dry t. The Canadian inventory studies, which included reasonably comprehensive sets of biomass categories, estimate availability to range from 64 million green t to 561 million dry t. The largest biomass categories for the U.S. are energy crops and agricultural residues, while for Canada they are expected to be energy crops and logging residues. The significant differences in study estimates are due in large part to the number of biomass categories included, whether economic considerations are incorporated, assumptions about energy crop yields and land areas, and level of optimism of assumptions of the study.

Keywords: Biomass supply; Resource assessment; Lignocellulosic biomass

*Contact information: a: Department of Civil Engineering, University of Toronto, 35 St. George St. Toronto, ON Canada M5S 1A4; b: Department of Agricultural Economics, Michigan State University, East Lansing, MI USA 48824; c: School of Public Policy and Governance, University of Toronto. *Corresponding author: email: hmaclean@ecf.utoronto.ca*

INTRODUCTION

Geopolitical issues surrounding petroleum and its volatile price, along with promise of improved environmental performance, have led to policies promoting domestically produced renewable transportation fuels and have motivated the associated rapid expansion of the biofuels industry. In North America, renewable fuel expansion programs such as the U.S.'s Energy Independence and Security Act of 2007, which mandates 49 billion L of renewable liquid transportation fuels by 2010 and 138 billion L by 2020 (RFA 2008); and Canada's required 5% renewable fuel content in gasoline by year 2010 are encouraging increased biofuel production. In 2007 the U.S. produced 26.5 billion L of ethanol and 1.7 billion L of biodiesel, while Canada produced 1 billion L of ethanol and 97 million L of biodiesel (FAO 2008). The majority of ethanol production was from corn grain, and the majority of biodiesel was from soybean oil in the U.S. and from waste oil/grease in Canada. In spite of these considerable quantities, the amounts represent just 5% of U.S. and 2% of Canadian gasoline consumption (by volume).

Recent public, governmental, and other stakeholder outcry about escalating food commodity prices and food versus fuel debates are increasingly motivating the development of alternative biofuels that are not produced from food crops. In addition to facilitating the realization of national renewable fuel targets, lignocellulosic biomass feedstocks are a potentially attractive option from energy security, economic, social, and environmental standpoints. Lignocellulosic feedstocks, often referred to as "second generation" feedstocks, include residues, wastes, and "energy" crops – crops grown specifically for the purpose of converting them into energy. These feedstocks can stimulate local, rural economies, increase domestic biofuel production, and can be utilized to produce a wide range of products. Farrell and Gopal (2008) present a comprehensive set of biomass conversion pathways involving final energy and other end-products. De La Torre Ugarte et al. (2007) predicted that as many as 229 billion L of ethanol, derived from lignocellulosic feedstocks, can be produced annually in the U.S. by the year 2030, injecting $360 billion of cumulative economic gains, creating 2.4 million new jobs, and reducing petroleum imports by $629 billion between the years 2007 and 2030. Compared to grain ethanol, lignocellulosic ethanol has considerably lower life cycle greenhouse gas emissions (Wang et al. 2007) and can offer other environmental benefits. Furthermore, the use of lignocellulosic biomass can reduce the demand for "first generation" feedstocks (sugar, starch and oilseed crops); in addition, it has the potential to provide animal feed (Carolan et al. 2007). A disadvantage of these feedstocks is that they are "recalcitrant" and more difficult to break down than sugar and starch feedstocks. Therefore, they require advanced conversion technologies, which are not yet at a commercial scale, but are undergoing rapid development. For example, six commercial second-generation ethanol plants are anticipated to come on line by 2011 in the U.S. They will utilize agricultural residues, energy crops, and wood waste to produce a combined annual cellulosic ethanol output of over 500 million L (USDOE 2007).

An improved understanding of lignocellulosic feedstock availability is critical for assessing the potential of biofuels and facilitating the development of appropriate biofuel policies and regulatory initiatives. International organizations such as the World Energy Council (2001) have emphasized that effective decision-making on energy issues is constrained by incomplete inventories and uncertainty or discrepancies among estimates. A number of recent studies have been published which estimate the lignocellulosic biomass potential in various regions worldwide. Berndes et al. (2003) reviewed 17 biomass supply studies that presented estimates on a global scale. These estimates ranged from 47-450 EJ/yr, compared to the global primary energy consumption of 487 EJ in 2005, which is projected to increase to 732 EJ by 2030 (USDOE, 2008). Berndes et al. attribute the range largely to differing assumptions about energy crop yields, land availability, competing uses for feedstocks, and exclusion of major feedstock categories in some studies. They conclude that energy crops, forest biomass, and agricultural residues are expected to become the most significant contributors to future biomass supply globally. Binder et al. (2007) also reviewed global biomass studies by including the estimates of three more recent studies in addition to those included in the study of Berndes et al., and concluded that biomass can potentially contribute 250-500 EJ/yr by

2050, although some pessimistic estimates are as low as 2% of the World's primary energy consumption.

In spite of a number of studies that report biomass estimates for the U.S. and/or Canada and the importance of improving our understanding of biomass availability in order to support future industry development in these countries, there has not been a comprehensive review of these studies, although one study each for the U.S. and Canada has noted selected prior biomass estimates. For the U.S., Walsh (2008) provides rigorous estimates of cellulosic biomass supply at various prices at the detail of individual counties in the U.S. Her estimated aggregate supply of cellulosic biomass in the U.S. ranges from 6 million dry metric tonnes (dry t) at a price of $22 dry t to 256 million dry t at a price of $110/dry t for the year 2010, increasing to a range of 46 million to 577 million dry t by the year 2020 at these prices. Walsh also qualitatively and quantitatively summarized several prior studies that conducted economic analyses of biomass supply. However, previous estimates of individual biomass feedstock were discussed prior to Walsh presenting her estimates, but a comparative analysis of the range of estimates obtained in the prior literature was not included. For Canada, Layzell et al. (2006) reviewed estimates of biomass energy potential from three previous studies and found that the estimates ranged from 425 million to 1000 million dry t per year. However, these reviews cover only a limited number of prior studies and do not systematically identify and present the sources of observed differences in feedstock estimates.

The overall objective of this paper is to investigate lignocellulosic biomass supply for the U.S. and Canada by: 1) critically evaluating a large set of biomass supply studies in the published literature and comparing their inventory estimates, and, 2) elucidating key sources of differences in the studies and parameters influencing biomass availability. The scope of the analysis is limited to U.S and Canada, mainly to enable more in-depth review. Further, prior studies of global biomass supply have already been reviewed by Berndes et al. (2003) and Binder et al. (2007). Although markets for liquid biofuels are likely to be global, biomass markets will mostly be regional due to low biomass bulk density and high transportation costs. Hence such regional studies will be useful.

APPROACH

Academic, governmental, and industrial literature were reviewed to identify studies reporting lignocellulosic biomass availability for the U.S. and Canada. To be included in the analysis, the following criteria had to be satisfied by the studies. 1) The studies either specifically focused on, or reported disaggregated country-level results for the U.S. and/or Canada. (2) Studies investigating biomass availability only at a state or provincial level were excluded, as were global biomass comparisons that did not disaggregate U.S. and Canadian estimates. 3) The biomass resource assessment estimates were based on primary research, i.e., they did not exclusively use biomass inventory results of other researchers. This criterion eliminated redundancy and ensured that the estimation methodology was available. Studies were not eliminated, however, if they used common data sources to generate their estimates (e.g., yield, residue, or waste production data). 4) The studies' primary intent was to quantify biomass availability or to demonstrate sufficient supply for bioenergy purposes, and the assumptions and estimation methodology were reasonably transparent. 5) The estimates presented in the studies were comprehensive representations of the respective biomass categories, permitting equivalent comparisons, and, 6) If a study was revised by the authors, only the estimates of their most recent study were included in the analysis. For example, we excluded Antares (1999), which has been previously used in the U.S. Department of Energy's modeling, because these estimates have been updated by more recent studies by others. Similarly Graham et al. (2007) and Kadam and McMillan (2007) were excluded because they investigated only one type of agricultural residue, namely corn stover. Other studies excluded for some of the above reasons include Love (1980), Kim and Dale (2004), Walsh et al. (2000), McLaughlin et al. (2002), Etcheverry et al. (2004), Layzell et al. (2006), Champagne (2007), and Levin et al. (2007). Based on the above criteria, fifteen studies (listed in Table 1) were selected for detailed review.

Lignocellulosic biomass estimates were grouped into six categories; energy crops, agricultural residues, logging residues, mill residues, forest resources, and urban wastes. Other feedstocks reported by some studies, such as manure, are not included in our analysis. The energy crop category includes lignocellulosic crops grown for the purpose of converting them to energy, such as herbaceous crops (e.g., switchgrass) and short rotation woody crops (e.g., hybrid poplar, willow). The agricultural residue category consists of the lignocellulosic portions of the plant remaining after primary harvest. Lignocellulosic biomass originating from the forest is disaggregated into three categories because the biomass originates from different sources and operations. The first two categories are comprised of residues produced by industry. Logging residues are generated from forest management and harvesting activities. Other removals such as downed stock or those from cultural and land-clearing operations are also included in this category, because these materials are commonly grouped together in the studies, or, because they could not be disaggregated from logging residues. Mill residues are produced by wood processing operations and include primary and secondary mill residues, as well as pulping residues. In the forest resources category, we grouped fuel treatment, thinning activities, and the standing forest biomass harvested for "fuelwood". Lastly, the urban waste category consists of the lignocellulosic portion of residential, commercial, and industrial waste typically disposed by landfilling and also includes urban wood wastes such as woody yard trimmings and construction and demolition debris.

To facilitate inter-study and intra-study comparisons (the latter for studies presenting several scenarios) and to elucidate causes underlying differences in the results, the following key study assumptions were examined; temporal and spatial boundaries, crop yields, crop types, land areas, residue to grain ratios, land classification types, land management practices (e.g., tillage), restrictions on residue collection, harvesting technologies, competing land uses or competition with other industries for biomass feedstocks, consideration of the feasibility (e.g., site accessibility) and economics of biomass removal, and sustainability considerations (e.g., biomass removal practices aimed at maintaining soil organic content, soil tilth, and fertility, minimizing erosion, and promoting carbon storage, soil moisture maintenance, wildlife preservation, and site regeneration). Relevant assumptions (e.g., yields, land area) and study results were standardized to metric units, and monetary values were converted to year 2007 U.S. dollars using consumer price indices (USBLS 2008). Feedstock supply prices when presented are farm-gate (agricultural biomass) or equivalent prices (non-agricultural feedstock).

The biomass estimates reported by the 15 studies, and including selected study scenarios within several of the studies, were tabulated according to the six biomass categories. U.S. and Canadian estimates are presented, and key sources of variation between estimates and factors influencing each feedstock category are elucidated through detailed review of the study and in some cases, communication with the study authors. We limit our analysis to estimates of biomass feedstock quantities and do not analyze potential liquid transportation fuel production from these feedstocks. A number of potential conversion pathways (e.g. biochemical, thermochemical, and combination of the two) and unit process options (e.g. dilute acid or ammonia fiber expansion for pretreatment of biomass) are under active consideration. The appropriate conversion processes and yields of transportation fuels vary across feedstocks and conversion technologies are rapidly evolving. Hence, our analysis is limited to feedstock quantities and thus avoids adding another layer of uncertainty about conversion processes. However, it must be cautioned that these feedstocks are not strictly interchangeable in conversion into biofuels.

FINDINGS AND DISCUSSION

Description of the Selected Studies

Table 1 presents select details for each study. Three studies include biomass estimates for both the U.S. and Canada, while seven report results only for the U.S. and five only for Canada. The studies vary in their temporal scopes, ranging from assessments performed for the time period when the study was conducted to long-range forecasts (up to the year 2100). The geographical detail also varies across studies. While some are top-down or aggregate national estimates based on national average estimates of yields, land availability, accessibility, costs, etc.; other studies use a bottom-up approach of starting with disaggregate (state, province or county) estimates that are based on local estimates of productivity, costs, local industry demand, and other constraints. These are then aggregated into national estimates. Studies focusing on a single feedstock, e.g., Gallagher et al. (2003) for agricultural residues, and De La Torre Ugarte et al. (2003) for energy crops, generally use a bottom-up approach, while studies covering a larger number of feedstocks tend to use a top-down approach (e.g., Bauen et al. 2004) or draw on other estimates that use a bottom-up approach, e.g., Perlack et al. (2005). Walsh (2008) and Milbrandt (2005) use a bottom-up approach, although they include all the major feedstocks. The estimates of biomass availability generally tend to be lower for studies using a bottom-up approach mainly because of the cumulative effect of local constraints.

Table 1. Summary of Key Features of the Selected Biomass Studies

	Study	Methodology	Time-frame	Feed-stocks Studied[1]	Method	Competing Uses Considered?[2]
U.S. and Canadian Studies	Bauen et al. (2004)	Literature-based approach using residue production factors, land area, and yields.	2020	AR, EC, LR, MR	Inventory	No (EC grown on unused crop and forest land)
	Hoogwijk et al. (2005)	Economic, energy, and land-use model; four scenarios.	2050 & 2100	EC	Inventory	No (EC do not affect food and forestry production)
	Mabee et al. (2004)	Literature-based calculations using residue generation rates, sustainability factors, and demand for alternative uses.	2004	MR, AR	Inventory	AR for feed, MR with industry
Canadian Studies	BW McCloy and CCS (2005)	Literature-based calculations using production data combined with a survey-based approach.	2004	MR	Inventory	MR with industry
	Mabee et al. (2006)	Literature-based calculations using yield and land area data residue generation rates, sustainability factors, and demand for alternative uses.	Near-term	AR, EC, F, LR, MR	Inventory	AR for feed, LMR with industry
	Robinson (1987)	Literature-based calculations using yield, land area, crop production, and waste generation data.	1976 - 1984	EC, AR, LR, MR, UW	Inventory	Not included
	Wood and Layzell (2003)	Literature-based calculations using yield, land area, crop production, harvest, and waste generation data and sustainability factors.	1990 - 2001	AR, F, MR, UW	Inventory	AC and AR for traditional uses
	Yemshanov and McKenney (2008)	Utilization of the spatial Canadian forest service afforestation feasibility model (CFS-AFM) with an energy crop extension.	Not indicated	EC	Economic (supply curves)	EC with AC for land

[1] AR = Agricultural Residues, AC = agricultural crops, EC = Energy Crops, LR = Logging Residues, MR = Mill Residues, F = Forest Resources, UW = Urban Waste; [2] Whether competition with existing industries for biomass or land area was considered.

Table 1 (continued). Summary of Key Features of Selected Biomass Studies

	Study	Methodology	Time-frame	Feed-stocks Studied[1]	Method	Competing Uses Consid-ered?[2]
U.S. Studies	Gallagher et al. (2003)	Supply curve generation using productivity and opportunity cost calculations, and consideration of yields, competing uses, residue density, and sustainability.	2003	AR	Econ-omic (supply curves)	AR for feed, hunting industry
	Haq and Easterly 2006)	Synthesis of literature supply curve data (POLYSYS model) and literature-based calculations (e.g., yields, production data, transportation costs).	Near-term and 2025	AR	Econ-omic (supply curves)	Not included
	Jones et al. (2007)	Literature-based calculations and optimization of cropland for EC, given food security constraints.	Near-term	AR, EC, LR, MR, UW	Inven-tory	EC with AC for land, LR and MR with industry
	Milbrandt (2005)	Literature-based calculations using crop production, yield, census data, and waste generation factors.	Not indi-cated	EC, LR, MR, UW	Inven-tory	AR & MR with industry
	Perlack et al. (2005)	Literature-based calculations using yield, land area, crop production, harvest, and waste generation data and economic, recoverability and sustainability factors.	2005 - 2030	AR, EC, F, LR, MR, UW	Inven-tory	EC with AC for land
	Walsh (2008)	Supply curve generation using the economy and agricultural sector model POLYSYS with energy crop extension; literature-based calculations.	2007 - 2030	AR, EC, LR, MR, UW	Econ-omic (supply curves)	EC with AC for land, LMR & AR with industry
	De La Torre Ugarte et al. (2003)	Supply curve generation using the economy and agricultural sector model POLYSYS with energy crop extension.	2008	EC	Econ-omic (supply curves)	EC with AC for land

[1] AR = Agricultural Residues, AC = agricultural crops, EC = Energy Crops, LR = Logging Residues, MR = Mill Residues, F = Forest Resources, UW = Urban Waste; [2] Whether competition with existing industries for biomass or land area was considered.

For our analysis, we classify the methods underlying the studies into two categories, namely "inventory" and "economic" methods. Six studies reporting U.S. estimates, and all but one of the studies reporting Canadian estimates, utilize inventory methods. Inventory studies report biomass quantities using biomass production data (e.g., crop yields, land area, residue, and waste generation factors). Most of these studies assume that any biomass resources currently used by other industries are unavailable and deduct them from the available resource base. In contrast, the economic studies use models to estimate the quantities of biomass that could be supplied at various prices. These studies address competition by assuming that energy crops compete for land with conventional crops. Land is allocated to energy crops if the returns from energy crops are greater than the returns from conventional crops, subject to other constraints such as land quality, food/feed needs, local industry needs, etc. The economic studies that include residues also assume that the residues can be bid away from their current uses if the price is high enough. Walsh (2008), a U.S. study, is the only economic study that considers a comprehensive set of lignocellulosic feedstocks; the remaining economic studies focus on only one feedstock category. Only one Canadian study (Yemshanov and McKenney 2008) investigates the economics of biomass removal. Due to the exclusion of economic constraints, biomass estimates may be over-reported in many of the studies. Some study authors (e.g., Robinson 1987; Jones et al. 2007) take a more optimistic perspective in that they examine the physical limits of biomass resources without considering economics, while others adopt a more conservative approach (e.g., Mabee et al. 2006) by focusing on immediate biomass reserves, which can provide subsidiary economic benefits (e.g., reducing cropland vulnerability to droughts and forest vulnerability to fire, insects, and diseases), thereby encouraging their development to support initial biorefineries. Other conservative studies (Mabee et al. 2004; BW McCloy and CCS 2005) consider only unused residue streams.

Biomass conversion facilities will require sufficient, long-term biomass supply at reasonable costs and within a reasonable transportation radius. Such factors can further constrain biomass availability. Aside from Gallagher et al. (2003) and Yemshanov and McKenney (2008), the studies did not directly address the proximity and sufficiency of biomass supply from the perspective of a biorefinery. Perlack et al. (2005) and Walsh (2008) did, however, consider accessibility factors such as terrain characteristics or proximity to roads when estimating forest biomass.

A number of the studies discuss sustainability considerations in their assumptions. The studies recommend biomass removal practices in the agricultural and forestry sectors that promote the maintenance of soil organic content and soil moisture and the minimization of erosion. However, only Gallagher et al. (2003) and Walsh (2008) employ county-specific soil erosion considerations in their calculations of residue removal quantities; other studies utilize state or national average removal requirements. Other sustainability considerations include wildlife protection (e.g. De La Torre Ugarte et al. 2003) and protection of recreational hunting species (Gallagher et al. 2003).

Overview of Biomass Supply Estimates for the U.S. and Canada

Figures 1 and 2 present U.S. and Canadian biomass inventory estimates for the studies, and in some cases for selected study scenarios (several studies report near-/ mid-term or more conservative/ optimistic scenarios). For some of the studies (e.g., Walsh 2008) that present many scenarios, not all scenarios are presented, due to space limitations. Scenarios presented, however, generally are representative of the ranges of values presented in the study.

The underlying data for the figures are presented in Appendices 1 and 2, respectively. There are large ranges in the reported biomass estimates for the U.S. and Canada, both within different study scenarios and between studies. These ranges result from differing study methods and assumptions and will be discussed in the subsequent sections describing the specific biomass categories. All the studies report the quantities of dry biomass feedstocks, with the exception of Mabee et al. (2004; 2006), which report quantities of all feedstocks in green (undried) t, and Robinson (1987) and Jones et al. (2007), which report only the municipal solid waste (MSW) portion of urban waste in green t.

Comparing the estimates reported by different researchers is difficult due to varying study boundaries and assumed constraints about biomass availability, and whether economics of supply has been incorporated. Considering the studies that present a relatively comprehensive set of biomass categories, the U.S. economic studies, which included reasonably comprehensive sets of biomass categories, estimate annual biomass availability to range from 6 million to 577 million dry t (Walsh 2008), depending on offered price, while estimates from inventory studies range from 190 million to 3849 million dry t (Jones et al. 2007).

The Canadian inventory studies that include reasonably comprehensive sets of biomass categories estimate availability to range from 64 million green t to 561 million dry t (Mabee et al. 2006, and Robinson 1987, respectively). The 6 million dry t estimate of Walsh (2008) for the U.S. is for biomass available at $22/dry t. For an offered biomass price of $55/dry t, the estimated supply quantity increases to 193 million dry t. The upper bound estimate of the inventory studies (Jones et al. 2007) assumes maximum technical potential of energy crops, which the authors clearly state would not be the reality in the future.

An estimate by Perlack et al. (2005) in their optimistic scenario (1120 million dry t) is considerably lower than that of Jones et al. in their high scenario. In our judgment, the estimates of Perlack (2005) provide more reasonable "optimistic" scenarios for the U.S. than those of Jones et al., because the high estimates of Jones et al. assume that either corn or energy crops are grown on all of the U.S.'s agricultural cropland. Perlack et al. assume optimistic future scenarios of technology improvements (characterized by increased proportions of no-till cultivation and increasing yields in energy crop production).

With respect to coverage of the six biomass categories, only Perlack et al. (2005) present estimates for all categories. Walsh (2008) and Milbrandt (2005) include all categories except for forest resources. As expected, studies that only include one or two feedstock categories report lesser overall amounts of biomass to be available. The exception to this is Hoogwijk et al. (2005), which only examines energy crops but reports the highest biomass estimate for Canada and the second highest biomass estimate for the U.S. Hoogwijk assumes energy crop production on very large land areas in comparison to those assumed in other studies. Of the studies that examine a number of scenarios with different timeframes (Perlack et al. 2005; Walsh, 2008; Hoogwijk et al. 2005), the long-term estimates are nearly always higher than the near-term estimates due to assumptions of future yield and collection technology improvements (the exception being certain future scenarios in Hoogwijk et al., which assume increased nature conservation and food requirements).

Estimates of U.S. biomass supply are consistently higher than those of Canadian supply for the three studies that report estimates for both countries and as well, generally, when examining the studies reporting results for the individual countries. The U.S. has approximately two and a half times more agricultural land than Canada (Perlack et al. 2005; Wood and Layzell 2003) and produced approximately 26 times more cereal and maize than Canada in 2002 (Mabee et al. 2004), indicating greater biomass potential from agricultural residues and energy crops. Furthermore, Canada's northern climate restricts the growing season and yields, accounting for reduced biomass potential. Although the amount of productive forestland is not much greater in the U.S. than in Canada, the U.S. forest industry harvests nearly twice the amount of industrial roundwood (Mabee et al. 2004), accordingly generating larger quantities of logging and mill residues.

Studies considering economic feasibility generally report lower amounts of biomass available than do those that do not consider economics. For example, Walsh (2008) presents lower estimates than Perlack et al. (2005) for the near-term timeframe for all biomass categories considered by both studies. This trend is most evident at lower prices (e.g., less than $33/dry t), where only small quantities in the various biomass categories are economically attractive, as reported by Walsh (2008). These quantities are considerably lower than those estimated by Perlack et al. (2005), a study that does not explicitly include economic considerations. Often the economic study estimates are close to the lower estimates of the inventory studies. The following sections discuss the estimates for the six biomass categories in greater detail.

As mentioned before, estimates from studies using a top-down approach tend to be higher in comparison to estimates that use a bottom-up approach mainly because of the cumulative effect of local constraints. However, these studies often use a mixture of top-down and bottom-up approaches with varying degrees of geographical disaggregation (county, agricultural district, state, province, and region). Depending on data availability, some studies use different approaches for different feedstocks. For example, the estimates of Perlack et al. (2005) for energy crops are based on results from the POLYSYS model that uses a bottom-up approach where local parameters and constraints are at the level of agricultural districts or counties, while other feedstock estimates are mostly top-down.

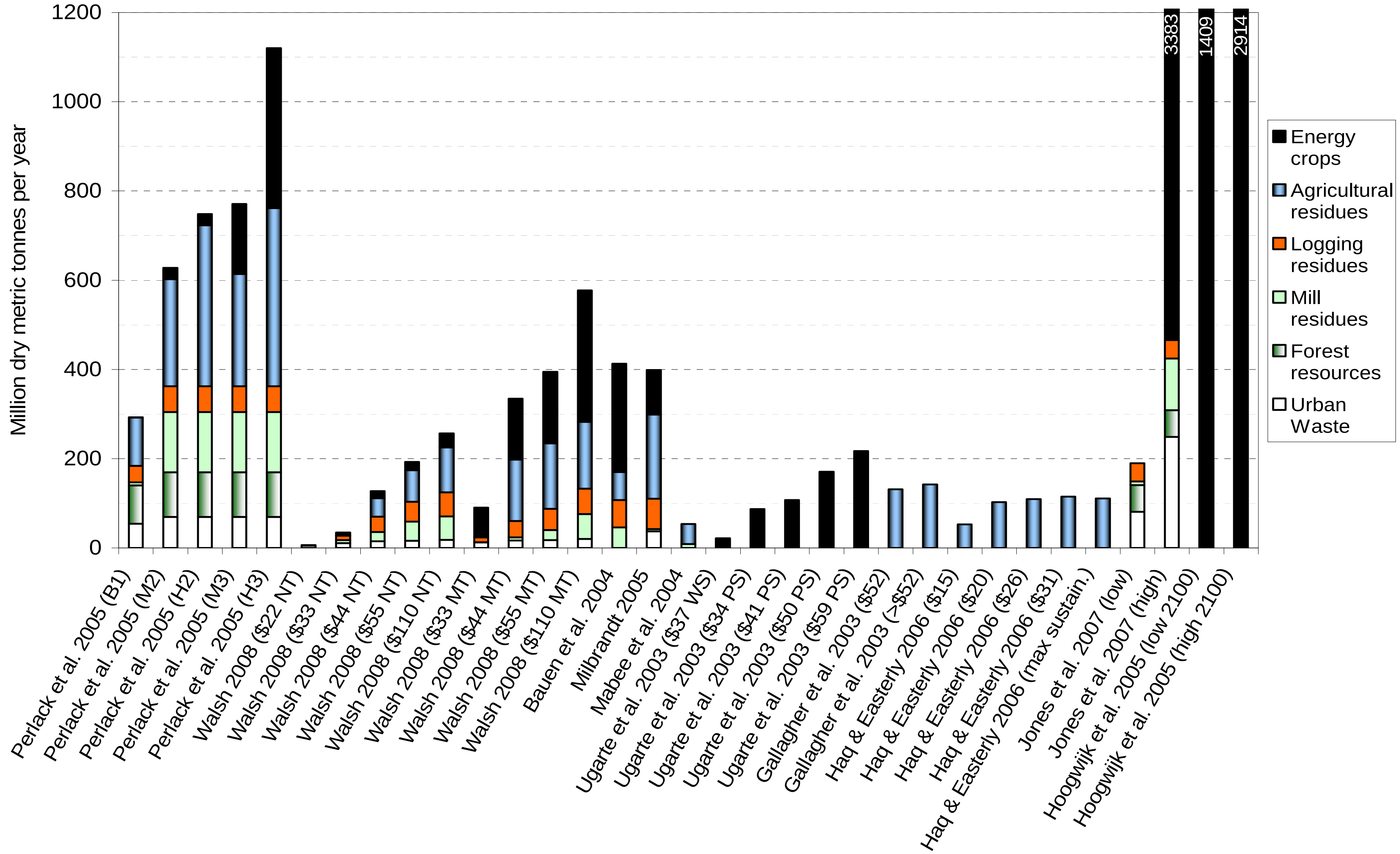

Fig. 1. U.S. annual biomass supply estimates (million dry t, unless otherwise stated in notes to the figure).

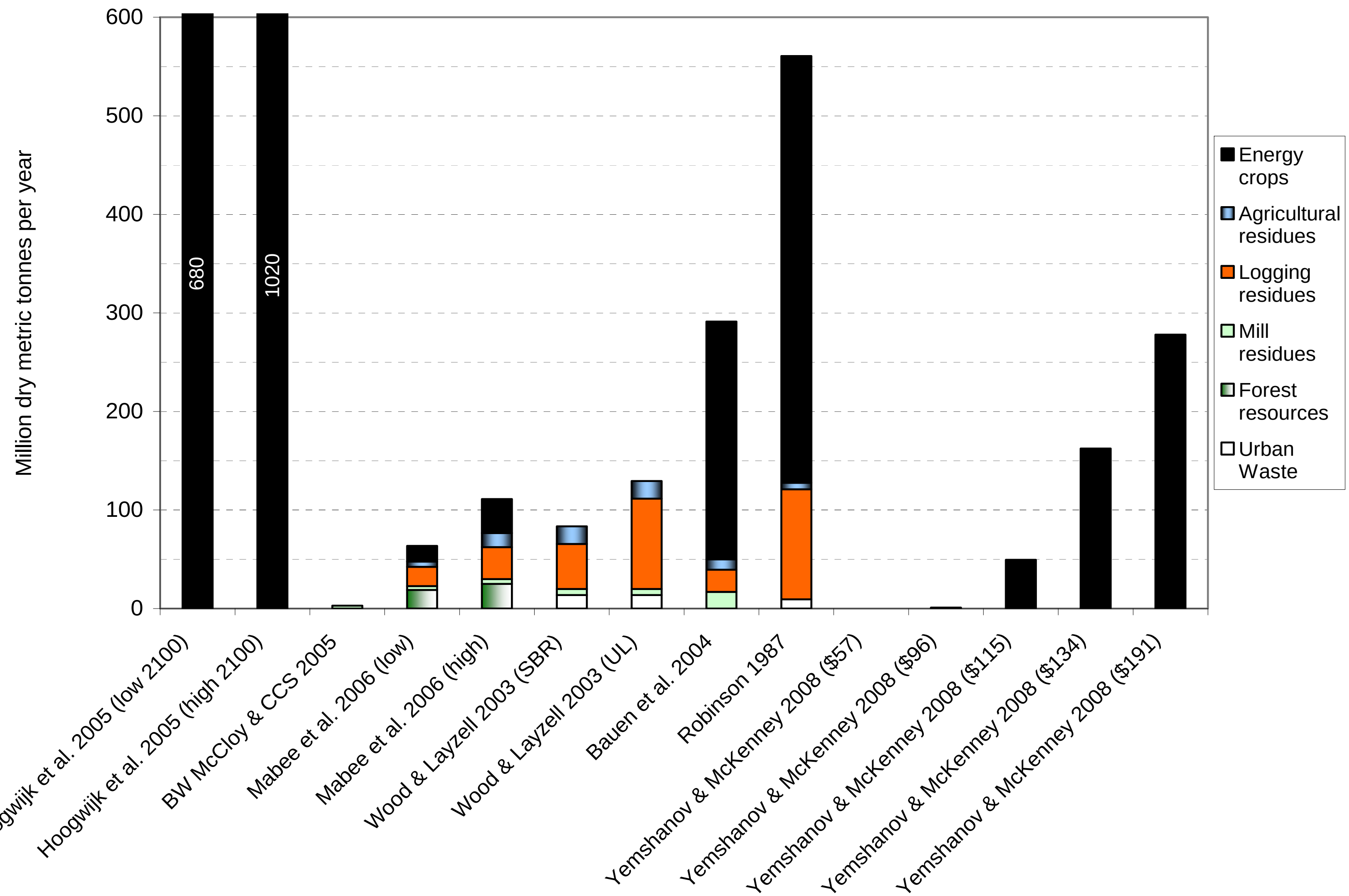

Fig. 2. Canadian annual biomass supply estimates (million dry t, unless otherwise stated in notes to the figure).

Notes for Figs. 1 and 2

Notes for Fig. 1: For some of the studies (e.g., Walsh 2008) that present many scenarios/years, not all scenarios/years are presented due to space limitations. Scenarios/years presented, however, generally cover the range of values presented in the study. All monetary values represent the farmgate (or equivalent for forest and urban biomass) price in $US/dry t. For Perlack et al. (2005), letters and numbers indicate scenarios: B = base case, M = moderate technology and yield changes, H = optimistic. For Walsh (2008), NT = near-term, year 2010; MT = mid-term, year 2020. Walsh presents data for year 2007-2030, however, we selected 2010 and 2020 as representative years to report in this paper. Mabee et al. (2004) present green biomass units. For De La Torre Ugarte et al. (2003) (referred to in the figure as Ugarte et al. due to space limitations), WS = wildlife scenario; PS = production scenario. For Haq and Easterly (2006), the "max sustain." scenario represents the present maximum quantity of sustainably removable agricultural residues in the U.S. Jones et al. (2007) also reports agricultural residue estimates between 701 and 1147 million dry t. However, energy crops and agricultural residues are mutually exclusive under this study's scenarios. Therefore, only the energy crop estimates are shown in the figure. For urban wood waste, forest resources, logging residues, and mill residues, Jones et al. (2007) draw on Perlack et al. (2005)'s estimates. However, they over-report Perlack et al.'s original forest and mill residue estimates, which are in short tons, by reporting them in dry Mg. Jones et al. (2007) present the MSW portion of urban waste in green biomass units. In order to show reasonable resolution of the studies' details, bars for Jones et al. and Hoogwijk et al. are not shown to scale. The values on the bars refer to amounts of energy crops available (note that Hoogwijk et al. only include energy crops, so the value for energy crops is equal to the total of biomass reported in this study). Hoogwijk et al. (2005) report optimistic energy crop estimates for four scenarios for the year 2050 and four scenarios for the year 2100, with varying assumptions such as population size and food requirements or land availability. The values indicated represent the lowest and highest estimates reported by this study.

Notes for Fig. 2:
All monetary values represent the farmgate (or equivalent for forest and urban biomass) price in $US/dry t. The biomass amount is the cumulative amount available at the price stated. Hoogwijk et al. (2005) report optimistic energy crop estimates for four scenarios for the year 2050 and four scenarios for the year 2100, with varying assumptions, such as population size and food requirements or land availability. The values indicated represent the lowest and highest estimates reported by this study. In order to show reasonable resolution of the studies' details, bars for Hoogwijk et al. are not shown to scale. Mabee et al. (2006) report green biomass quantities. Mabee et al. (2006) report two scenarios, where low and high represent more conservative and optimistic, respectively, assumptions about biomass availability (e.g., residue generation rates, yields). For Wood and Layzell (2003), SBR = sustainable biomass removal, UL = upper limit of biomass removal. Robinson (1987) reports combined logging and mill residues (indicated by one bar segment). This study also reports the MSW portion of urban waste in green biomass units.

Energy Crops

Switchgrass and hybrid poplars are attractive energy crops because they promote soil carbon storage, are fast-growing and tolerant to a wide range of soil and moisture conditions, and degrade less during handling and storage compared to conventional crops (Worldwatch Institute 2006). Energy crops however are not yet produced on a large scale in the U.S. or Canada and have not received agronomic development attention close to the level that conventional crops have. The majority of crop yield data in the biomass studies originate from test plots in the U.S. and Canada. There is considerable uncertainty in the yields that can be attained by these crops in the future, as well as the land areas that will be dedicated to them, making estimates of biomass availability challenging. Many studies assume that energy crops will be grown on agricultural land (see Table 1), and therefore will compete for this land with conventional crops. In the economic studies, the area of land that will be shifted away from traditional crops will be that where the returns over production costs of energy crops are higher than those of traditional crops, subject to other constraints such as land quality, farmer inertia, risk/reversibility considerations, food/feed impacts, and local industry needs, etc. In contrast, inventory studies commonly assume that human and livestock requirements are first met, deducting the land area required to do this. Both categories of studies assume that a portion of the land area dedicated to energy crop production will include marginal, prairie, or fallow land, and in the U.S., conservation reserve program (CRP) land. Appendices 1 and 2 present energy crop estimates for the U.S. and Canada, respectively, and Table 2 presents the assumptions about crop type, yield, land area, and land use for the studies evaluating this feedstock category.

At higher prices (in the economic studies) and in moderate to optimistic scenarios (in the inventory studies), energy crops are predicted to represent the highest or second highest category of biomass availability (depending on the study). Annual energy crop estimates in the U.S. range from none being available to 3383 million dry t (Walsh 2008 and Jones et al. 2007, respectively). Walsh et al. assume that below a farmgate price of $22/dry t, energy crops are not economically viable to produce, while at higher prices increased amounts are available. Walsh's farm gate prices do not include returns to suppliers or a risk premium, which would further increase the minimum price at which supply becomes feasible. Jones et al. (2007) results are derived from more optimistic supply predictions based on a combination of a high assumed yield for switchgrass (22 dry t/ha) and large land area utilized for energy crop production (154 million ha). In this scenario, Jones et al. estimate the maximum technical potential of energy crops, fully displacing land previously used to grow food, feed, and exports.

Walsh (2008) and Perlack et al. (2005) utilize similar assumptions (e.g., harvest technology, sustainability considerations), but the former study directly considers economics, while the latter does not. The result is that the estimates in Walsh, particularly at the lower prices, tend to be more conservative than those in Perlack et al. At higher farmgate prices, estimates of the two studies are fairly close. The above indicates the importance of economic considerations.

The two economic studies that include energy crop estimates for the U.S. (De La Torre Ugarte et al. 2003; Walsh 2008) both utilize the agricultural sector model POLYSYS (for additional detail, see De La Torre Ugarte et al. 2003). Within POLYSYS, it is assumed that the entire U.S. cropland could be potentially used to grow energy crops and that the land area allocated to energy crops is dependent on the returns from those crops, subject to food, feed, export and industry demands being met. Walsh (2008) uses a more recent version of POLYSYS, which includes updated crop management and yield assumptions, an updated baseline and multiple timeframes, and is limited to switchgrass as an energy crop (the model in De La Torre Ugarte et al. also includes hybrid poplar and willow). De La Torre Ugarte et al. (2003) investigated energy crop production potential on agricultural cropland, pasture, and idle land as well as CRP land. The results of two scenarios in De La Torre Ugarte et al., assuming different production intensities on CRP land are presented in Fig. 1 and Appendix 1. Under the wildlife scenario (WS), which assumes less intensive cropping practices, the inclusion of 3.3 million ha of CRP land adds 31 million dry t of biomass to the supply from the other land types, given a farmgate price of $33/dry t. Under the production scenario (PS) the inclusion of 5.2 million ha of CRP land adds 50 million dry t of biomass at a farmgate price of $44/dry t. The energy crop estimates of Walsh (2008) for 2010 are lower than those predicted by De La Torre Ugarte et al. (2003) at comparable farmgate prices. One likely factor contributing to this effect is that De La Torre Ugarte et al. (2003) assume that CRP and idle land are available for energy crop production, whereas Walsh (2008) does not.

Canadian energy crop estimates range from 0 to 433 million dry t (Yemshanov and McKenney (2008) and Robinson (1987), respectively). Similar to the U.S., the lower bound estimate originates from a study that considers economic factors, and the estimates increase as the farmgate price increases, approaching the more optimistic estimates of Bauen et al. (2004) (241 million dry t) and Robinson (1987). Robinson (1987) assumes a yield of 14 dry t/ha and a land area of 31 million ha for energy crop production. Compared to the U.S. studies, Yemshanov and McKenney (2008) predict that, in Canada, energy crops will be available at significantly higher prices (generally starting at $96/dry t, compared to $33/dry t for the U.S.). This could be due to average crop yields in Canada being lower than those in the U.S. (although the study did not state yield assumptions), and in addition, that Yemshanov and McKenney assume short rotation woody rather than herbaceous crops (the former being generally more costly to produce). Further commercial development of energy crops is needed in order to be able to ascertain their economics in Canada and the U.S.

Similarly to the U.S., sources of differences in the Canadian estimates result from variations in land area and yield assumptions in the studies. Bauen et al. (2004) assume an annual yield of 10 dry t/ha and that 23 million ha of land area are dedicated to energy crops, which are very different from the assumptions of Robinson (1987), as shown in Table 2. Mabee et al. (2006) assume conservative yields (3 to 6.5 green t/ha), and unlike the other studies, Mabee et al. focus on developing biomass reserves to support initial biorefineries. The study recommends replacing 10% of the most drought-prone marginal farmland and 3 million ha of abandoned cropland with more drought-resistant hybrid poplar stands, thus, avoiding drought-induced losses. Such practices may increase the initial feasibility of energy crops in Canada. This agricultural management strategy is supported by preliminary results of Kumarappan and Joshi (2008), which indicate that the low profitability of some field crops in Canada may lead to considerable conversion of agricultural crops to energy crops.

Table 2. Key Assumptions for Estimating Energy Crop Supply in Select Studies

	Study	Crop Type[1]	Yield (dry t/ha)	Land Area Considered in Production (million ha)	Land Use[2]	Quantity (million dry t)[3]
U.S. studies	Jones et al. 2007	HC (SW)	22	53-154	ACL, CRP	1178-3383
	Milbrandt 2005	HC (SW)	Not indicated	Not indicated	CRP	100
	Perlack et al. 2005	HC (SW, PG), SRWC (HP)	4.5 (PG), 11-18 (SW & HP)	0-11 (PG), 0.4-24 (SW & HP)	ACL, CRP, P	0.2-358
	Walsh 2008	HC (SW)	<6-16	Not indicated[6]	ACL, P	0-295
	De La Torre Ugarte et al. 2003	HC (SW), SRWC (HP, HW)	5-16.6	Not indicated[6]	ACL, CRP, IL, P	22-217
Canadian and U.S. studies	Bauen et al. 2004[4]	HC, SRWC	10	US: 53[4]	ACL, WL	US: 243
				CAN: 23[4]		CAN: 241
	Hoogwijk et al. 2005	SRWC	3-55.8	US: >75-185	ACL, WL, ML, AFL, RL	US: 1409-2914
				CAN: Not indicated		CAN: 680-1020
Canadian studies	Mabee et al. 2006[5]	SRWC (HP)	3-6.5	5.3	ACL, ML	16-35
	Robinson 1987	SRWC (HP)	14	31	ML, AFL	393
	Yemshanov and McKenney 2008	SRWC (HP)	Not indicated	Not indicated	ACL	0-278

[1] HC = herbaceous crop, SW = switchgrass, PG = prairie grass; SRWC = short rotation woody crop, HP = hybrid poplar, HW = hybrid willow; [2] ACL = agricultural cropland, WL = woodland, AFL = abandoned farmland, IL = idle land, P = Pasture land, ML = marginal land, RL = rest land; [3] Quantity may not equal product of yield and land area as some studies make additional assumptions about constraints (e.g., sustainability requirements, harvest efficiency, economic feasibility); [4] Bauen et al. 2004 assumes 5% crop, forest and woodland area, which is converted using land area figures from Perlack et al. (2005) for the U.S. and Wood and Layzell (2003) for Canada; [5] reports values as green biomass.[6] utilizes POLYSYS model as discussed in text.

Agricultural Residues

Factors that affect the supply of agricultural residues include the crop type, crop yield, residue-to-grain ratio, management practice, residue collection technology, and harvest and storage losses. Both the U.S. Department of Agriculture and Agriculture and Agri-food Canada recommend soil conservation on certain land classes by way of leaving a specified proportion of residues on the soil to maintain soil organic content, soil tilth and fertility, and to minimize erosion (Wood and Layzell 2003). The majority of studies recognize this requirement, although Jones et al. (2007) and Robinson (1987) instead assume optimistic residue removal rates. Different management systems require different soil conservation practices. For example, no-till practices generally permit more biomass removal than conventional tillage practices (Haq and Easterly 2006). Perlack et al. (2005), Walsh (2008), and Haq and Easterly (2006) anticipate a trend toward increased no-till practices in the future; currently no-till is practiced on over 20 million ha in the U.S. and 13 million ha in Canada (Statistics Canada, 2007).

In examining the studies, agricultural residues generally are estimated to be the first or second highest category of biomass to be available. Appendices 1 and 2 present agricultural residue supply estimates reported by the studies. In the U.S., annual agricultural residue estimates range from none being available to 1147 million dry t (Walsh 2008 and Jones et al. 2007, respectively). As with the energy crop estimates, the lower bound estimate represents a farmgate price ($22/dry t) too low to justify removal of the residues. The Jones et al. (2007) estimate represents a scenario only for illustrative purposes, where all crops in the U.S. are completely displaced with corn and 75% of stover is harvested (this scenario is not included in Appendix 1). The next highest estimate (399 million dry t) is that of an optimistic future scenario (H3) of Perlack et al. (2005), who assume that no-till cultivation practices are adopted on all cropland and that the residue collection rate improves from the current 40% to 75% (or less, depending on the crop).

Walsh (2008), Gallagher et al. (2003), and Haq and Easterly (2006) develop supply curves for agricultural residues, taking into account the economics of residue harvest and collection, and the replacement cost of the nutrients (through fertilizer application) that agricultural residues would otherwise provide if left on the ground. Walsh (2008) estimates 0.1 million dry t of agricultural residues are available at a price of $33/dry t by the year 2020, but this amount is considerably lower than the 115 million dry t reported by Haq and Easterly (2006) to be available at a farmgate price of $31/dry t and at an equivalent timeframe. Gallagher et al. report amounts of residues only at $52/dry t, and this amount corresponds closely to those reported to be available at $44 and $55/dry t in 2020 by Walsh. Many of the studies note reductions in the quantities of agricultural residues available in the future due to the shift of land from conventional crops to energy crops.

Canadian studies estimate that agricultural residues range from 5 million green t to 18 million dry t (Mabee et al. 2006; and Wood and Layzell 2003, respectively). Although both studies' estimates are for agricultural residues and for similar time frames (the years that the studies were completed), the estimates differ significantly, in part because they assume that different quantities of residues are generated by conventional agricultural practice (37 million green t and 56 million dry t, respectively). Wood and Layzell (2003) assume that 80% of crop residues can be sustainably removed (15% for soybeans), and of this portion, only 70% can be collected using near-term technology, Aside from Wood and Layzell, none of the other studies report these critical parameters.

In the studies that consider a comprehensive set of agricultural residues, corn stover is estimated to contribute between 42% and 73% of agricultural residue biomass, followed by wheat straw representing between 6% and 24% (Perlack et al. 2005; and Haq and Easterley 2006, respectively) in the U.S. In Haq and Easterley, the proportion of residues that is corn stover decreases with increasing farmgate price, indicating other crop residue feedstocks would be more costly.

There is a competitive market for many agricultural residues, and there is demand for these residues (often at high prices) for livestock feed and bedding, mulching, and insulation materials (Wood and Layzell, 2003). An emerging biofuels sector would compete with these existing uses. Perlack et al. (2005), Mabee et al. (2004), Haq and Easterly (2006), Wood and Layzell (2003), Gallagher et al. (2003), and Millbrandt (2005) estimate and deduct the quantity of residues dedicated to existing uses, most commonly animal fodder. Gallagher et al. (2003) extend their analysis a step further than other studies in this regard by estimating the price required for feed residues to be bid away from cattle and diverted to energy purposes and the resulting additional residues that would be available.

Logging Residues

The availability of logging residues is obviously dependent on continuing forestry operations. Constraints related to their supply include accessibility of the resource, sustainability requirements to maintain carbon storage and soil moisture, preserve wildlife habitat, and site regeneration, and as well, economic feasibility (Perlack et al. 2005; Wood and Layzell 2003).

The availability of forest biomass is presented in Appendices 1 and 2. For the U.S., logging residues range from 0.08 million dry t available in 2010 at $22/dry t to 57 million dry t at $110/dry t in 2020. Both estimates originate from Walsh (2008), a study that considers residue density and recoverability, forest accessibility, and hauling costs for present and future timeframes and also projects future timber harvest for each county in the U.S; however, the study does not discuss whether sustainability considerations are included. Bauen et al. (2004) and Milbrandt (2005) present similar estimates (61 and 68 million dry t, respectively) to that of Walsh's higher estimate. Perlack et al. (2005) assume that 65% recovery of logging residues is possible with current technology and that a portion of the residues are left to maintain logging site productivity. This study anticipates that an additional 21 million dry t (compared to a current estimate of 37 million dry t) will become available in the future due to a larger standing forest inventory (annual forest growth is projected to continue to exceed annual removals), coupled with harvesting and wood processing efficiency improvements. Perlack et al. also reports that the demand for forest products is projected to increase but at a lower rate than that of historical growth. Perlack et al. (2005) estimate that the majority of logging and other residues (91%) originate from privately owned land. In the U.S. 58% percent of forestland is privately owned (Perlack et al. 2005), whereas only 6% of Canadian forestland is privately owned (NRCan 2000).

Canadian estimates range from 20 million green t (Mabee et al. 2006) to 92 million dry t (Wood and Layzell 2003). Mabee et al. (2006) report that from 20 to 33 million green t of logging residues are generated in Canada (derived from the assumed residue generation rates of 15% and 25%, respectively, of total timber harvested), but emphasize that the need for erosion and nutrient loss prevention to promote forest regeneration will reduce these quantities. In contrast, the variation in the estimates reported by Wood and Layzell (2003) is largely driven by sustainability considerations. Wood and Layzell estimate that 92 million dry t is the upper limit of biomass removal and recommends that half of this should remain at the harvest site, leaving 46 million dry t for sustainable harvest. Since none of these studies account for accessibility and feasibility factors, Canadian estimates may be over-reported.

Mill Residues

A significant quantity of mill residues is already utilized by the forestry industry. According to Perlack et al. (2005), upwards of 98% of primary mill residues and 60% of secondary mill residues are currently used for energy and value added products in the U.S., while Wood and Layzell (2003) estimate this quantity to be 70% in Canada.

In the U.S., the amount of mill residues reported to be available ranges from 0.5 million dry t at $22/dry t to 135 million dry t (Walsh 2008; and Perlack et al. 2005, respectively). Appendices 1 and 2 report mill residues for the U.S. and Canada, respect-tively. As with the other biomass categories, Walsh (2008) reports the quantities of mill residues available at various prices, and at lower prices, only small amounts of residues are feasible to recover. The upper estimate originates from a future scenario presented by Perlack et al. and includes the mill residues presently utilized by the forestry industry. In more near-term scenarios, Perlack et al. (2005), Millbrandt (2005), and Mabee et al. (2004) all assume that residues used currently by the industry are not available. The studies estimate that currently unused mill residues that would be available for producing biofuels would range only from 5 million to 9 million dry t. Perlack et al. (2005) estimate that future demand for forestry products could increase the amount of mill residues available by 35 million dry t. However, fewer residues will become available if existing industry demand also rises (e.g., current pulp and paper operations already utilize residues and need to further supplement their fuel requirements with fossil fuels). Walsh (2008) differs from the other studies by assuming that existing uses can be diverted to biofuels if the industry is willing to pay a high enough price, therefore, up to 52 million dry t are assumed available in 2010 and another 3 million dry t could become available by 2020 (depending on the price).

In Canada, the amount of mill residues reported to be available ranges from 3 to 17 dry t (BW McCloy and CCS (2005) and Bauen et al. (2004), respectively). The low estimate is likely conservative, because the study reports only residues available after satisfying all competing uses [the same assumption is made in the studies of Wood and Layzell (2003) and Mabee et al. (2006)]. The studies do not consider that residues could be bid away from other industries if the biofuels industry is willing to pay high enough prices. The high estimate results from an assumption that 50% of harvested roundwood will become mill residues. However, Bauen et al. mention that the industry will use a portion of the residues to produce products and that this estimate will be smaller in practice. The estimate (112 million dry t) of Robinson (1987) represents an aggregate value, comprising both mill and logging residues, but excludes residues used for non-energy purposes (e.g., fiber products). Given that a large proportion of these residues are currently utilized for process energy, it is likely that Robinson overestimates mill residues.

Forest Resources

The excess build-up of woody material in North American forests has, in some regions, increased their susceptibility to natural disturbances. The removal of excess biomass as well as reducing stand density via fuel treatment or thinning activities have proven to be effective ways of suppressing fire and insect infestation (Mabee et al. 2006; Perlack et al. 2005). Using these materials for biofuel production may render forest management to be more economically attractive (Jones et al. 2007). Forest management operations are limited by operational accessibility and economic feasibility, which are largely dependent on the proximity of the material to transportation infrastructure. These aspects, coupled with the diffuse nature of the resource, make the economics of this feedstock challenging. Consequently, Mabee et al. (2006) suggest that removals be restricted to areas that are economically vulnerable to natural disturbances and to forest-urban interface zones. Furthermore, timber stocks damaged by natural disturbances can be utilized to recoup some of the economic losses.

In the U.S., forest resource estimates range from 60 to 100 million dry t (Jones et al. 2007; and Perlack et al. 2005, respectively). See Appendices 1 and 2 for quantities of forest resources available in the U.S. and Canada. The Jones et al. (2007) estimate originates from Perlack et al. (2005); however, it appears that Jones et al. state the value in dry t but the value is identical to the estimate in short tons presented by Perlack et al., indicating a conversion problem. Perlack et al. (2005) estimate a total of 8.4 billion tons of biomass is potentially available from forests. They assume that 60-80% of it is accessible over a 30 year harvest cycle, resulting in 54 million dry t of fuel treatment thinnings available for sustainable removal from forestlands. They further assume that 32 million dry t of biomass currently utilized for residential space-heating and industrial heat, steam, and electricity generation is also available. In the future, the fuelwood category is predicted to increase by 14 million dry t. Although Perlack et al. (2005) is the only study to include fuelwood in their estimate, Walsh (2008) also recognizes these materials to be a potential source of forest biomass. In Canada, only Mabee et al. (2006) estimate forest resource amounts and report that 19 and 25 million green t of biomass (low and high estimates, respectively) could be available, largely resulting from forest disturbances such as fires and insect-killed trees and to a lesser degree from forest management activities.

Urban Waste

Compared to other lignocellulosic feedstocks, urban waste has several advantages. It provides an opportunity to utilize an existing waste stream, thus reducing the need for conventional waste management; it has an existing collection system; and it is available at reduced costs because landfills or other waste management systems typically charge tipping fees. Urban waste is composed of two major waste streams: MSW and urban wood. Although both originate from an urban setting, some studies like Wood and Layzell (2003), Walsh (2008), and Robinson (1987) combine the two categories in their aggregate estimates, while others like Perlack et al. (2005), Millbrandt (2005), and Jones et al. (2007) treat urban wood waste as a forest resource or residue. However, Walsh (2008) provides separate estimates along with estimation methods, for various components of urban waste, such as yard trimmings, MSW wood, residential and non-residential demolition waste, and residential renovation wastes.

For the U.S., four studies report results for urban waste availability (see Appendices 1 and 2 for U.S. and Canadian urban waste values reported in the studies).

These results range from 5 million dry t to 249 million t. The lower estimate is from Walsh (2008) and reflects the availability at a price of $22/dry t, while the upper estimate is from Jones et al. (2007) and reflects the study's most optimistic estimate. Walsh (2008) estimates the amount of tree and yard trimmings, the wood component of MSW residential renovation waste, and construction and demolition debris, excluding recycled and contaminated materials, available at various prices. MSW and wood waste estimates are reported together. Jones et al. (2007) reports more optimistic estimates than does Walsh, although the study utilizes the same data source as Walsh (state MSW surveys) to estimate the lignocellulosic components of MSW (reporting it to be between 61 million and 229 million t), and unlike Walsh (and Perlack et al.), Jones et al. also include organic and paper materials. Jones et al.'s upper estimate for MSW includes waste materials that are currently combusted and recycled for energy, while the low estimate does not. For the urban wood fraction of urban waste, Jones et al. utilize the construction and demolition debris estimate of Perlack et al. (2005), which in fact is drawn from McKeever (2004), of 20 million dry t. Perlack et al. include the same categories of waste as does Walsh, except that Perlack et al. do not include residential renovation waste. However, the estimates of Perlack et al. (43 million dry t of urban wood and 27 million dry t of MSW associated with the agricultural industry, reported for most scenarios) are considerably higher than those of Walsh, even at Walsh's highest price (only 20 million dry t of urban waste are reported to be available even at a price of $110/dry t). The consideration of economics likely is responsible for a significant portion of the difference in the results.

Canada generates about one tenth the amount of MSW as the U.S. (Wood and Layzell 2003; Walsh 2008). While these amounts are roughly in proportion to the countries' populations, the urban waste results reported in the Canadian studies are generally greater than 10% of those reported in the U.S. studies. Urban wastes are estimated only by Robinson (1987) and Wood and Layzell (2003). Wood and Layzell report 14 million dry t of biomass to be available for energy production by assuming that 85% of disposed MSW is combustible, and an additional 4 million dry t of material to be available from recycling. The estimate of 9 million green t reported by Robinson (1987) represents total theoretical potential and does not take into account the feasibility of recovery. One would expect this amount to be higher than that of Wood and Layzell, but the opposite is the case. This is likely in part due to Robinson's study being completed over 20 years ago, although this does not fully explain the difference. Neither of these Canadian studies includes economic considerations.

Recommendations for Future Research

The above discussion points to substantial variation in biomass feedstock estimates across studies and identifies some key reasons for these variations. Hence, future lignocellulosic biomass assessments would benefit from: thorough and transparent documentation of methodologies and all key assumptions, inclusion of a comprehensive set of biomass categories, sustainability (ecological, economic and social) considerations, analyses of competing feedstock uses, and consideration of the proximity and sufficiency of biomass supply to potential biorefinery locations. Future studies should also include comparisons with prior studies and an explanation of key sources of differences. Detailed regional biomass assessments are needed to facilitate planning and development of biofuel industries and associated infrastructure, especially in view of high transportation costs and resulting relatively low collection radius for biomass. To facilitate this, a bottom-up economic approach is recommended over a top-down national inventory approach. Canadian biomass resource studies should be improved by including economic considerations on a regional level in addition to feedstock competition, accessibility and sustainability considerations. Future U.S. and Canadian studies would further benefit from integrating the modeling results of regionalized agricultural economic models with proximity and sufficiency of biomass supply considerations in relation to prospective biorefinery locations.

Studies that provide a basis for more detailed site-specific assessments are required for stakeholders in specific bioenergy projects. However, developing such comprehensive bottom-up estimates is resource intensive and time consuming. For example, Walsh (2008), which in our judgment is closest to such an ideal study, has been refined and updated over nearly 20 years, and as the author discusses, still has significant room for improvement. One can question whether public investments are necessary in such research and capability/model building and argue that private investors in future biorefineries have a vested interest in such research. However, biofuel policies are still evolving, and a number of policy debates are ongoing over food versus fuel use of land, sustainable levels of agricultural residue removal, biodiversity and other impacts from forest biomass removal, indirect land use related carbon emissions due to expansion of agriculture into tropical forests, and best use of biomass (transportation fuel versus electricity generation and other uses). Future biomass availability estimates that can address these public policy issues are critical. Hence, we recommend expanded capacity building that can address these issues and enable informed tradeoffs. These tradeoffs include decisions about prioritizing feedstocks based on their expected future potential.

CONCLUSIONS

1. Large differences in reported lignocellulosic biomass availability in the U.S. and Canada were found in the studies examined. We differentiate between inventory studies where quantities of biomass potentially available are estimated without rigorous consideration of the costs of supply, and economic studies that take into consideration various opportunity costs and competition. The U.S. economic studies, which included reasonably comprehensive sets of biomass categories, estimate annual biomass availability to range from 6 million to 577 million dry t depending on offered price, while estimates from inventory studies range from 190 million to 3849 million dry t. The Canadian inventory studies estimate availability to range from 64 million green t to 561 million dry t. Key sources of differences in the studies include; whether the studies take a top-down or bottom-up approach, whether economics and competition for existing resources are considered, assumptions about energy crop yields and the land areas on which these crops are assumed to be grown, and the study timeframe. However, the complexity of biomass availability and the associated large number of determining factors coupled with differing study methodologies and,

in some cases, lack of transparent documentation, make it difficult to reconcile and accurately attribute all the sources of differences to specific variables.

2. Although the U.S. studies differ in scope and estimates of biomass availability, they generally report that agricultural residues and energy crops are expected to contribute the largest proportions of future lignocellulosic biomass supply. These sources are related, as energy crops will compete for agricultural land with traditional agricultural crops, which are the sources of the residues, although some marginal lands may be suitable for energy crop production. Traditional agricultural crops have two potential revenue streams, those from grain and residues. Energy crops may have multiple revenue streams as well, e.g., energy feedstock and animal feed. Potential energy crop producers will need to evaluate the feasibility of switching from traditional agricultural crop production. Kumarappan and Joshi (2008) suggest that farmers may require an additional risk premium to switch to energy crops arising from farming inexperience and uncertain markets for the feedstock. Until producer confidence and the marketplace sufficiently mature, energy crops are predicted to play a minor role; however, this feedstock category has future promise in both countries.
3. The Canadian studies do not agree as closely as the U.S. studies with respect to the major biomass categories. Few of the Canadian studies include a reasonably comprehensive set of biomass categories and those that do, differ substantially in their estimates. Studies that include estimates of energy crops generally report these as the largest expected contributor to lignocellulosic biomass. In addition, several studies report considerable quantities of logging residues to be available. Unlike the U.S. studies, only modest amounts of agricultural residues are estimated to be available.
4. The removal of existing material in both U.S. and Canadian forests in order to reduce fire and pest susceptibility and to improve forest health more generally has the potential to provide mutual benefits to a bioenergy sector and forest management initiatives. Whether existing fuel wood and the mill residues consumed by forestry operations will become available for a bioenergy sector will depend on economic and other considerations. Once the sector matures, it may be able to bid these resources away from existing uses, given sufficient demand and favorable economics.
5. While these studies provide estimates of potential biomass supply, establishing a successful biomass feedstock supply chain is a different critical challenge. A consistent, economically viable feedstock supply system requires addressing and optimizing diverse harvesting, storage, preprocessing, and transportation infrastructure needs and logistical challenges. Other issues relating to economies of scale, market power, reversibility of investments also need attention.

ACKNOWLEDGMENTS

We thank General Motors, Natural Sciences and Engineering Research Council, AUTO21 Network Centre of Excellence, and Ontario Government Early Researcher Award (H. L. MacLean) for support. The authors are grateful to four anonymous reviewers who provided comments to improve the manuscript.

REFERENCES CITED

Antares Group Incorporated. (1999). Biomass Residue Supply Curves for the United States, National Renewable Energy Laboratory, Task No. ACG-7-17078-07, Contract No. ACG-7-17078.

Bauen, A., Woods, J., and Hailes, R. (2004). "Biopowerswitch! A biomass blueprint to meet 15% of OECD electricity demand by 2020," WWF the global conservation organization, (http://www.wwfgreatermekong.org/about_wwf/what_we_do/climate_change/publications/policy.cfm?uNewsID=13322).

Berndes, G., Hoogwijk, M., and van den Broek, R. (2003). "The contribution of biomass in the future global energy system: A review of 17 studies," *Biomass and Bioenergy* 25(1), 1–28.

Binder, T. P., Benemann, J. R., Cavalieri, R. P., Faaij, A. P. C., Flavell, R., Gunstone, F. D., Hickman, J. S., Kindler, K. A., Linville, C. D., Shoemaker, S. P., Warren, M. A., and White, E. H. (2007). "Topic paper #8: Biomass. Working Document of the NPC Global Oil & Gas Study," (http://downloadcenter.connectlive.com/events/npc071807/pdf-downloads/Study_Topic_Papers/8-STG-Biomass.pdf.)

BW McCloy and Climate Change Solutions (CCS). (2005). "Estimated production, consumption and surplus mill wood residues in Canada – 2004: A national report," Natural Resources Canada and Forest Products Association of Canada.

Carolan, J. E., Joshi, S. V., and Dale, B. E. (2007). "Technical and financial feasibility analysis of distributed bioprocessing using regional biomass pre-processing centers," *Journal of Agricultural and Food Industrial Organization* (5) 1-27.

Champagne, P. (2007). "Feasibility of producing bio-ethanol from waste residues: A Canadian perspective; Feasibility of producing bio-ethanol from waste residues in Canada." *Resources, Conservation and Recycling* 50, 211-230.

De la Torre Ugarte, D. G., English, B. C., and Jensen, K. (2007). "Sixty billion gallons by 2030: Economic and agricultural impacts of ethanol and biodiesel expansion," *American Journal of Agricultural Economics* 89(5), 1290-1295.

De La Torre Ugarte, D. G., Walsh, M. E. Shapouri, H., and Slinsky, S. P. (2003). "The economic impacts of bioenergy crop production on U.S. agriculture," *Agricultural Economic Report No. 816*, U.S. Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses.

Etcheverry, J., Gipe, P., Kemp, W., Samson, R., Vis, M., Eggertson, B., McMonagle, R., Marchildon, S., and Marshall, D. (2004). *Smart Generation: Powering Ontario With Renewable Energy*, David Suzuki Foundation, Vancouver, BC, Canada.

Farrell, A. E., and Gopal, A. R. (2008). "Bioenergy research needs for heat, electricity, and liquid fuels," *MRS Bulletin* (33), 373-380.

Food and Agriculture Organization of the United Nations (FAO) (2008). "The state of food and agriculture. Biofuels: prospects, risks, and opportunities," ISSN 0081-4539. Rome, Italy.

Gallagher, P., Dikeman, M., Fritz, J., Wailes, E., Gauthier, W., and Shapouri, H. (2003). "Supply and social cost estimates for biomass from crop residues in the United States," *Environmental and Resource Economics* 24, 335-358.

Graham, R. L., Nelson, R., Sheehan, J., Perlack, R. D., and Wright, L. L. (2007). "Current and potential U.S. corn stover supplies," *Agronomy Journal.* 99, 1-11.
Haq, Z., and Easterly, J. L. (2006). "Agricultural residue availability in the United States," *Applied Biochemistry and Biotechnology* 129, 1-3.
Hoogwijk, M., Faaij, A., Eickhout, B., deVries, B., and Turkenburg, W. (2005). "Potential for biomass energy out to 2100, for four IPCC SRES land-use scenarios," *Biomass and Bioenergy* 29, 225-257.
Jones, A., O'Hare, M., and Farrell, A. (2007). "Biofuel boundaries: Estimating the medium-term supply potential of domestic biofuels," Paper UCB-ITS-TSRC-RR-2007-4, University of California, Berkeley.
Kadam, K. L., and McMillan, J. D. (2003). "Availability of corn stover as a sustainable feedstock for bioethanol production." *Bioresource Technology* 88, 17-25.
Kim, S., and Dale, B. E. (2004). "Global potential bioethanol production from wasted crops and crop residues," *Biomass and Bioenergy* 26, 361-375.
Kumarappan, S., and Joshi, S. (2008) "Economic competitiveness of energy crops – A stochastic efficiency analysis," Poster presented at The Fifth Annual World Congress on Industrial Biotechnology & Bioprocessing, Chicago, IL.
Layzell, D. B., Stephen, J., and Wood, S. M. (2006). *Exploring the Potential for Biomass Power in Ontario, A Response to the OPA Supply Mix Advice Report*, BIOCAP Canada Foundation, Kinston, ON, Canada.
Levin, D. B., Zhu, H., Beland, M., Cicek, N., and Holbein, B. E. (2007). "Potential for hydrogen and methane production from biomass residues in Canada," *Bioresource Technology* 98, 654-660.
Love, P. (1980). "Biomass energy in Canada. Its potential contribution to future energy supply," Energy, Mines and Resources, Report ER 80-4E.
Mabee, W. E., Fraser, E. D. G., McFarlane, P. N., and Saddler, J. (2006). "Canadian biomass reserves for biorefining," *Applied Biochemistry and Biotechnology* 129-132.
Mabee, W., Gregg, D., and Saddler, J. (2004). "Ethanol from lignocellulosics: Views to implementation," *Report to IEA Bioenergy Task 39*, Vancouver, Canada. http://www.studio255.com/crfa/pdf/res/200409_IEA_Final_Report_Task_39.pdf
McKeever, D. (2004). Inventories of woody residues and solid wood waste in the United States. Ninth International Conferences, Inorganic-Bonded Composite Materials. Vancouver, British Columbia. October 10-13.
McLaughlin, S. B., De La Torre Ugarte Jr., D. G., Garten, C. T., Lynd, L. R., Sanderson, M. A., Tolbert, V. R., and Wolf, D. D. (2002). "High-value renewable energy from prairie grasses," *Environmental Science & Technology* 36(10), 2122 -2129.
Milbrandt, A. (2005). "A geographic perspective on the current biomass resource availability in the United States," National Renewable Energy Laboratory, Golden, CO, USA, (http://www.nrel.gov/biomass).
Natural Resources Canada (NRCan). (2000). "Canada's Forests," http://canadaforests.nrcan.gc.ca/articletopic/85 (May 29, 2008).
Perlack, R., Wright, L., Sturhollow, A., Graham, R., Stokes, B., and Erbach, D. (2005). "Biomass as a feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply," Contract DE-AC05-000R22725.
Renewable Fuels Association (RFA). (2008). "Renewable Fuels Standard,"

http://www.ethanolrfa.org/resource/standard/ (July 30, 2008).
Robinson, J. (1987). "An embarrassment of riches: Canada's energy supply resources," *Energy* 12, 379-402.
Statistics Canada. (2007). "2006 census of agriculture, farm data and farm operator Data," *Catalogue no. 95-629-XWE*.
U.S. Department of Labor Bureau of Labor Statistics (USBLS). (2008). "All urban consumers - (CPI-U), U.S. city average, all items 1982-84=100," ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt (June 3, 2008).
U.S. Department of Energy (USDOE). (2008), International Energy Outlook 2008, Report #:DOE/EIA-0484(2008) http://www.eia.doe.gov/oiaf/ieo/pdf/table1.pdf (October 20, 2008)
U.S. Department of Energy (USDOE). (2007). "DOE selects six cellulosic ethanol plants for up to $385 million in federal funding," http://www.energy.gov/print/4827.htm (May 29, 2008).
Walsh, M. (2008). "U.S. cellulosic biomass feedstock supplies and distribution," http://ageconsearch.umn.edu/bitstream/7625/2/U.S.%20Biomass%20Supplies.pdf (July 30, 2008).
Walsh, M. E., Perlack, R. L., Turhollow, A., De La Torre Ugarte, D., Becker, D. A., Graham, R. L., Slinsky, S. E., and Ray, D. E. (2000). "Biomass feedstock availability in the United States: 1999 state level analysis," Oak Ridge National Laboratory, Oak Ridge, TN, USA.
Wang, M., Wu, M., and Huo, H. 2007. "Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types," *Environ. Res. Lett.* (2), 024001.
Wood, S., and Layzell, D. (2003). "A Canadian biomass inventory: Feedstocks for a bio-based economy," *Canadian BIOCAP Foundation*, Kingston, ON, Canada.
World Energy Council. (2001). "Survey of Energy Resources 2001," World Energy Council, London, UK, (http://www.worldenergy.org/).
Worldwatch Institute. (2006). "Biofuels for Transportation, Global Potential and Implications for Sustainable Agriculture and Energy in the 21st Century." A report prepared for the German Federal Ministry of Food, Agriculture and Consumer Protection, (http://www.worldwatch. org/taxonomy/term/445).
Yemshanov, D., and McKenney, D. (2008). "Fast-growing poplar plantations as a bioenergy supply source for Canada," *Biomass and Bioenergy* (32), 185-197.

Article submitted: July 30, 2008; peer review completed: Sept. 1, 2008; revised version received and accepted Nov. 10, 2008; Published: Nov. 12, 2008.

Appendix 1. Reported U.S. Biomass Estimates (in million dry t unless otherwise indicated in notes to table)

Study	Scenario	EC	AR	LR	MR	F	UW	Total
Perlack et al. 2005	Base line	0.2	108	37	7	86	54	293
Perlack et al. 2005	Moderate technology and yield changes	25	240	58	135	100	69	628
Perlack et al. 2005	Optimistic technology and yield changes	25	361	58	135	100	69	748
Perlack et al. 2005	Moderate technology and yield changes, and significant land use changes	157	251	58	135	100	69	771
Perlack et al., 2005	Optimistic technology and yield changes, and significant land use changes	358	399	58	135	100	69	1120
Walsh , 2008	$22/dry t; year 2010	0	0	0.08	0.5	---	5	6
Walsh, 2008	$33/dry t; year 2010	7	0.1	10	7	---	11	34
Walsh, 2008	$44/dry t; year 2010	16	41	35	21	---	15	127
Walsh., 2008	$55/dry t; year 2010	19	70	45	43	---	16	193
Walsh, 2008	$110/dry t; year 2010	31	100	54	52	---	18	256
Walsh., 2008	$33/dry t; year 2020	66	1	11	1	---	12	90
Walsh, 2008	$44/dry t; year 2020	137	137	37	7	---	17	334
Walsh., 2008	$55/dry t; year 2020	160	147	47	23	---	18	395
Walsh., 2008	$110/dry t; year 2020	295	149	57	55	---	20	577
Bauen 2004	25% residues collected	243	63	61	46	---	---	413
Milbrandt 2005	one scenario	100	189	68	5	---	37	399
Mabee et al. 2004	one scenario	---	45	---	9	---	---	54

Notes: EC = Energy Crops, AR = Agricultural Residues, LR = logging Residues, MR = mill residues,
F = Forest Resources, UW = Urban Waste, --- not included in study. Biomass categories may not reflect those in original study as adjustments had to be made in some cases to make categorization as consistent as possible across studies. For some of the studies (e.g., Walsh 2008) that present many scenarios, not all scenarios are presented due to space limitations. Scenarios presented, however, correspond to those presented in Figure 1 and generally cover the range of values presented in the study. In some cases biomass quantities were presented in units of energy and were converted to dry t utilizing conversions reported in the studies or other literature if not reported in the study. Mabee et al. (2004) present green biomass quantities; Jones et al. (2007) present the MSW portion of urban waste in green units. Totals may not add due to rounding. Value for forest resource is misreported in Jones et al. (2007) as being in dry t but is actually in dry short tons.

Appendix 1 (continued). Reported U.S. Biomass Estimates (in million dry t unless otherwise indicated in notes to table)

Study	Scenario	EC	AR	LR	MR	F	UW	Total
Ugarte et al. 2003	$37/dry t (wildlife scenario)	87	---	---	---	---	---	87
Ugarte et al. 2003	$34/dry t (production scenario)	22	---	---	---	---	---	22
Ugarte et al. 2003	$41/dry t (production scenario)	107	---	---	---	---	---	107
Ugarte et al. 2003	$50/dry t (production scenario)	171	---	---	---	---	---	171
Ugarte et al. 2003	$59/dry t (production scenario)	217	---	---	---	---	---	217
Gallagher et al. 2003	$52/dry t	---	132	---	---	---	---	132
Gallagher et al. 2003	>$52/dry t	---	142	---	---	---	---	142
Haq and Easterley 2006	$15/dry t	---	52	---	---	---	---	52
Haq and Easterley 2006	$20/dry t	---	103	---	---	---	---	103
Haq and Easterley 2006	$26/dry t	---	109	---	---	---	---	109
Haq and Easterley 2006	$31/dry t	---	115	---	---	---	---	115
Haq and Easterley 2006	maximum sustainable removal	---	111	---	---	---	---	111
Jones et al. 2007	low estimate	---	---	41	8	60	81	190
Jones et al. 2007	high estimate	3383	---	41	116	60	249	3849
Hookwijk et al. 2005	low estimate; year 2100	1409	---	---	---	---	---	1409
Hookwijk et al. 2005	high estimate; year 2100	2914	---	---	---	---	---	2914

Notes: EC = Energy Crops, AR = Agricultural Residues, LR = logging Residues, MR = mill residues,
F = Forest Resources, UW = Urban Waste, --- not included in study. Biomass categories may not reflect those in original study as adjustments had to be made in some cases to make categorization as consistent as possible across studies. For some of the studies (e.g., Walsh 2008) that present many scenarios, not all scenarios are presented due to space limitations. Scenarios presented, however, correspond to those presented in Figure 1 and generally cover the range of values presented in the study. In some cases biomass quantities were presented in units of energy and were converted to dry t utilizing conversions reported in the studies or other literature if not reported in the study. Mabee et al. (2004) present green biomass quantities; Jones et al. (2007) present the MSW portion of urban waste in green units. Totals may not add due to rounding. Value for forest resource is misreported in Jones et al. (2007) as being in dry t but is actually in dry short tons.

Appendix 2. Reported Canadian Biomass Estimates (in million dry t unless otherwise indicated in notes to table)

Study	Scenario	EC	AR	LR	MR	F	UW	Total
Hoogwijk et al. 2005	low estimate; year 2100	680	---	---	---	---	---	680
Hoogwijk et al. 2005	high estimate; year 2100	1020	---	---	---	---	---	1020
BW McCloy and CCS 2005	one scenario	---	---	---	3	---	---	3
Mabee et al. 2006	low estimate	16	5	20	4	19	---	64
Mabee et al. 2006	high estimate	35	14	33	5	25	---	111
Wood and Layzell 2003	sustainable biomass removal	---	18	46	6	---	14	83
Wood and Layzell 2003	upper limit of biomass removal	---	18	92	6	---	14	129
Bauen et al. 2004	25% residues collected	241	11	22	17	---	---	291
Robinson 1987	one scenario	433	6	112	---	---	9	561
Yemshanov and McKenney 2008	$57/dry t	0	---	---	---	---	---	0
Yemshanov and McKenney 2008	$96/dry t	1	---	---	---	---	---	1
Yemshanov and McKenney 2008	$115/dry t	49	---	---	---	---	---	49
Yemshanov and McKenney 2008	$134/dry t	162	---	---	---	---	---	162
Yemshanov and McKenney 2008	$191/dry t	278	---	---	---	---	---	278

Notes: EC = Energy Crops, AR = Agricultural Residues, LR = logging Residues, MR = mill residues,
F = Forest Resources, UW = Urban Waste, --- not included in study. Biomass categories may not reflect those in original study as adjustments had to be made in some cases to make categorization as consistent as possible across studies. For some of the studies, not all scenarios are presented due to space limitations. Scenarios presented, however, correspond to those presented in Figure 2 and generally cover the range of values presented in the study. In some cases biomass quantities were presented in units of energy and were converted to dry t utilizing conversions reported in the studies or other literature if not reported in the study. Mabee et al. report green biomass quantities. Robinson reports the MSW portion of urban waste in green biomass units. Totals may not add due to rounding.