Life cycle assessment of corn stover production for cellulosic ethanol in Quebec

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Whitman, T., Yanni, S.F. and Whalen, J.K. 2011. **Life cycle assessment of corn stover production for cellulosic ethanol in Quebec**. Can. J. Soil Sci. **91**: 997–1012. The province of Quebec has a target of 5% ethanol (EtOH) content in fuel by 2012, which means the province will require about 400 million L of ethanol per year based on current consumption. Current research is focused on ''second generation biofuels'' such as cellulosic EtOH, which can be produced from agricultural by-products like corn stover. A life cycle assessment (LCA) evaluates the ''cradle to gate'' impact of corn stover feedstock production for cellulosic EtOH production in three corn-producing regions in Quebec for two impact categories: energy and greenhouse gas (GHG) impacts. The modelled system boundaries include in-field processes: corn stover production, collection, transport, soil organic carbon (SOC) loss, and N_2O emissions, as well as background processes: herbicide, fertilizer, seed, and fuel production and transport. Sensitivity analyses vary the percentage of corn stover collected, contrast a multiple-pass with a one-pass stover-grain collection system, and compare mass, economic and system expansion allocation methods. Total energy impact is 931–1442 MJ t^{-1} dry stover collected under 15% stover collection, with stover harvest, transport, and field operations contributing most strongly to the total impact. Total GHG emissions from corn stover production and transport of stover to the ethanol facility are 320–488 kg CO_2e t^{-1} dry stover under 15% stover collection, with SOC loss, N_2O emissions, and stover harvest contributing the most to the total impact. Sensitivity analysis reveals that the energy and GHG impacts of stover production are strongly influenced by the mass of stover collected, the use of a one-pass system, and the choice of allocation methods. Scaling-up results from the modelled system suggest that 100% of Quebec's EtOH targets could technically be supplied using corn stover feedstock, but this may come at the expense of GHG emissions and soil health.

Key words: Agricultural feedstock, biofuel, environmental impact, life cycle analysis, maize, soil organic matter conservation

Whitman, T., Yanni, S. F. et Whalen, J. K. 2011. **Évaluation du cycle de vie du fourrage de maïs destiné à la fabrication d'éthanol cellulosique au Québec**. Can. J. Soil Sci. **91**: 997–1012. Le Québec s'est donné pour objectif d'ajouter 5 % d'éthanol (EtOH) à l'essence d'ici 2012, ce qui signifie que la province aura besoin d'environ 400 millions de litres d'éthanol par année, étant donné la demande existante. Les recherches actuelles mettent l'accent sur les « biocarburants de deuxième génération » comme l'EtOH cellulosique, qu'on tire de sous-produits agricoles tel le fourrage de maïs. L'évaluation du cycle de vie détermine l'incidence de la production du fourrage de maïs destiné à la fabrication d'EtOH cellulosique au Québec pour deux sortes d'impact : l'énergie et les émissions de gaz à effet de serre (GES). Les limites du système modélisé comprennent les opérations sur le terrain (culture du fourrage, collecte, transport, perte de carbone organique et dégagements de N_2O) ainsi que les processus secondaires (herbicides, engrais, semences, fabrication du carburant et transport). Les analyses de sensibilité font varier la proportion de fourrage récoltée, opposent un système de collecte à passages multiples à la collecte unique du fourrage et du grain, et comparent les méthodes d'affectation selon la masse, les paramètres économiques et l'expansion des systèmes. L'impact total sur l'énergie varie de 931à 1 442 MJ par tonne de fourrage sec récoltée, la collecte du fourrage, son transport et les opérations sur le terrain concourant le plus à l'impact global. Les émissions totales de GES issues de la production du fourrage de maïs et de son transport jusqu'à l'usine fabriquant l'éthanol varient de 320 à 488 kg de CO_2 par tonne de fourrage sec, les pertes de carbone organique, les dégagements de N_2O et la récolte du fourrage contribuant le plus à l'impact global. L'analyse de sensibilité révèle que l'incidence de la production de fourrage sur l'énergie et sur les émissions de GES subit fortement l'influence de la masse du fourrage recueilli, de l'adoption d'un système à passage unique et du choix des méthodes d'affectation. Lorsqu'on met les résultats du modèle à l'échelle, on constate que la totalité des objectifs du Québec concernant l'EtOH pourraient techniquement être atteints avec comme matière première le fourrage de maïs, mais cela, uniquement aux dépens des émissions de GES et de la fertilité du sol.

Mots clés: Matière première agricole, biocarburant, impact sur l'environnement, analyse du cycle de vie, maïs, conservation de la matière organique du sol

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Abbreviations: **EtOH**, ethanol; **GHG**, greenhouse gas; **LCA**, life cycle assessment; **SOC**, soil organic carbon

Biofuels hold promise for improving energy security while mitigating climate change because they have the potential to be renewable, produced locally, and have a neutral climate impact, if designed carefully (Karp and Shield 2008). However, due to concerns with global food security as food crops are diverted for fuels and additional land is cleared for biofuels production, there has been global resistance to the expansion of "first generation" corn (*Zea mays* L.) grain ethanol (EtOH) production (Food and Agriculture Organization 2010). Because of this, research is now focused on "second generation" or cellulosic EtOH, produced from agricultural by-products such as corn stover, urban and forestry wastes, or perennial grasses, which could be grown on marginal lands (Solomon 2010; Bhardwaj et al. 2011) [see Gomiero et al. (2011) for a discussion of the issues associated with cultivating marginal lands]. Incorporating hydrolytic enzymes or gasification into the refining process makes it possible to use these low-sugar, high-cellulose and -lignin materials as feedstocks (Prasad et al. 2007). Thus, second generation biofuels can rely on feedstocks that are less likely to affect food production directly.

In Canada, the federal government's ecoENERGY program, initiated in 2008, will provide $1.5 billion over 9 years toward the production of renewable alternatives to gasoline and diesel fuels, including financial incentives at $0.10 L^{-1} for the first 3 years and gradually diminishing to $0.043 L^{-1} by 2017. The federally supported ecoAGRICULTURE Biofuels Capital (ecoABC) initiative allocated $200 million to agricultural producers from 2007 to 2011, supporting the production of agricultural materials for biofuels (Government of Canada 2011). In response to concerns about first generation biofuels, the federal government earmarked $500 million for private sector investment in large-scale second-generation biofuel production facilities (NRCan 2011). These initiatives and others will contribute to the nationally legislated target of 5% EtOH in gasoline, which came into effect in 2010 (Government of Canada 2008). Prior to this, the province of Quebec had created a similar target of 5% ethanol in all gasoline sold in Quebec by 2012, which will require about 400 million L EtOH yr^{-1} (Radoactif 2007; Statistics Canada 2011a).

It is still debatable whether biofuels can be considered "carbon-neutral" (Shapouri et al. 2002). Energy is used and GHGs are emitted during biofuel manufacturing (starting when feedstocks are planted, harvested and transported to biorefineries), which can equal or exceed fossil fuel production and use. As well, crop residues that appear to be waste on an agricultural field, and hence potential biofuel feedstocks, may be critical for nutrient cycling, soil health or protecting soil from erosion. Increasing EtOH production in Quebec must not be done at the expense of the environment, and to make good decisions, the impacts of selecting agricultural feedstock for EtOH production must be evaluated carefully using a standard and transparent process. Life Cycle Assessment (LCA) assesses the impact of a product through all its stages, from "cradle-to-grave", using a transparent methodology, for the purpose of comparing and improving processes and providing a basis for decision-making. The International Organization for Standardization (ISO) has developed standard methods and procedures for LCAs (ISO 14040:2006 and ISO 14044:2006). LCA can be used to evaluate second-generation biofuels, as it provides a way to address the diverse environmental impacts associated with the complexity of agroecosystem management.

A number of LCA and energy analysis studies have been conducted on cellulosic ethanol production with varying results, depending on how the system boundaries were set and the allocation methods chosen. Fu et al. (2003), Sheehan et al. (2004), Kim and Dale (2005), Adler et al. (2007), and Gonzalez-Garcia et al. (2010) all showed reductions in GHG emissions and global warming potential and, in general, a net energy credit from production and use of ethanol (different gasoline-EtOH blends) from different cellulosic materials [a combination of wet-milling corn grain and corn stover in the case of Kim and Dale (2005)] compared with gasoline. Luo et al. (2009) used energy, mass, and economic allocation in an LCA to assess corn stover ethanol production and reported that replacing gasoline with ethanol reduces the levels of numerous environmental impacts, including acidification and eutrophication potentials, irrespective of allocation method. However, they found that the global warming potential, measured in CO_2 equivalents, was dependent on the allocation method where mass and energy allocations give better scores to ethanol compared with gasoline, while an economic allocation gives the opposite result. Soil carbon stocks were not considered to be a limiting factor for biomass removal, as they assumed that a 60% stover removal scheme would not affect soil fertility.

While high-input systems may not register a drop in fertility under such a removal system, ignoring the impact of this removal on soil carbon stocks may be problematic. Because of this, some studies now model soil carbon and nutrient dynamics explicitly (Sheehan et al. 2004; Kim and Dale 2005; Adler et al. 2007). Sheehan et al. (2004) used LCA to study the impact of corn stover-derived EtOH, taking into account soil carbon stocks as a limiting factor for stover collection in the US Midwest, but assumed that farmers would switch to no-till farming simultaneously, somewhat obscuring the impact of stover harvest. It is critical to consider the impact of stover removal on soil carbon stocks, as Cherubini and Ulgiati (2010) reported that land-use change effects, including soil carbon loss as a consequence of crop residue removal, contribute to about 50% of the GHG emissions in a cellulosic ethanol production system. The studies above that considered soil N_2O emissions (e.g., Sheehan et al. 2003; Adler et al. 2007) reported increases due to changes in N fertilization and other agricultural activities required to grow cellulosic biomass, but in these studies, the N_2O emissions were offset by other system processes that acted as a sink for CO_2, such as displaced fossil fuel use or changes in soil carbon dynamics, resulting in a net decrease in GHG impact. In contrast, Kim et al. (2009) found that corn stover harvest decreased N_2O emissions from soils because there was less residual organic matter to provide a source of N. Despite the Canadian government's pledge to increase EtOH production from second-generation biofuels, there is limited information published on the environmental consequences of this policy. An LCA of corn-stover ethanol production for Ontario (Spatari et al. 2005) is available, but did not consider changes in soil carbon stocks resulting from stover removal, and there are no similar studies examining the impact of corn stover collection for EtOH in Quebec.

The global objective of this study was to perform an LCA on the impact of producing corn stover as a feedstock for cellulosic EtOH in Quebec. Input data for the LCA was based on agricultural practices and environmental conditions that are common in the Montéregie, Centre du Québec, and the Chaudière-Appalaches regions of Quebec (Fig. 1), where about 80% of Quebec's corn is produced (BDSO 2010). The impact categories considered in the LCA were: (1) Energy cost – total energy needed to produce 1 t of corn stover for EtOH production; (2) Greenhouse gases (GHGs) – total CO_2 equivalents emitted to produce 1 t of corn stover for EtOH production.

This LCA aims to provide robust, regionally-specific data to (1) characterize the impacts of corn stover production in the two key impact categories mentioned above and (2) investigate the relative importance of key parameters using sensitivity analyses to determine how management practices, system design, and accounting choices affect the measured impact.

MATERIALS AND METHODS

Goal and Scope

The energy and climate change impact from the production of corn stover for EtOH production are estimated using process-based LCA in Microsoft Excel (2007). The goal of the LCA is to quantify the energy and GHG impacts associated with the production of corn stover for EtOH in the Montérégie, Centre du Québec, and Chaudière-Appalaches regions of Quebec. The system has one co-product, which is corn grain. The functional unit for the system is the production and delivery of 1 t of dry corn stover to an EtOH plant. There are a number of by-products of the ethanol production process that can be used and/or sold and which have the potential of making ethanol production more efficient in terms of energy use [for example, sugar and syrup by-products can be used in the animal feed industry and solid residues and lignin can be used to produce energy or sold to other industries (Fu et al. 2003; Luo et al. 2009)]. These possibilities have not been considered in this study (allocation would need to occur at the EtOH plant level, which is outside the system boundary) and therefore could cause an underestimation of the system efficiency with respect to EtOH.

System Boundaries

The system boundaries are illustrated in Fig. 2. The LCA is designed for a cornfield with soils, agroecosystem management and climatic conditions typical of the Montérégie, Centre du Québec, and Chaudière-Appalaches regions of Quebec. The system includes all field-level processes needed to grow, harvest, and transport the stover, and also includes the processes used to produce fertilizers, herbicides, seeds, and fuel.

Field Operations

The system includes in-field production, collection, and transport of corn stover, hereafter referred to as stover, to the cellulosic EtOH production facility. The modelled field is under continuous corn production, ploughed in

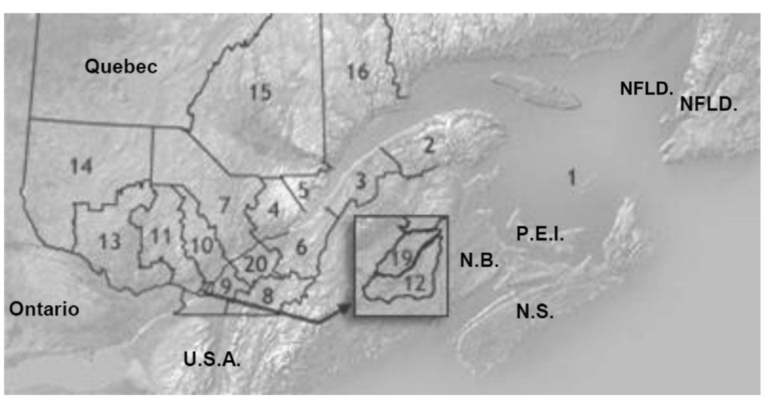

Fig. 1. Regions of Quebec. Montérégie – 9; Centre du Québec – 20; Chaudière-Appalaches – 6 (Bonjour Québec 2010).

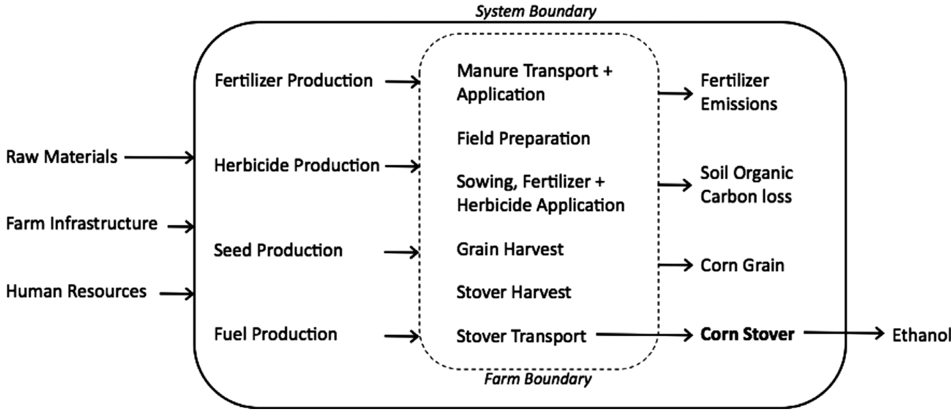

Fig. 2. Life cycle assessment (LCA) system boundary: Production of corn stover as a feedstock for cellulosic ethanol.

the fall with a moldboard plough, and cultivated in spring with a disc harrow. [Note: although other rotational practices are also common in the region, this practice is not uncommon (Ghazalian 2009; MAPAQ 2009) and assuming continuous corn production simplifies analysis, avoiding allocating over a variety of crops with varying uses – this same approach is used in Luo et al. (2009)]. Liquid pig manure is transported in a 26500 L tanker from a nearby farm (1.5 km from the field), applied with a broadcast sprayer and incorporated with a harrow before sowing, resulting in the application of 114 kg N ha^{-1} and 36 kg P ha^{-1} (CRAAQ 2007). The herbicide metolachlor (2-chloro-N-(2,6-diethylphenyl)-N-(methoxymethyl) acetamide) is applied with a tractor and a boom sprayer at 1.9 kg ha^{-1} (Leblanc et al. 1995). Corn is directly seeded with 9.5 kg mineral N ha^{-1} of starter fertilizer as ammonium nitrate (NH_4NO_3) at a rate of 81545 seeds ha^{-1}, for a target plant population of 75000 plants. Atrazine (6-chloro-N^2-ethyl-N^4-isopropyl-1,3,5-triazine-2,4-diamine) is applied in the same manner as metolachlor at a rate of 1.0 kg ha^{-1} after seedling emergence (Leblanc et al. 1995). When the crop reaches physiological maturity in mid-October, the corn grain is harvested with a combine, leaving stover on the field until dry, after which it is shredded, raked into rows, baled, and loaded onto an eight-bale trailer with a bale lifter and a 50 HP tractor. Twelve bales are loaded per hour, then the trailer is pulled 0.5 km to the roadside by the tractor at 20 km h^{-1}. Bales are transported 100 km to the cellulosic EtOH production facility by a 9 t truck, which returns with an empty load.

For each field operation using machinery, the diesel fuel required per hectare was estimated using data from two sources (Downs and Hansen 1996; Lazarus and Smale 2010) weighted to give equivalent values at 0.167 L hp^{-1} h^{-1}. Then the GHG emission rates for eastern Canada in 2010 were determined with GHGenius3.19 (NRCan 2010). Emissions from a diesel tractor in the GHGenius3.19 model are based on EPA AP-42 emission regulation factors and projected changes over time. Specific data for various tractor models are not available with GHGenius, but the algorithm provides similar estimates for most farm equipment (D. O'Connor, personal communication, 2008). For the transport truck, heavy duty diesel vehicle (HDDV) emissions rates were used at the default settings in GHGenius, including 50% "city driving" to account for stopping and slower speeds in towns.

Energy use for each on-farm process represents direct energy consumption, based on the heating value of 36.6 MJ L^{-1} for diesel oil (NRCan 2005) plus 4.8 MJ L^{-1} to account for indirect energy consumption during fuel production, including extracting raw materials, refining/processing, transporting and retailing the fuel (McLean and Barton 2008). Table 1 lists direct and indirect energy consumption values for all on-farm processes.

Total GHG emissions (CO_2, CH_4, and N_2O) from on-farm machinery account for the GHGs released during production and burning of diesel fuel in the tractors (but do not include indirect emissions from the manufacture and maintenance of machinery and other farm systems).

Table 1. Total energy consumption of farm processes (MJ ha^{-1}) used in this life cycle assessment (LCA) (Note: values are not yet weighted by stover production and collection)

Process	Direct energy	Indirect energy
Ploughing	551	73
Cultivator	213	28
Metolachlor application	33	4
Manure transport	299	39
Manure application	305	40
Manure incorporation	148	20
Sowing+mineral fert.	164	22
Atrazine application	33	4
Harvesting grain	525	69
Shredding stover	236	31
Raking stover	49	7
Baling stover	276	36
Loading stover	33	4
Stover to roadside	1	0.1

Emissions from the transport truck used to transport stover to the EtOH processing facility were calculated using the GHGenius3.19 model (NRCan 2010) emission rates.

Crop Yield and Soil Carbon Budget

Crop yield is 6.1 t dry grain ha^{-1}, which is the average for 2001–2010 for the modelled regions (Institut de la statistique du Québec 2011), accompanied by an equal mass of stover (CRAAQ 2000). Fifteen percent (by mass) of this stover is collected and removed from the field, and the remainder is incorporated into the soil when the field is ploughed in the fall. This leaves 2.1 t stover C ha^{-1} on the soil. Because regional accounting protocols have not yet been developed for changes in soil organic carbon (SOC) stocks due to changes in crop residue management (VandenBygaart et al. 2008), Intergovernmental Panel on Climate Change (IPCC) values are used (Cherubini and Ulgiati 2010). Initial SOC content (before changing stover harvesting practice) is predicted at 79 t C ha^{-1} using the IPCC default for ecosystems representative of this region ("cool temperate moist") and cropping system (IPCC 2006a, b), and is consistent with measured soil C contents in the study area (Liang et al. 1998; Bolinder et al. 1999; Poirier et al. 2009). The resulting loss in SOC is calculated using IPCC factors for ecosystems representative of this region for switching management practices from leaving residues on the soil to harvesting all residues (IPCC 2006a, c), scaled linearly by the fraction of stover that is collected, resulting in an annual loss of 0.32 t SOC ha^{-1} yr^{-1} under full stover removal. The GHG impact of SOC loss is considered to be equivalent to all lost SOC being converted to CO_2.

The impact of increased C additions as manure applications are augmented to account for nutrient removal through the stover harvest is not directly modelled. However, a rough estimate of the effects of its inclusion can be developed. While it is likely that the two forms of C would have different decomposition rates, Triberti et al. (2008) found that additions of cow manure slurry or crop residues to a corn-wheat rotation in Italy over 34 yr both increased SOC content and showed no significantly different effects. However, normalization of additions on a dry matter basis, rather than a nutrient basis, in the Triberti et al. study resulted in carbon and nitrogen additions and crop yields all being higher in the slurry treatment, making it difficult to directly compare the results of Triberti et al. (2008) to those of this study. Still, the findings of Triberti et al. (2008) are consistent with the IPCC SOC change factors for these two management choices (IPCC 2006c). The effect of leaving crop residues on the soil is predicted to be equivalent to that of adding supplemental manure to soils where residues are removed (IPCC 2006c). However, this likely assumes that an equivalent amount of C is added in manure as is removed with the stover, which is not the case for this system. Under full stover removal, manure application would increase by 9500 L ha^{-1} $year^{-1}$ to compensate for N and P losses. This manure addition, with an expected C content of 0.008–0.012 kg C L^{-1} (CRAAQ 2007; Velthof et al. 2005), would result in a direct C input of 0.08–0.12 t C ha^{-1} yr^{-1}, compared with the 2.44 t C ha^{-1} yr^{-1} removed with the stover. Thus, after nutrient losses are fully compensated for through manure additions, C losses are only 3–5% compensated for, since the C:N and C:P ratios for stover are substantially higher than for manure. Thus, to provide a rough estimate of the effect of increased manure additions on SOC stocks, the magnitude of the predicted SOC losses could be decreased by $\sim$4% to 0.31 t SOC ha^{-1} yr^{-1} under full stover removal. While this reduction factor is not included in the analysis, this omission does not substantially change the results or conclusions.

Nutrient Budget

The nutrient budget for a 1 ha corn-producing agroecosystem was designed around N and P due to their contribution to eutrophication in Canadian fresh water ecosystems (Schindler et al. 2006). Using the average yields from 2001 to 2010 from the Montérégie, Centre du Quebec, and Chaudière-Appalaches regions of Quebec (Institut de la statistique du Québec 2010) and the nutritional composition of corn grain and stover (Burgess et al. 2002; Lang 2002; NRCan 2005), the total nutrients required per hectare of corn production are estimated. Liquid pig manure, widely available in the Montérégie, Centre du Quebec, and Chaudière-Appalaches regions, is designated as the principal fertilizer source with the nutrient composition described by Choudhary et al. (1996). The application rate for liquid pig manure is designed to satisfy the P needs of the corn crop and results in an application of 36 kg P ha^{-1} and 114 kg N ha^{-1}, based on an assumption of moderate soil fertility. To ensure adequate N supply, 9.5 kg Nha^{-1} of NH_4NO_3 are added at sowing. N deposition from the atmosphere (Chambers et al. 2001), N leaching and volatilization based on IPCC emission factors (IPCC 2006d), P losses based on mid-range values for fields in Quebec under moderate risk for P loss from agroecosystems (Beaudin 2006), mineralization of organic nutrients in the soil based on residue inputs (CRAAQ 2000), and the export of nutrients through grain and stover harvest together provide the overall nutrient budget (Table 2). This nutrient budget results in efficiency factors of 0.63 and 0.84 for N and P fertilizer sources, respectively, which are consistent with average efficiency factors for liquid pig manure fertilization (CRAAQ 2000). N_2O emissions are calculated using IPCC equations with emission factors developed specifically for Quebec (IPCC 2006d; Rochette et al. 2008) and parameters from the system described here.

Table 2. Nutrient budget for corn production

	Source	N (kg ha^{-1})	P (kg ha^{-1})
Extractions	Grain	68	24
	Total stover (15% collected stover)	41 (6)	17 (3)
	Total	109	41
Losses	Leaching	18	0.7
	NH_3 volatilization	15	–
	NO_x volatilization	8.3	–
	N_2O volatilization	3.1	–
	P runoff	–	1.8
	P loss from fertilizer	–	0.2
	P immobilization	–	3.0
	Total	45	5.7
Additions	Pig manure	114	36
	Residual in soil	27	11
	Mineral fertilizer	9.5	–
	Deposition	3.4	–
	Total	154	47
Total budget	Add.-loss.-extract.	0.0	0.0

Fertilizers
Energy used for mineral N fertilizer manufacture was based on data from the Canadian fertilizer industry from 2003 (GHGenius3.19), which are adjusted to 2010 levels by assuming an efficiency gain of 0.3% less energy required per year to produce the starter N fertilizer. The study on which this was based considers energy required to produce ammonia, the starting material for all mineral N fertilizers (NRCan 2005, 2010). Energy required to transport fertilizer from the manufacturing facility to the farm was based on the distances and modes of fertilizer transport from American census data from 1993, compiled by NRCan (2005). The GHG emissions from fertilizer manufacture were calculated using values from GHGenius3.19 (NRCan 2010) and are proportional to energy use.

The pig farm that supplies liquid manure fertilizer for the cornfield requires energy and resources to operate and emits GHGs, nutrients, and other pollutants. Due to high production levels and environmental eutrophication issues in the regions of Quebec considered in this study, manure is a waste rather than a valuable co-product (BAPE 2003). Thus, all impacts related to the manure production are allocated to the pig production system, which is consistent with standard LCA allocation methods (e.g., Nemecek et al. 2011; discussion in Knudsen et al. 2010).

Herbicides
Energy use and GHG emissions due to herbicide production and transportation were based on the total energy required for atrazine and metolachlor production from Bhat et al. (1994), combined with the energy use breakdown for the chemical industry in 1994 and corresponding emission rates given in GHGenius3.19 (NRCan 2010). These estimates include the energy required to create the chemical compounds for herbicide manufacture and to transport herbicides to the farm, based on energy costs of 10 MJ kg^{-1} for processing the herbicides into granules, 2 MJ kg^{-1} for packaging, and 1 MJ kg^{-1} for domestic transport. This results in energy usage rates of 203 MJ g^{-1} a.i. and 289 MJ g^{-1} a.i. and GHG emissions of 17 kg CO_2e g^{-1} a.i. and 24 kg CO_2e g^{-1} a.i. for atrazine and metolachlor, respectively. Note that Bhat et al. (1994) used data from 1990, so it is likely that energy efficiencies have increased since then, but a literature search did not find more current data for energy costs associated with herbicide production.

Seeds
Energy for seed production was used from Graboski (2002), which considers a production system located in the United States using some irrigation and different N and P levels; it was selected for this study because it was judged to be the only study with satisfactory seed energy analysis by Hill et al. (2006). The seed production system considers the energy used directly in planting, drying, cleaning through to packaging and the energy required to produce most fuels and the feedstocks used in the process. Because the study did not provide updated GHG emission rates, the GHG emissions associated with seed production were determined using the energy use from Graboski (2002), assuming the energy composition would be the same as that used in GHGenius3.19 (NRCan 2010), based on a seeding rate of 82000 seeds ha^{-1} and a seed mass of 0.3 g.

Allocation Methods
The production of 1 ha of corn yields two co-products under this system: grain and stover, so an appropriate method to allocate the impacts of the system between the two products must be determined. The ISO standard for LCAs (ISO 1997) recommends that allocation be avoided if possible and suggests dividing more complex, larger process into sub-processes or expanding the system boundaries to include the co-products and all their functions. If this is not possible, it is recommended that allocation reflect underlying relationships between the co-products (ISO 1997). However, the challenge for this study is not that the impacts for all co-products are not inventoried, but, rather, that the relative contributions of corn grain and stover to the total impacts are not immediately evident. A few approaches are regularly used in such scenarios, including mass-based allocation, economic-based allocation or system expansion allocation. Because each of these allocation methods has its flaws, we compare the impact of using each approach, as described in the sensitivity analysis section below.

Life Cycle Inventory
The energy use and GHG impacts for each portion of the system within the system boundaries were recorded in a life cycle inventory. To facilitate discussion of results, impacts were grouped by process type as

Table 3. Process impact categories

Category	Processes included (replaced with grain+stover harvesting process in a one-pass system)
Fertilizer production+transport	N fertilizer production
	N fertilizer transport Manure transport
Herbicide production	Herbicide production
Seed production	Seed production
Field operations	Ploughing Cultivator Sowing+mineral fertilizer Manure application Incorporation Metolachlor application Atrazine application (Harvesting grain)
Stover harvest	(Shredding stover) (Raking stover) (Baling stover) (Stover to fieldside)
Stover transport	Loading stover Stover to plant
Fertilizer emissions	Fertilizer emissions
SOC loss	SOC losses

described in Table 3. All energy use is reported as MJ t^{-1} dry stover collected and GHG emissions are reported in terms of CO_2-equivalents (CO_2e) t^{-1} dry stover collected. The impact of GHG from CO_2, N_2O, and CH_4 are considered and are made comparable by using the 100-yr characterization factors from the IPCC third assessment report (Forster et al. 2007) (1, 298, and 25 CO_2e GHG_{mass}^{-1}, respectively).

Sensitivity Analyses

Fraction of Stover Harvested

There are contrasting pressures for increasing or decreasing the proportion of stover that is harvested. For example, increasing the fraction of stover harvested could decrease the marginal cost of production or decrease the energy impact of field operations per tonne of stover collected. However, increased harvesting of residues increases the risk of soil erosion and decreases the inputs that sustain SOC stocks in soils. Thus, we investigate the effects of removing stover at rates of 15, 45, and 75%, with 15% as the default scenario. The nutrient requirements are adjusted accordingly and the predicted SOC losses are scaled linearly with increased gathering.

Development of a "One-Pass" System

Although the machinery to harvest grain while simultaneously collecting and baling stover is not yet at a commercial scale (Shinners et al. 2009), it is certain that farmers would want to minimize the energy and effort required to harvest grain and stover and reduce the number of times they must drive heavy machinery on their fields. We investigate the impact of a one-pass system as compared with a post-harvest shredding, raking, and baling system, which is the modelled default here. The fuel requirements of a one pass machine are those of the best-performing machine described by Shinners et al. (2009) (17 L diesel fuel ha^{-1}, resulting in 704 MJ ha^{-1} total energy use), and replace the impacts from harvesting grain and shredding, raking, and baling stover.

Allocation Methods

Three different methods of allocation are investigated: mass-based allocation, economic-based allocation and system expansion allocation. Mass-based allocation takes a physical approach by partitioning impacts based on the relative mass of the co-products. Under this allocation scenario, the impacts from field processes would be allocated to stover based on the relative mass of stover collected compared to the total mass of grain and collected stover. For fertilizer emissions, the relative mass of N in collected stover is divided by the total mass of N in grain and collected stover. For stover harvesting and transport, all emissions would be allocated to the stover. The drawback to this approach is that the relative masses of the co-products do not necessarily reflect their relative importance or value, or the degree to which they are causing the system to operate as it does.

Economic allocation attempts to solve this issue by assigning impacts proportional to the value of the co-products. For this system, we would use the market value of a hectare of stover divided by the total market value of a hectare of the entire crop (grain plus stover):

$$\frac{\text{Value of collected stover}}{\text{Value of stover + grain}} = \frac{0.9\ kg\ ha^{-1} \times \$0.065\ kg^{-1}}{(0.9\ kg\ ha^{-1} \times \$0.065\ kg^{-1}) + (6.1\ kg\ ha^{-1} \times \$0.175\ kg^{-1})} = 0.053$$

The market value of corn grain used here is the mean price for 2009–2011 in Canada (Agriculture and Agri-Food Canada 2011). It is challenging to determine a price for corn stover, because it has only recently become a commodity for EtOH production, which is still developing a market share as well. Recent studies have used values in the range of \$50-\$80 t^{-1} corn stover (WRI 2009), so we use a mid-range value of \$65 t^{-1} corn stover here. This allocation factor would be applied to all processes that involve both stover and corn grain, while those that are exclusive to stover production would again receive full weighting. The major issue with this approach is that it could easily change as markets change, which is particularly relevant here, since the same expansion of biofuels that may increase grain prices would be expected to increase the development and prices of feedstocks for cellulosic EtOH. The allocation factors that would be used for each method are listed in Table 4 (note that these factors change as the proportion of stover gathered from the field increases).

Under system expansion, a baseline scenario is designated (here, this would be corn grain production), and then any changes from the values under the baseline scenario are attributed to the new activity (here, this would be the corn stover harvest) (Kim and Dale 2002). For example, all field processes associated with planting the corn would receive an allocation factor of zero for the corn stover; impacts associated with fertilizer emissions would be scaled to the relative increase in fertilizer necessary to replace nutrients from the removed stover, and impacts associated with harvesting the stover would receive an allocation factor of one. This approach is straightforward, but it is only appropriate as long as grain harvesting is the baseline scenario. If conditions change so that cellulosic EtOH production increases the demand for stover and its collection becomes a standard practice, it would become inappropriate to assign none of the field-based impacts to corn stover (Schmidt 2008).

RESULTS AND DISCUSSION

Energy

Total energy use in corn stover production at 15% collection under a multiple-pass harvesting scenario ranged from 931.2 to 1442.6 MJ t^{-1} dry stover collected, depending on the allocation approach (Table 5). These numbers are slightly lower than those produced by Kim et al. (2009) for stover production and harvest in the US Midwest. A portion of the discrepancies are likely due to the lower mineral fertilizer inputs in this system, which relies predominantly on the waste product, pig manure, for nutrient inputs. If EtOH yield from corn stover is predicted to be 280 L t^{-1} dry stover (Lal 2008) and energy content of the final EtOH product is 21.1 MJ L^{-1} (ORNL 2010), this would mean feedstock production and transport consumes energy equivalent to 16–24% of the energy in the final EtOH. While energy use during feedstock conversion, storage and distribution is beyond the scope of this study and would need to be quantified, this indicates the potential for a positive energy balance. If the efficiency of the conversion process is increased (280 L t^{-1} dry feedstock is likely relatively conservative) or energy co-products such as biogas, electricity, and heat are captured (Cherubini and Ulgiati 2010), the relative energy required for corn stover production would decrease. If feedstock gathering were increased, relative energy required would decrease further, as discussed in the sensitivity analysis.

The most energy-intensive processes were stover harvest and transport, followed by field operations where applicable (Fig. 3). Background processes including seed, herbicide, and mineral fertilizer production, contributed the least to the total energy impact. This is in contrast to Kim et al. (2009) who found that agrochemicals contributed the most to the total energy impact. This is again largely because most of the additional nutrient requirements in this LCA are met through the application of pig manure, which is considered a waste. Thus, this system may mask somewhat the energy impact of increasing nutrient input requirements.

To roughly predict whether this system of stover production could meet the demands of the government mandate of 5% EtOH in gasoline, we multiplied the mean annual area of grain corn that is harvested in the study's regions between 2001 and 2010 (330000 ha) (Institut de la Statistique du Québec 2011) by the amount of stover collected at 15, 45, and 75% collection (0.9, 2.8, and 4.6 t ha^{-1}), and compared this with the volume of EtOH required to replace 5% of the 8.1×10^9 L sold annually in Quebec (Statistics Canada 2011a).

Table 4. Output allocation factors for corn stover production under each rate of stover collection

	Mass allocation			Economic allocation			System expansion		
	15%	45%	75%	15%	45%	75%	15%	45%	75%
Fertilizer production + transport	0.08	0.22	0.31	0.05	0.14	0.22	0.00	0.00	0.00
Herbicide production	0.13	0.31	0.43	0.05	0.13	0.22	0.00	0.00	0.00
Seed production	0.13	0.31	0.43	0.05	0.13	0.22	0.00	0.00	0.00
Field operations	0.13	0.31	0.43	0.05	0.13	0.22	0.00	0.00	0.00
Stover harvest	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Stover transport	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Fertilizer emissions	0.08	0.22	0.31	0.05	0.14	0.22	0.02	0.05	0.08
SOC loss	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
One-pass	0.13	0.31	0.43	0.05	0.14	0.22	0.16	0.16	0.16

Table 5. Energy impact for all scenarios by impact category (MJ t^{-1} dry stover collected)

Stover collected	Passes	Allocation method[z]	Fertilizer production + transport	Herbicide production	Seed production	Field operations	Stover harvest	Stover transport	Total
15%	Multiple	Mass	68.5	95.4	31.1	315.7	690.3	241.6	1442.6
		Econ.	43.1	38.5	12.6	127.5	690.3	241.6	1153.6
		Syst. exp.	0.0	0.0	0.0	0.0	690.3	241.6	931.9
	One	Mass	68.5	95.4	31.1	231.6	99.6	241.6	767.8
		Econ.	43.1	38.5	12.6	93.5	40.2	241.6	469.6
		Syst. exp.	0.0	0.0	0.0	0.0	119.4	241.6	361.0
45%	Multiple	Mass	59.9	75.7	24.7	250.4	231.1	241.6	883.4
		Econ.	39.8	34.9	11.4	115.3	231.1	241.6	674.1
		Syst. exp.	0.0	0.0	0.0	0.0	231.1	241.6	472.7
	One	Mass	59.9	75.7	24.7	183.7	79.0	241.6	664.6
		Econ.	39.8	34.9	11.4	84.6	36.4	241.6	448.7
		Syst. exp.	0.0	0.0	0.0	0.0	39.8	241.6	281.4
75%	Multiple	Mass	53.5	62.7	20.5	207.4	139.3	241.6	725.0
		Econ.	37.1	31.8	10.4	105.3	139.3	241.6	565.5
		Syst. exp.	0.0	0.0	0.0	0.0	139.3	241.6	380.9
	One	Mass	53.5	62.7	20.5	152.2	65.5	241.6	596.0
		Econ.	37.1	31.8	10.4	77.3	33.2	241.6	431.4
		Syst. exp.	0.0	0.0	0.0	0.0	23.9	241.6	265.5

[z]Econ., economic; Syst. exp., system expansion.

Using a lower conversion rate of 280 L EtOH t^{-1} dry stover (Lal 2008) or a higher conversion rate of 445 L EtOH t^{-1} dry stover (mean of the three values calculated in Shinners et al. 2009), we find that under the lower conversion scenario, 100% of the demand would be met only at 75% stover collection, while under the more efficient conversion rate, 45% stover collection would provide sufficient stover from these corn grain-producing regions of Quebec to meet the provincial demand (Table 6). These numbers are the technical potentials – achievable only if every cornfield in the region began producing stover for EtOH – which is, of course, unrealistic, and would not account for field-level differences in corn production systems. However, even at these maximum values and supplemented by the 120 million L that are currently being produced annually at the GreenField Ethanol grain ethanol plant in Varennes, QC (Green Field Ethanol 2011), the necessary rates of stover gathering to produce sufficient EtOH for the needs of the province within the province would result in substantial removal of stover from fields, increasing erosion risk and depleting soil carbon. These tradeoffs between energy impact, GHG impact, and soil health are discussed in the following sections.

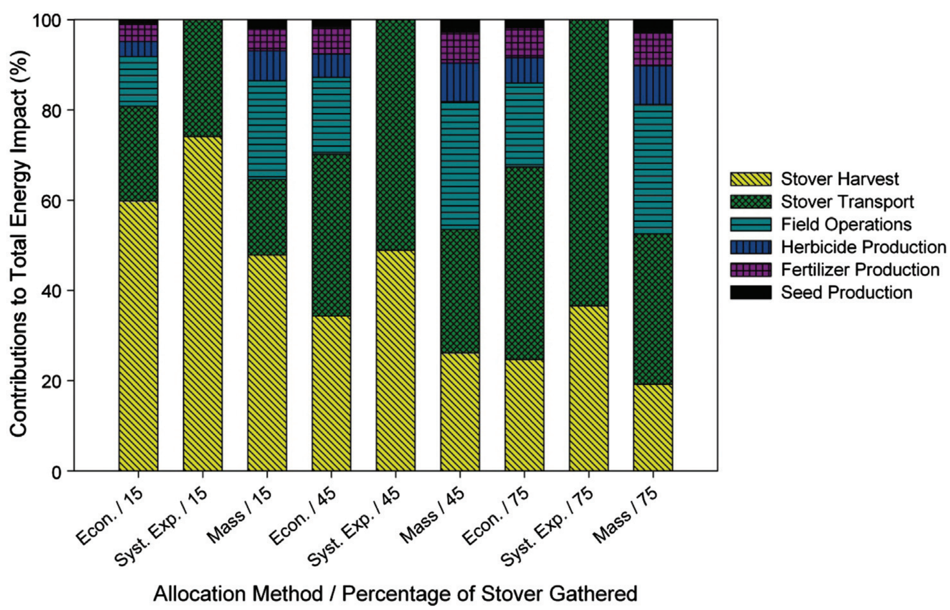

Fig. 3. Breakdown of total energy impact by process category for a multiple-pass stover collection system.

Table 6. Maximum percentage of current Quebec EtOH demand that could be met by the Montérégie, Centre du Québec and Chaudière-Appalaches regions considered in this study

	EtOH conversion rate (L t^{-1} dry stover)	
Stover collected (%)	280 (Lal 2008)	445 (Shinners et al. 2009)
15	21	33
45	63	100
75	105	167

GHG Emissions

With anthropogenic climate change at the forefront of today's global issues, reducing GHG emissions is of the utmost importance (IPCC 2007). Farming practices have substantial potential to reduce GHG emissions or store carbon, but can also be a substantial source of emissions due to on- and off-farm processes, N_2O emissions from fertilizer, and the loss of soil C due to poor soil management and crop residue removal (UNFCCC 2008).

After allocation, total GHG emissions in corn stover production at 15% collection under a multiple-pass harvesting scenario ranged from 319.7 to 488.3 kg CO_2 e t^{-1} dry stover collected, depending on the allocation method (Table 7). To put these results into perspective, the GHG impact for each tonne of stover collected from farmland in Quebec would be equivalent to about 2% of Canada's 2009 per-capita emissions at a 15% collection rate, and 6–9% at a 75% collection rate (Environment Canada 2011; Statistics Canada 2011). These GHG impact values are substantially greater than those reported by Spatari et al. (2005) for corn stover-based cellulosic EtOH production in Ontario (106 kg CO_2 e t^{-1} dry stover produced and transported to EtOH facility). This is largely because SOC losses and N_2O emissions were not included in the LCA of Spatari et al. (2005). If only the field operations, stover harvest, transport, and seed, herbicide, and mineral fertilizer production processes are considered, the values from this study are similar to those reported by Spatari et al. (2005). However, this difference highlights the importance of considering the GHG offset through C storage as well as N_2O emissions. Indeed, these GHG impact results are within the range calculated by Kim et al. (2009) for corn stover production in the US Midwest, which mostly range between ~40 and 300 kg CO_2e t^{-1} dry corn stover, with this study tending to produce somewhat higher values. They are also similar to those calculated by Cherubini and Ulgiati (2010) for a corn stover EtOH production system; summing the SOC losses, soil GHG emissions and CO_2e from biomass pellet transport gives a net GHG impact of about 260 kg CO_2e t^{-1} dry corn stover.

The most important contributor to the total GHG impact was SOC loss (40–61%) (Fig. 4), followed by emissions of N_2O (10–31%) and stover harvest (14–22%), depending on the fraction of stover collected and the allocation method. When more stover is removed from the field, the relative importance of SOC loss and stover transport in producing GHG increases, while the relative contribution of GHG from stover harvest decreases.

Sensitivity Analysis

Development of a "One-Pass" System

This LCA was based on conditions representing the present technology available in Quebec to collect stover:

Table 7. Greenhouse gas (GHG) impact for all scenarios by impact category (kg CO_2e t^{-1}dry stover collected)

Stover collected	Passes	Allocation method[z]	Fertilizer production + transport	Herbicide production	Seed production	Field operations	Stover harvest	Stover transport	Fertilizer emissions	SOC loss	Total
15%	Multiple	Mass	5.4	8.2	2.5	32.2	70.4	23.7	151.6	194.4	488.3
		Econ.	3.4	3.3	1.0	13.0	70.4	23.7	95.4	194.4	404.6
		Syst. exp.	0.0	0.0	0.0	0.0	70.4	23.7	31.2	194.4	319.7
	One	Mass	0.0	8.2	0.0	0.0	12.2	23.7	31.2	194.4	419.5
		Econ.	5.4	3.3	2.5	23.6	10.2	23.7	151.6	194.4	334.8
		Syst. exp.	3.4	0.0	1.0	9.5	4.1	23.7	95.4	194.4	261.4
45%	Multiple	Mass	14.3	19.5	5.9	76.6	70.8	71.0	403.0	583.1	1244.1
		Econ.	9.5	9.0	2.7	35.3	70.8	71.0	267.8	583.1	1049.1
		Syst. exp.	0.0	0.0	0.0	0.0	70.8	71.0	93.6	583.1	818.4
	One	Mass	14.3	19.5	5.9	56.2	24.2	71.0	403.0	583.1	1177.1
		Econ.	9.5	9.0	2.7	25.9	11.1	71.0	267.8	583.1	980.1
		Syst. exp.	0.0	0.0	0.0	0.0	12.2	71.0	93.6	583.1	759.9
75%	Multiple	Mass	21.5	27.0	8.1	105.8	71.1	118.4	606.9	971.8	1930.6
		Econ.	14.9	13.7	4.1	53.7	71.1	118.4	421.1	971.8	1668.8
		Syst. exp.	0.0	0.0	0.0	0.0	71.1	118.4	156.0	971.8	1317.2
	One	Mass	21.5	27.0	8.1	77.6	33.4	118.4	606.9	971.8	1864.7
		Econ.	14.9	13.7	4.1	39.4	17.0	118.4	421.1	971.8	1600.3
		Syst. exp.	0.0	0.0	0.0	0.0	12.2	118.4	156.0	971.8	1258.3

[z]Econ., economic; Syst. exp., system expansion.

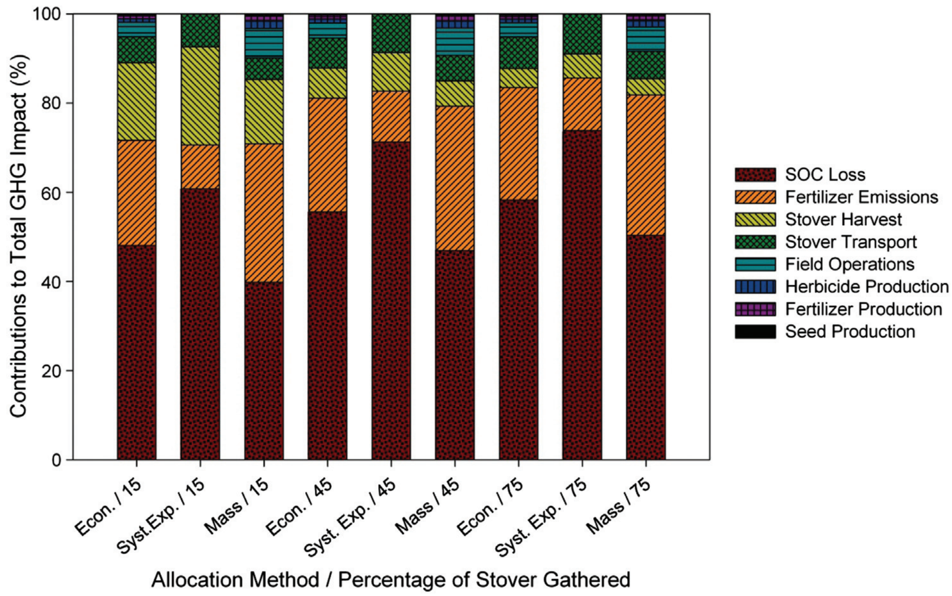

Fig. 4. Breakdown of total greenhouse gas (GHG) emissions by process category for a multiple-pass stover collection system.

shredding, raking, and then baling (a three-pass system), accounting for the largest energy expenditure and third-largest GHG impact (after SOC loss and soil N_2O emissions). If it were possible to harvest the corn grain and stover at the same time, in a system such as the single-pass corn grain and stover simultaneous harvester profiled in Shinners et al. (2009), it would greatly reduce the system's GHG emissions, particularly because the impacts from the stover collection processes would have an allocation weight of 1.0 under all allocation methods. We considered the replacement of the three-pass stover harvesting system and the combine harvester with the ''ear-snapper'' system described in Shinners et al. (2009), which requires 17 L diesel fuel ha^{-1} (the mean value for the three speeds at which it was tested). The GHG emission rates were then calculated based on the same emission rates applied to diesel fuel use in tractors in the rest of the LCA (NRCan 2010). In addition, the impacts from this new, combined process required allocation between grain and stover production. The mass and economic allocation methods used the same factor applied to the other field-level operations. The system expansion approach considers only those impacts that are additional to those which would occur under the baseline system (corn grain harvesting). Thus, the allocation factor would be: $(I_1\text{-}I_{comb})/I_1$, where I_1 is the impact from the one-pass harvesting system and I_{comb} is the impact from the combine under the baseline system (Table 4). At 15% stover gathering, this yields a value of 0.156.

By replacing the three-step stover collection process and the combine with a one-pass harvest system, the energy impact was reduced by 47–61%, depending on the allocation method at 15% stover gathering (Table 8). This dramatic reduction is because stover harvest makes up a large portion of the energy requirements of the system, and because the allocation of these impacts is dramatically reduced once some of the impacts can be borne by the grain. Increased stover gathering reduces the effect of introducing the one-pass system.

The one-pass system reduced GHG impact substantially – by 14–18%, depending on the allocation method (Table 8) – but affected the GHG impact much less than the energy impact. This is because the impact of the stover harvest makes up less of the total GHG impacts than it does the total energy impacts. Therefore, reducing the impact of stover harvest affects the total GHG budget less than it does the total energy budget. The differences between the combine and three-pass system and the one-pass system as represented here would likely also alter the transportation system, since the stover is no longer baled, but we would not expect these differences to alter the results substantially.

Table 8. Reduction of impact with a one-pass system (%reduction relative to a multiple-pass system) considering mass allocation, economic allocation and system expansion (Syst. exp.) allocation

Energy	% stover	Mass	Economic	Syst. exp.
	15	46.77	59.30	61.26
	45	24.77	33.44	40.47
	75	17.80	23.71	30.30
GHG	% stover	Mass	Economic	Syst. exp.
	15	14.10	17.25	18.22
	45	5.38	6.58	7.16
	75	3.41	4.10	4.47

Fraction of Stover Harvested

We investigated the effect of removing 15, 45, and 75% of stover from the fields. The lowest number is more consistent with the goal of sustaining soil C stocks, while also protecting soil from erosion (Johnson et al. 2006), while the higher numbers are in the ranges that have been cited in other EtOH LCA studies (Stumborg et al. 1996; Levelton Engineering Ltd 2000; Sheehan et al. 2004; Spatari et al. 2005; Adler et al. 2007). Changing the mass of stover harvested affects the impacts in a number of ways: changing the economic and mass-based allocation factors, changing the per-tonne of dry stover final values, and changing the nutrient and carbon inputs and outputs in the soil, resulting in complex dynamics.

Increasing stover harvest reduced the energy impact per tonne of dry stover (Table 9), largely due to a decreased burden from the field-level processes (Fig. 3). Increasing stover harvest affected the GHG impact in the opposite way from the energy impact (Table 9), with SOC losses increasing dramatically, and the gains from increased efficiency being balanced by increased allocation of impact to the stover under the mass and economic allocation scenarios (Fig. 4).

These opposite reactions between energy and GHG impact are important (Fig. 5). While the desire to increase energy efficiency pushes for greater stover collection, the need to preserve SOC and protect soils from erosion would advise against it. This points to the importance of field-specific assessments of SOC dynamics – combining increased stover collection with other SOC conservation strategies (Sheehan et al. 2003; Kim et al. 2009; Cherubini and Ulgiati 2010) are likely essential to maintain soil health. However, although Quebec has instituted a “carbon tax” on fuel oil (Gouvernement du Québec 2007) and is regulating industrial GHG emissions as part of the Western Climate Initiative (Gouvernement du Québec 2010), regulating field-level GHG emissions remains a challenge. With a price on fuel, but without a price on SOC loss, there is a potentially dangerous incentive to reduce the energy impact of corn stover harvest and transport at the expense of increasing the total GHG impact.

Table 9. Change in impact with increased stover harvest (% change relative to 15% stover gathering) considering mass allocation, economic allocation and system expansion (Syst. exp.) allocation

Energy	% stover	Mass	Econ.	Syst. exp.
Multiple pass	45	−38.77	−41.56	−49.28
	75	−17.93	−16.11	−19.43
One pass	45	−13.45	−4.45	−22.05
	75	−10.33	−3.84	−5.66
GHG	% Stover	Mass	Econ.	Syst. exp.
Multiple pass	45	154.78	159.33	156.03
	75	295.36	312.49	312.06
One pass	45	180.64	192.79	190.68
	75	344.56	378.06	381.36

Allocation Methods

Choosing an appropriate allocation method is challenging for this system, and can strongly influence results. System expansion consistently gives the lowest impact, while mass-based allocation gives the highest (Fig. 5). As long as corn stover remains less valuable than corn grain on a per-mass basis, the economic allocation will remain lower than the mass-based allocation. Energy impact is 35 to 58% higher and GHG impact is 32 to 38% higher under mass-based allocation than under system expansion, depending on the fraction of stover collected and whether a one or multiple pass scenario is considered (Tables 5 and 7). These results partially echo those of Luo et al. (2009), who found that allocation methods are critical in determining the impact

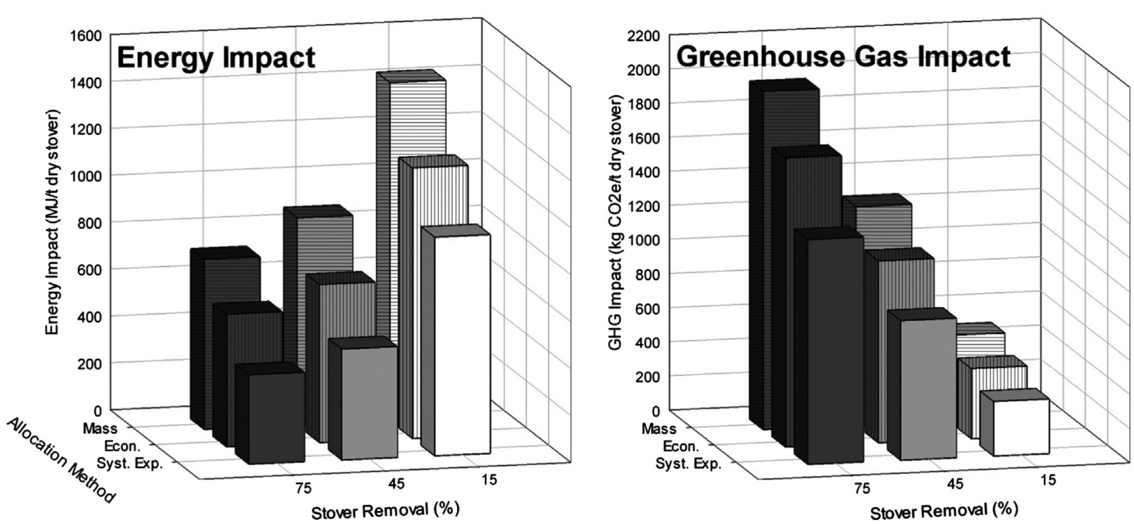

Fig. 5. Relative importance of allocation method and percentage of stover removal on energy and greenhouse gas impact.

of corn-stover based EtOH. Kim et al. (2009) suggest that system expansion is the preferred allocation method. While appealing due to its clarity and because it is preferred by the ISO above other allocation procedures (ISO 1997) where possible, system expansion is a risky approach to use for allocation within this system, because if the ‘‘baseline scenario’’ comes to include the harvest of corn stover as cellulosic EtOH or other biofuel production increases, the reasoning behind its application becomes weak. Furthermore, it is the least conservative approach for estimating this system’s impact, predicting energy and GHG impacts equal to less than half those predicted under mass allocation in some cases (this study and Kim et al. 2009). However, it is interesting to note that because the field operations are given a weight of zero under the system expansion approach, the relative contribution of SOC loss to the total GHG impact is greatest for this approach.

Study Limitations

Because this LCA has indicated that soil carbon dynamics are a major contributor to the total GHG impact of this system, it would be ideal to move beyond using the climate zone-specific IPCC factors for SOC loss under different management systems to a more comprehensive and regionally specific approach. A SOC modelling approach in LCAs has been applied by Adler et al. (2007) and Kim and Dale (2009), who apply the DAYCENT model to Pennsylvania and the US Mid-west, respectively. However, as noted by VandenBygaart et al. (2008), the application of such models can require substantial adjustments for a given region. VandenBygaart et al. (2008) developed factors specific to Canadian regions to predict the greenhouse gas effects of land management changes from annual to perennial cropping, tillage to no-tillage, and summer fallow to continuous cropping. Their study found that the IPCC factors tended to over estimate the SOC losses compared with those calculated for the Canadian GHG Inventory using the CENTURY model. On average, the 20-yr SOC mean loss factors calculated for eastern central Canada were 37.6% of what the IPCC values would have predicted, likely due in part to the cooler climate in Canada. If the predicted SOC losses due to increased residue removal were similarly reduced, then the total GHG impact would be reduced by 25–38%, depending on the fraction of stover gathered and the allocation method. Because of the importance of SOC loss to the overall emissions, developing a regionally specific factor through a combination of modelling and field data is recommended.

This study considers the energy and GHG impact of corn stover production for EtOH only up to delivery at the production plant. Thus, it does not indicate the final impact of EtOH production in Quebec. However, these data provide a strong estimate for the impacts specific to the major Quebec corn-producing regions and their associated yields and production systems, and could be used to strengthen future studies that examine the next steps in the EtOH production process.

CONCLUSIONS

The desire to reduce both the energy impact and the GHG impact of corn stover production exerts opposite pressures on the amount of stover that is harvested from fields, creating a potentially important trade-off. The calculated energy and GHG impact of stover production for EtOH is strongly influenced by the mass of stover that is collected, whether an effective one-pass collection system is available, and the allocation method that is chosen. The most useful region-specific data to obtain would be the effect of removing stover from the field on SOC stocks, which could improve estimates of the GHG impact and provide guidance on the mass of stover that can be collected sustainably while maximizing collection efficiency.

Scaling up this model system to its maximum technical potential at the regional level predicts that farmers in the Montérégie, Chaudières-Appalaches, and Centre-du-Québec regions, could provide sufficient biomass required for enough EtOH to replace 5% of gasoline used in Quebec, as per governmental policy. However, this could potentially come at the expense of soil health, as pressure to gather more stover increases. Most importantly, the LCA presented here should not be used in isolation to inform planners and policy makers. As well as the environmental impacts profiled here, other environmental, economic, political, and social factors must be considered in making any long-term decisions regarding the production of cellulosic ethanol in Quebec.

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