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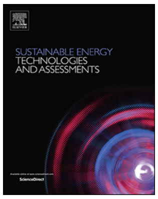

Original article

The life cycle greenhouse gas emission benefits from alternative uses of biofuel coproducts

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ABSTRACT

Coproducts from bioenergy processing have potential as alternative products in the market, thereby reducing greenhouse gas (GHG) emissions. Thus far, the environmental benefits from coproduct use have been overlooked in most studies because of the lack of knowledge on their effective use and the limited commercialization. The objective of this study is to investigate the energy and GHG emissions savings by using biofuel coproducts. The effects of coproduct use on the overall life cycle GHG emissions performance of biofuels were evaluated. Dry distiller grains in the wheat to ethanol pathway, and crude glycerine and canola meal from biodiesel, are assumed to replace animal feed, fossil fuel, fertilizer, synthetic glycerine. A system expansion approach was implemented to estimate GHG emissions savings. The results show that the overall life cycle GHG emissions from the wheat to ethanol pathway can be reduced by 2–34% when dry distiller grains displace fertilizer, fossil fuel, or animal feed. In the canola to biodiesel pathway, GHG emissions can be reduced by 5–26% and 8–41% when canola meal replaces animal feed and crude glycerine replaces synthetic glycerine. The study highlights the potential role of the coproducts from biofuel production in additional GHG emissions reduction over the life cycle.

Introduction

Around 71% of global anthropogenic greenhouse gas (GHG) emissions are caused by energy production and its subsequent use; this figure includes transportation emissions [1]. The growing concern over climate change and fossil fuel dependency has encouraged people to look for renewable energy sources. The share of renewables in the global energy demand has increased in the past decades. As of 2016, renewable energy comprised around 18% of the world energy mix [2]. Bioenergy makes up 14% of the total renewable sources energy production and is considered as one of the most effective energy transformation and climate change mitigation options in many countries [2]. Its future production is projected to constitute up to 35% of global energy by 2050 [3]. Bioenergy has been widely used in number of applications, namely transportation fuel, space heating from the domestic to the industrial scale, domestic cooking, water heating, electricity generation, and combined heat and power generation, and the growth of these application areas has gradually increased in recent years [4,2].

Among the liquid transportation biofuels, ethanol and biodiesel are the two most widely produced for the global market [4]. They are mainly sourced from agricultural products such as corn, palm oil, soybean, sugarcane, and wheat. Contributing to around 4% of global transportation fuels, the ethanol and biodiesel industries are emerging as the largest biofuel industries among all the renewables worldwide [5]. Global ethanol and biodiesel production was reported to be 98.6 billion litres and 30.8 billion litres, respectively, for the year 2016 [5], with a 9% increase in biodiesel production from 2015 [5]. The United States (U.S.) and Brazil are the world's leading biofuel producers, together contributing 80% of biofuels worldwide [2]. Global biofuel production is expected to increase and the cost to decrease in the coming decades because of renewable energy policy development in many countries and global trends in diesel and gasoline demands [6]. Among the policy measures that strongly support biofuel expansion is the U.S. Renewable Fuel Standard (RFS). The RFS sets a yearly requirement of a certain volume of renewable fuels to replace conventional transportation fuels, heating oil, or jet fuel in the U.S. The volume of renewable fuels increases every year and will go up to 36 billion gallons by 2022 [7,8]. The European Union (EU) has also established policies for the production and use of energy from renewable sources. Directive 2009/28/EC requires 20% of the energy consumed in the EU to come from renewable sources [9], while Directive 2003/30/

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EC requires Member States to set a target of a 5.75% share of biofuels in its road transportation fuel mix by 2010 [10]. The Canadian government mandated a 5% ethanol blend in fossil gasoline in late 2010 and 2% biodiesel in conventional diesel on July 1, 2011 [11]. In support of this mandate, Canada has produced an increasing amount of biofuels internally with a target of reducing Canada's yearly GHG emissions by up to four million tonnes [11]. The Government of Canada is also developing a clean fuel standard that aims to reduce 30 million tonnes of GHG emissions annually by 2030 through the increased use of low carbon fuels [12]. The biofuel industry can play an important role in helping to achieve all of these reductions targets [13].

Bioenergy could offer more environmental benefits than fossil fuel-based electricity, heating, and transportation [14] because they are renewable and have the potential to reduce GHG emissions. However, some studies suggest that the environmental impact from bioenergy could be worse than fossil fuel depending on how factors like direct and indirect land use change, the coproduct allocation option, and system boundary are considered [15–19]. The environmental and economic benefits of biofuel are not limited to the use of the main fuel but include the use of coproducts. In most cases, biofuel processes are multi-functional, i.e., they produce coproducts that have a wide range of potential applications. Evaluating the effects of coproduct applications on the overall environmental performance of biofuel production is challenging and needs to be handled carefully. This has been a topic of discussion in several LCA studies [18–22]. Due to the lack of information on the potential of biofuel technologies operated commercially and the lack of full consideration of coproduct use, along with inconsistencies in system boundary selection, assumptions and allocation approaches, there is high uncertainty and variability in biofuel LCA results. Depending on the feedstock type, coproduct yields and applications could differ greatly. For example, in Canada, ethanol is primarily produced from the dry milling of wheat [23], during which dry distiller grains (DDGs) are simultaneously produced as coproducts [23,24]. Around 3.5 kg of DDGs can be obtained per litre of ethanol [24]. Canadian wheat-based ethanol industries provide 1.46 billion litres of ethanol and 1.16 million tonnes of DDGs annually [23]. Some ethanol industries also coproduce acetic acid, electricity, glycerol, lactic acid, and pulp [25,26]. On the other hand, biodiesel from oil seeds such as canola or soybean seeds produces seed meal as a coproduct, around 60–80% of the feedstock [24]. Biodiesel industries also coproduce propylene glycol, depending on the feedstock [25,26].

Common biofuel coproducts such as DDGs, soybean meal, and canola meal have around 26%, 47%, and 35% crude protein, respectively [24]. Crude protein is a measure of the protein content in a food and it is fundamental in animal feed. DDGs contain important nutrients such as protein and fiber that are left unused after the starch in wheat grains is extracted to produce ethanol [25]. DDGs are widely available in the market in different forms such as dry distiller grains with solubles, modified distiller grains with solubles, wet distiller grains with solubles, and condensed distillers' solubles to be used as animal feed [27]. Around 84% of the DDGs supplied to the local and global feedstock market by U.S. ethanol industries are used as dairy and beef cattle feed (42% each), followed by swine feed (11%). The rest is used as poultry feed (5%) [27]. DDGs have a metabolizable energy of 7013 BTU/lb dry matter, which is comparable to that of corn, a commonly used animal feed (7178 BTU/lb dry matter) [28]. In addition, DDGs have a crude protein concentration of 32.2%, four times higher than that of corn (8.3%) [28]. This makes DDGs highly preferable sources of animal feed.

DDGs could also be used as a stand-alone heat source or as a compliment to coal in furnaces for space heating [23,29,30]. There are several studies that evaluate the combustion and fuel characterization of DDGs [30], highlighting their high sulfur and nitrogen content, high potassium concentration, and low calcium and magnesium concentrations, which are comparable with most other agricultural fuels. A 2018 study by Mansur et al. investigated the high potential of DDGs to be converted into biocrude oil, at a 38.2% oil recovery [31]. Because of the high moisture content and high oxygen levels, biomass has a lower heating value than conventional coal [23]. Cofiring densified biomass with coal can reduce combustion emissions significantly compared to conventional coal firing [32,33]. Biofuel coproducts such as DDGs can also be densified into cube, pellet, or briquette form to increase the bulk density and ultimately reduce transportation and storage costs [23]. Like conventional wood pellets, DDGs can be cofired with coal or burned on their own to provide heat [23]. DDGs pellets can achieve high bulk density, hardness, durability, and lower moisture and ash content, which make them ideal to be used as an energy substitute [23].

Organic fertilizer is another emerging potential market for biofuel coproducts. Because of high concentrations of plant nutrients, i.e., boron (B), calcium (Ca), iron (Fe), magnesium (Mg), manganese (Mn), nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and zinc (Zn), both DDGs and oilseed meals are of great interest to those in the organic fertilizer market [24]. The high nitrogen content and relatively low cost make DDGs preferable sources of nitrogen fertilizer than urea [34].

Canola meal is a coproduct from canola seed crushing in the canola oil production process, while glycerine is from the canola oil to biodiesel conversion process [35,36]. Due to the rapid expansion of biodiesel production and its potential as an alternative fuel, biodiesel industries are considering different uses of main coproducts like canola meal, crude glycerine or glycerol [37,38]. Three alternative applications are considered: (a) synthetic glycerine, (b) animal feed, and (c) fertilizer.

Glycerine is obtained in crude form during biodiesel production and is assumed to be upgraded before being sold as synthetic glycerine in the market. When used in cattle feed, glycerine displaces the starch content in the cattle feed rations. Schroder and Sudekum showed that 10% dry glycerine displaces around 50% of the starch content in the feed ration of steers [39]. Glycerine replaces corn starch when used in high and low forage diets for sheep and steers with an energy value ranging from 0.90 to 1.05 Mcal/lb [40]. Glycerine at 3.1% of dry matter in feed rations increases milk production rates and protein percentages [41]. Around 3–15% glycerine in feed ration dry matter has no lethal impact on cattle digestion, feed intake, milk composition, or milk production [38,39,42,43]. In addition, the energy value provided by the starch level in crude glycerine (2000–2300 kcal/kg) is equal to the energy provided by corn starch (2000 kcal/kg) used in animal feed [25,44,45]. Hence, crude glycerine obtained during biodiesel processing can replace animal feed in the market. Increased biodiesel production also created a new market for glycerine as an alternative green energy source replacing petroleum-based fossil fuels such as natural gas [25,46].

A number of studies have been conducted on different applications of biofuel coproducts and their associated energy and emissions impacts [23,24,28,47]. Saha evaluated and compared the on-site environmental impacts of DDG pellets and commercial wood pellets used as an energy source in a furnace [23]. However, the study did not include life cycle environmental impacts of producing DDG pellets commercially for space heating. Bremer et al. found that coproduct credits represent around 19–38% of the life cycle GHG emissions in the corn to ethanol pathway when DDGs are used as animal feed in cattle, poultry, and swine diets [47]. Henderson showed that full cycle GHG emissions decreased by 3.9% and 4.6% from 10% ethanol-blended gasoline in the years 2000 and 2010, respectively, when coproduct credits are obtained from the DDG and CO_2 produced during ethanol production from corn [48]. Falano et al. evaluated the potential GHG emissions savings when acetic acid, electricity, and lactic acid from ethanol production are considered. The study posited the possibility of around 72–87% GHG emissions reduction compared to conventional fuels [26]. Most of the existing LCA studies are based on ethanol production from corn [20,47,49,50]; there are few studies on coproducts from wheat processing. Furthermore, the studies on biofuel coproduct credits did not thoroughly discuss the commercial feasibility or the long-term policy implications of the coproduct uses. Moreover, most of the studies considered a single use of a coproduct in the biofuel life cycle [27,47]; alternative coproduct uses and potential environmental trade-offs were not evaluated. This paper, therefore, aims to answer research questions associated with the use of coproducts from biofuel as a potential substitutes for animal feed, fuel, or fertilizer. The paper attempts to address the following issues: Are the coproducts from the wheat to ethanol and the canola to biodiesel energy conversion pathways environmentally viable substitutes of animal feed, energy, or fertilizer applications? What are the net environmental benefits of using the coproducts as substitutions? How does one assign credit to the coproducts and how does doing so affects the overall results? What are the long-term policy implications of the various coproduct uses from bioenergy pathways? The insight from the study will provide valuable information to decision makers as it highlights the potential consequences of coproducts from rapidly growing bioenergy production.

Method

LCA is the method followed in this study. According to the ISO, LCA has four stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [51,52]. The research conducted for this study done through the ISO framework and principle is explained in this section.

Goal and scope of the study

The main purpose of this study is to identify the alternate environmental advantages related to potential applications of coproducts from two biofuel pathways: DDGs from wheat to ethanol and canola meal and glycerine from canola to biodiesel conversions. The effect of coproduct allocation on overall life cycle GHG emissions was investigated. The main findings from this study will provide the energy industry, mostly biofuel producers, insights on the environmental benefits of effective coproduct use. The information will also help policy makers to develop long-term policies on the commercialization of environmentally friendly valorization of biofuel coproducts.

The GHG emissions savings from the use of coproducts is evaluated through the functional unit of 1 MJ biofuel energy. This will allow an easy comparability with similar studies [53]. All energy and material input requirements are scaled to match the functional unit.

Fig. 1 shows the flow chart of the method followed to obtain the coproduct credits. First, an appropriate allocation type from all possible approaches was chosen. Allocation approaches are explained in Section "Allocation approach to coproduct credit". Different coproduct applications, the corresponding energy and emission factors associated with the displaced products, and the displacement ratios between the coproducts and the displaced products are explained in Sections "Data inventory: wheat to ethanol pathway" and "Data inventory: canola to biodiesel pathway" for both pathways. The coproduct credits were calculated by multiplying the amount of displaced products with the emission factors associated with the displaced products. The amount of the displaced products was determined by using the displacement ratios. Finally, a number of scenarios that considered different uses of coproducts were derived. The scenarios include both single and combined uses of different coproduct applications to determine the impacts of coproduct credits on overall life cycle GHG emissions of the biofuels.

Three applications of bioethanol coproduct DDGs were explored in the study. Fig. 2a–c illustrate the cradle-to-grave wheat to ethanol pathway system boundaries [35,54] when the coproduct is used to substitute (a) animal feed, (b) coal, and (c) fertilizer

As illustrated in Fig. 3a–d, canola meal is a coproduct from the crushing of canola seed in the canola oil production process, and glycerine comes from the canola oil to biodiesel conversion process [35,36]. The application of canola meal as animal feed and three applications of glycerin (as upgraded synthetic glycerin, animal feed, and fertilizer) were considered in this study.

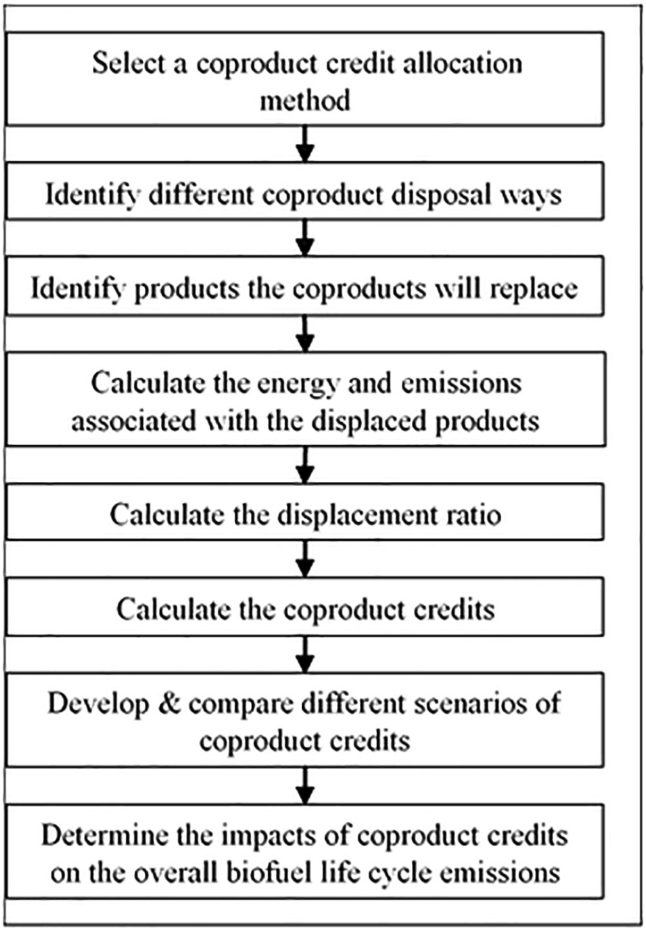

Fig. 1. Method followed to obtain biofuel coproduct credits.

Life cycle inventory analysis

The data requirements and the allocation procedures followed to calculate the coproduct credits for the biofuel pathways are discussed in this section [19].

Allocation approach to coproduct credit

There are different ways of assigning environmental burden between a main product and its coproducts [46]. According the ISO recommendation, allocation should be avoided whenever possible by partitioning the input and output requirements among the main product and its coproduct [52]. When this is not the case, the allocation hierarchy is to perform system expansion; this is a preferred allocation method in LCA for coproduct credit calculation [35,49,54–57]. The system expansion approach was followed in this study to evaluate the effect of coproduct credit on the overall life cycle GHG emissions of the biofuels.

The system expansion approach extends the boundary to include alternative products from the market that can be substituted or replaced by the coproduct [46]. The main advantage of the system expansion approach is that it takes into account the indirect effects of the coproduct use, thereby making the LCA results more reliable [54,58]. There are also arguments in favor of the system expansion approach in cases where fuel is a byproduct and non-fuel products are the main product, and when different fuel production pathways are compared [54,55,57,59]. According to Wang et al., the selection of a coproduct credit allocation method should be based on the biofuel pathway [35,59]. However, mass allocation, energy allocation, and market value allocations have been mentioned in the literature for coproduct credit

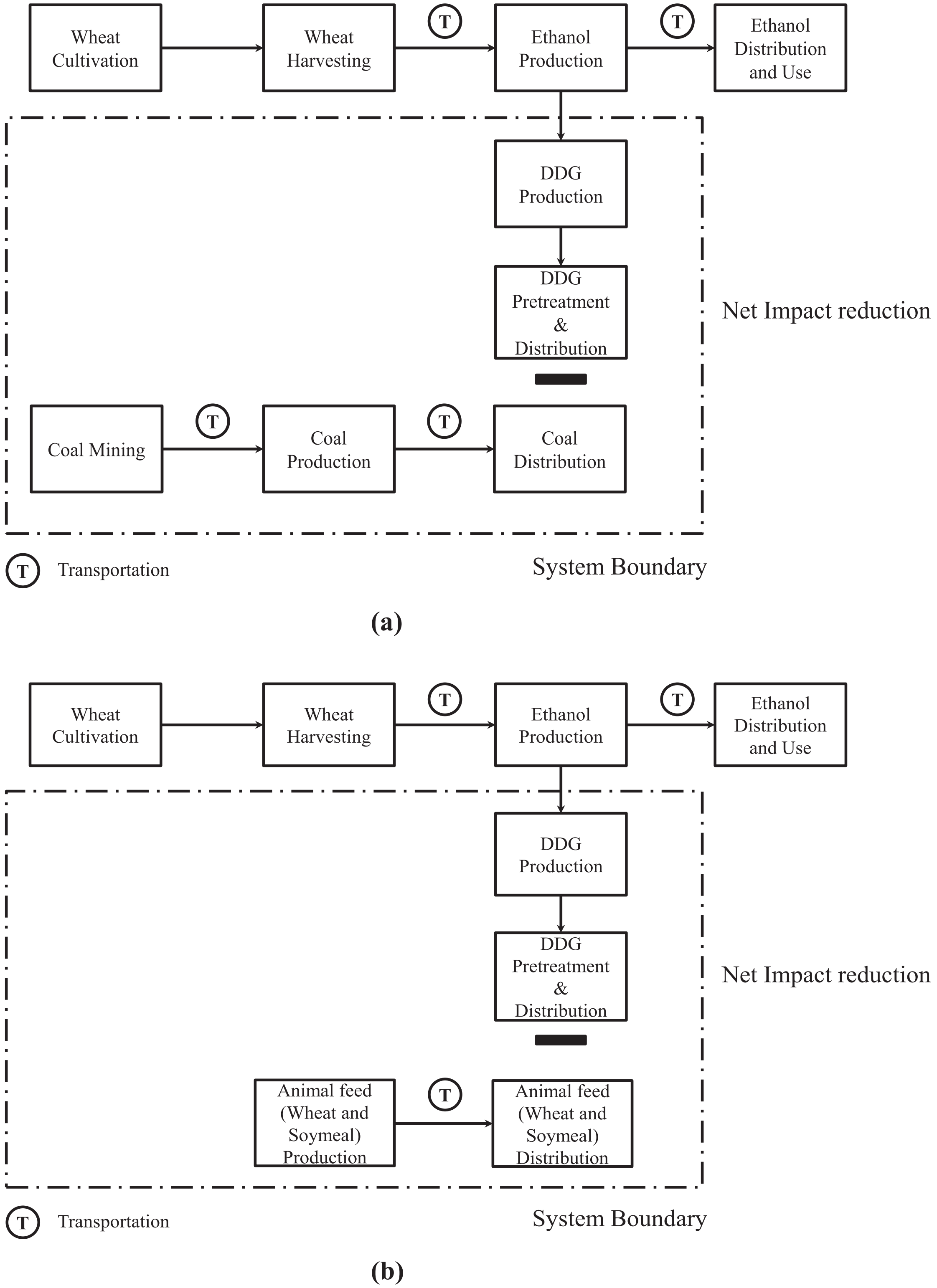

Fig. 2. Cradle-to-grave wheat to ethanol pathway system boundaries when the coproduct substitutes (a) coal, (b) animal feed, and (c) fertilizer.

calculation as well [54,60–63]. But limitations such as curtailed system boundaries, which exclude coproduct use, lower value of displaced products, and inconsistency in price result in improper allocation of emissions between the main product and its coproduct [35,54].

In the system expansion approach, the coproduct credit is obtained based on the assumption that the displaced product and the coproduct have the same energy and GHG emissions credit. The obtained coproduct credit is then subtracted from the total life cycle GHG emissions of the corresponding biofuel pathway [35,55]. To apply this approach, the following are necessary: the quantity of product to be displaced, the displacement ratio between the coproduct and displaced product, and, finally, the energy and emission impacts of the displaced product [35,54].

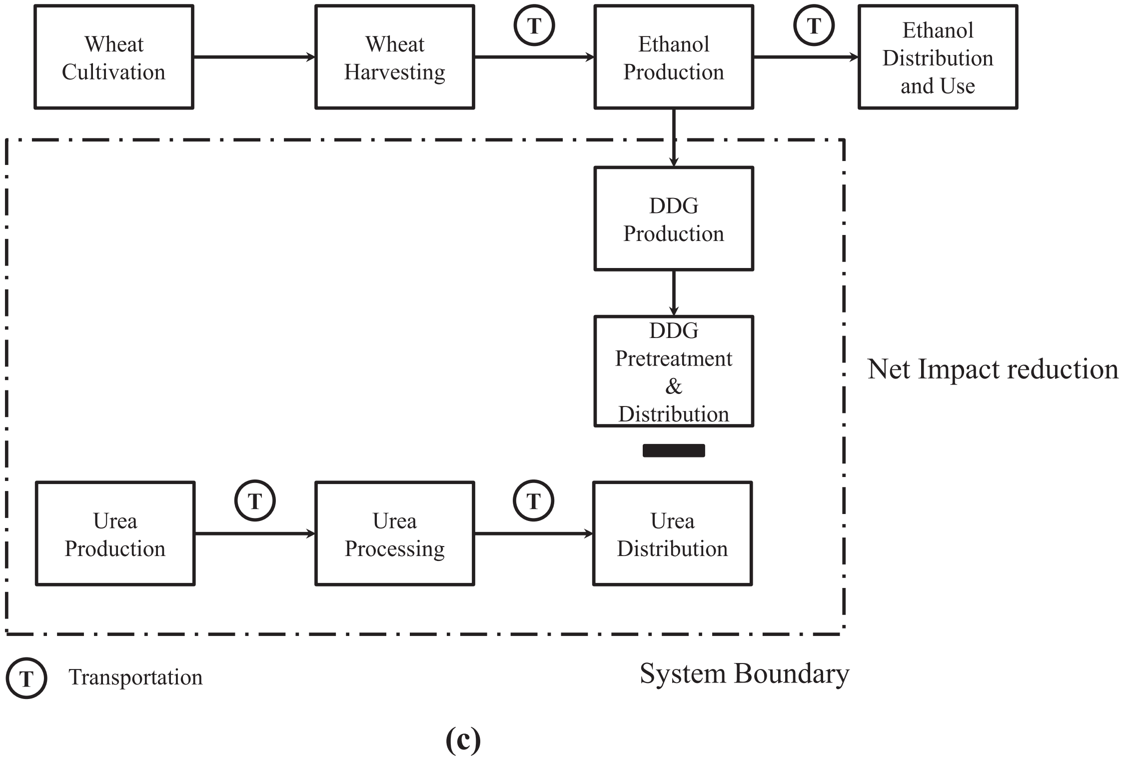

Fig. 2. (*continued*)

Data inventory: wheat to ethanol pathway

Table 1 shows the inputs and assumptions used to calculate coproduct credits when using DDGs from the wheat to ethanol pathway in the market as animal feed, fuel, and fertilizer.

The GHGenius model was used to calculate the coproduct credit when DDGs from the wheat to ethanol pathway displace animal feed [36]. The displacement ratio between DDGs and animal feed is calculated as 0.8 [36]. The animal feed is composed of 45% wheat and 55% soybean meal [36]. The displacement factor is calculated based on the digestible energy in kcal/kg of animal feed in pig diets [64,65]. DDGs have a digestible energy of 3924 kcal/kg, compared with wheat and soybean meal, which provide around 3350 and 3280 kcal/kg, respectively [64,65]. The energy and GHG emissions associated with the production and transportation of wheat and soybean for animal feed are included in the coproduct credit calculation. Methane emission savings of 3.74 g per kg of DDGs consumed as animal feed are assumed [25,36]. It is considered that feeding the ruminants DDGs in their cattle feed ratio produces 3.74 g less methane compared to feeding animals regular cattle feed.

When DDGs are used as energy fuel for space heating, a displacement ratio of 1.28 between DDGs and coal is assumed based on the combustion energy of DDG pellets and industrial coal (Table 1) [23,36]. That is, 1.28 kg of DDGs is needed to provide the same amount of energy from 1 kg of coal. The upstream and combustion emissions from coal are considered to calculate the GHG emission savings from substituting coal with DDGs. The life cycle GHG emissions from the consumption of 1 kg of coal were determined using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET 1) model [66].

The displacement ratio of 11.0 is considered for DDGs used as a fertilizer, urea. This ratio is based on experimental data that shows 11.0 kg of DDGs provides the same amount of nitrogen a 1 kg of urea could provide (0.5 kg of nitrogen per kg of urea) [34]. The direct emissions, mainly from the combustion of fossil sources like natural gas during urea production, and indirect emissions, such as unused CO_2 released to the atmosphere during urea production, were considered to calculate the coproduct credit [67].

Data inventory: canola to biodiesel pathway

Table 2 shows the data and assumptions used for calculating coproduct credits for biodiesel coproducts such as canola meal and glycerine.

For the canola to biodiesel pathway, the GHGenius model was used to calculate the coproduct credit and the system expansion approach was used to assess the credits for both coproducts [36]. The GHG emissions for processing canola meal and soybean meal are estimated to be 247 g CO_2eq per kg canola and 385 g CO_2eq per kg soybean [36]. These emission values were used to calculate the coproduct credit for canola meal when it replaces soybean meal as animal feed.

Following the study by Donkin et al., we assumed that 0.09 kg crude glycerine is obtained from 1 L of biodiesel from canola [38]. The crude glycerine is assumed to be upgraded in order to obtain refined food-grade glycerine that would replace synthetic glycerine in the market [25]. The energy and emission factors for the alternative production of synthetic glycerine were determined using the GHGenius model version 4.03 [36]. Around 6590 g CO_2eq per kg glycerine is saved when crude glycerine from biodiesel production is upgraded and used to displace synthetic glycerine in the market [36]. The emissions factor includes all the fossil energy required to process synthetic glycerine from crude glycerine.

Glycerine is a common ingredient in dairy cattle feed rations [25,38,45,46]. Glycerine's energy values of 2000–2300 kcal/kg are comparable to starch from corn in feed rations [25,40,45,46]. This study assumes that glycerine replaces corn in cattle feed rations with a displaced emission value of 400 g CO_2eq/kg of glycerine [25,36]. The emission factor has been calculated considering all the fossil energy sources involved in producing cattle feed from crude glycerine.

The displaced emission value for glycerine as an energy substitute for natural gas is assumed to be 300 g CO_2eq/kg of glycerine [25,36], which means around 300 g CO_2eq emissions are saved when glycerine

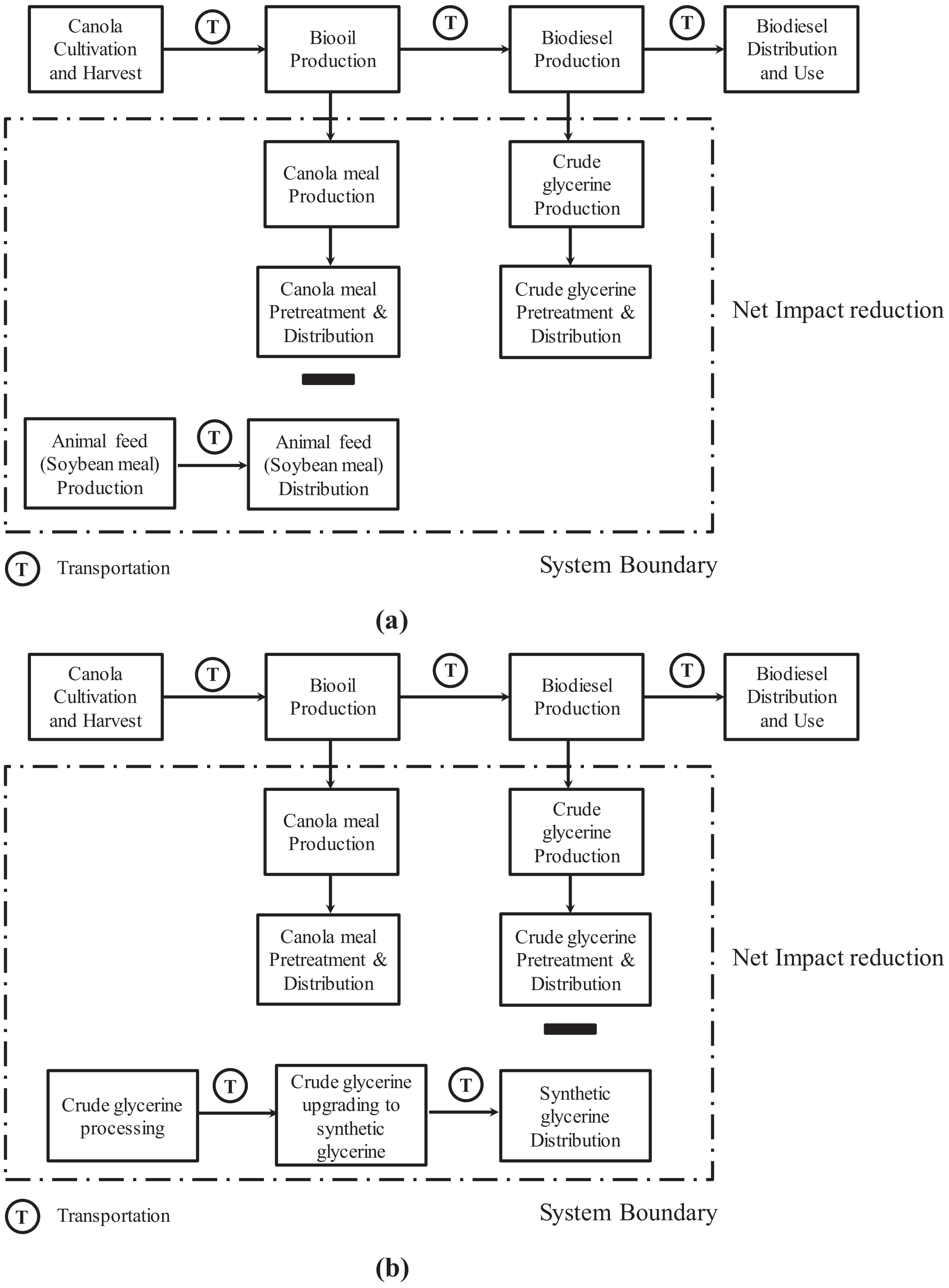

Fig. 3. Cradle-to-grave canola to biodiesel pathway system boundaries when the coproducts substitute (a) soybean meal, (b) synthetic glycerine, (c) animal feed, and (d) fossil energy.

is used in place of a fossil energy source, natural gas. All the emission factors include the fossil energy sources required to process crude glycerine into synthetic glycerine, animal feed, and/or alternative energy sources.

Life cycle impact assessment

Several scenarios were developed by considering individual and combined impacts from different coproduct uses. The most desirable scenario was determined based on the maximum coproduct credit or maximum GHG emissions savings. Predominantly Alberta-specific numbers and assumptions were used to develop the model. The three

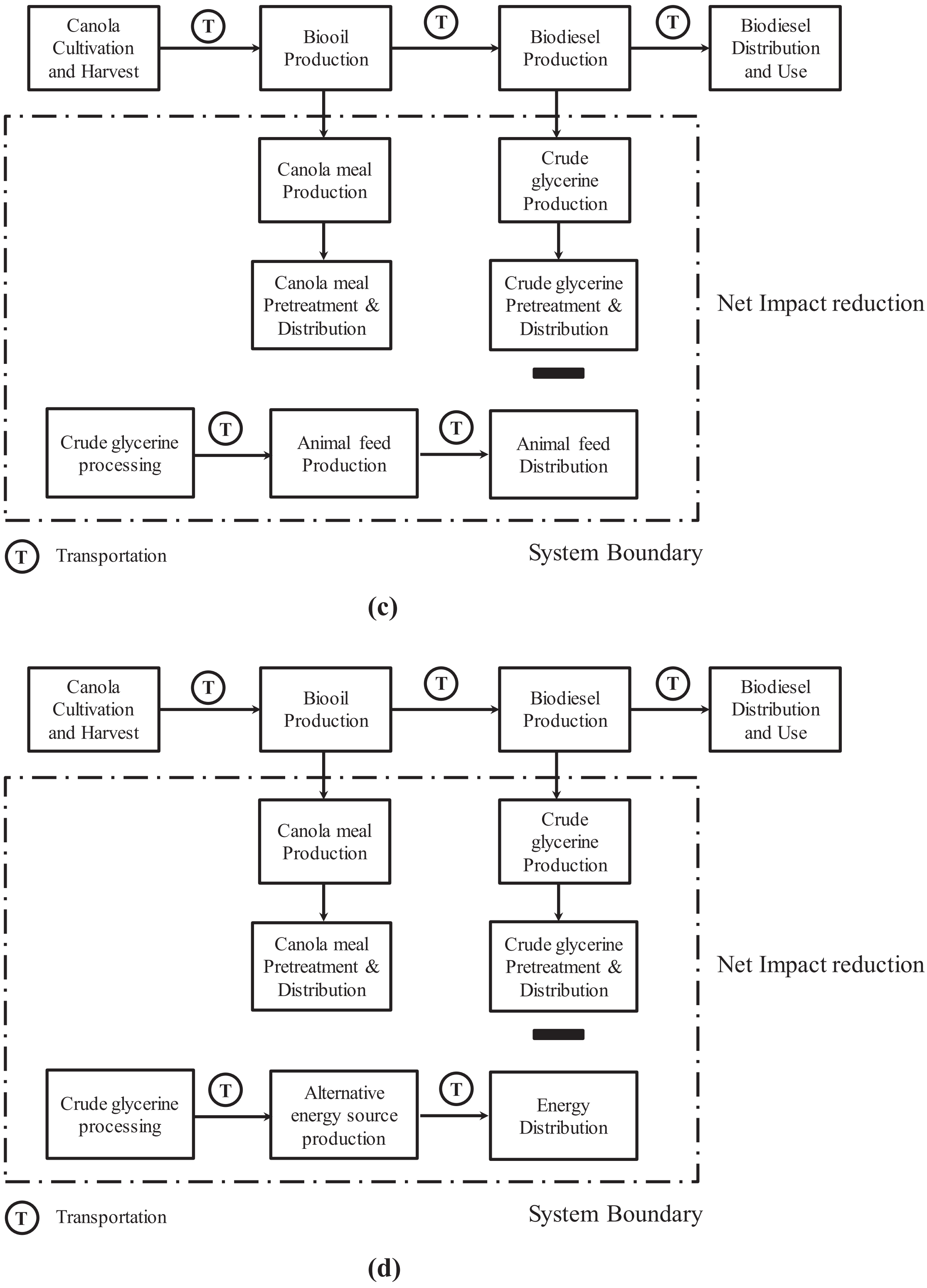

Fig. 3. (*continued*)

primary GHG emissions – carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) – were considered in this study to estimate the environmental impact. The global warming potential values are based on the Intergovernmental Panel on Climate Change (IPCC) 100-year time horizon [68,69]. A GHGenius model was used to calculate the coproduct credits and the life cycle GHG emission savings [70,71]. The model uses the system expansion approach for coproduct credit [35,54,55].

Sensitivity and uncertainty analyses

Since the model inputs and assumptions were taken from a wide range of studies, sensitivity and uncertainty analyses were conducted to prove the robustness of the model. Sensitivity analysis was conducted to identify the sensitive inputs, and uncertainty analysis was done to identify possible output ranges resulting from uncertain inputs. The Excel-based add-in software R-studio was used to conduct both the

Table 1
Data and assumptions for different uses of ethanol coproduct DDGs.

Assumptions/Properties	Units	Value	References
Wheat grain needed	kg/L	2.66	[1]
Displacement ratio (DDG to animal feed)		0.80	[1–3]
Fraction of wheat in animal feed to be displaced by DDGs		0.45	[1]
Fraction of soybean meal in animal feed to be displaced by DDGs		0.55	[1]
DDGs yield from ethanol plant	kg per kg wheat grain	0.38	[1]
Avoided methane emissions	g per kg DDG	3.74	[1]
Natural gas required	kWh per L of ethanol	0.32	[1]
Coal upstream emission factor	g/mm Btu	6178	[4]
Coal combustion emission factor	g/mm Btu	100,002	[4]
C footprint of 1 tonne DDG	tonne CO_2eq	0.33	Calculated
C footprint of 1 tonne coal	tonne CO_2eq	2.42	Calculated
Ethanol higher heating value	MJ/L	23.57	[1]
Combustion energy of coal	MJ/kg	24.02	[1]
Combustion energy f DDG pellet	MJ/kg	18.84	[5]
Displacement ratio (coal to DDGs)		1.28	Calculated
GHG emission from urea production	g CO_2eq/kg urea	1329.43	[6]
Displacement ratio (urea to DDGs)		11	[7]

Table 2
Data and assumptions for different uses of the biodiesel coproducts canola meal and glycerine.

Assumptions/Properties	Units	Value	References
Canola required per kg canola oil	kg/L	0.88	[1]
GHG emissions from soy bean milling	g CO_2eq/kg soy bean	385	[1]
GHG emissions from canola milling	g CO_2eq/kg canola	247	[1]
Canola meal fraction		0.57	[1]
Canola oil fraction		0.43	[1]
Biodiesel higher heating value	MJ/L	35.40	[1]
Glycerine yield	kg/L biodiesel	0.09	[8]
Displaced emission value for producing crude glycerine	g CO_2eq/kg	6590	[1]
Displaced emission value for glycerine used as fossil fuel	g CO_2eq/kg	300	[1]
Displaced emission value for glycerine used as animal feed	g CO_2eq/kg	400	[1]

sensitivity analysis and to run the Monte Carlo simulation for uncertainty analysis [72]. For the sensitivity analysis, the input values were changed from ± 25%. A triangular distribution was selected for the model inputs, since they support extreme value points resulting in a moderate output distribution [73]. The triangular distribution was generated by using three point estimates for the input variables, i.e., the maximum, minimum, and most likely values [73]. The maximum and minimum values were determined by assuming ± 10% of the input values. 50,000 samples were run for the Monte Carlo simulation, which results in an error less than 0.1 g CO_2eq/MJ at a 99% probability [73,74]. The results obtained were in the 5th and 95th percentiles and the most uncertain inputs were presented using tornado plots [73,74].

Results

This section presents and discusses the main findings of the study. First, the results are summarized. The significance of biofuel coproduct credits from different coproduct applications on the environment is discussed.

The coproduct credits or GHG emission savings were determined by changing the percentage of the coproduct use from 20% to 100% by increments of 20%, to understand the significant impacts of coproduct use (see Table 3). The results are presented in the functional unit of 1 MJ of energy produced from biofuel. Because DDGs have a higher moisture level and lower heating value than conventional coal, DDG combustion produces fewer GHG emissions per unit energy than industrial coal combustion. Hence, the highest coproduct credits were obtained from using DDGs pellets for heating as an alternative to coal firing. The GHG emissions savings range from 13.43 (20% use) to 67.14 (100% use) g CO_2eq/MJ of ethanol. The second highest emissions savings were obtained from using DDGs as animal feed, followed by as fertilizer. Because of the high protein content and digestible energy of DDGs, a higher coproduct credit is obtained when DDGs are used as animal feed compared to land applications. The GHG emissions savings from using DDGs as animal feed ranged from 8.31 to 17.29 g CO_2eq/MJ of ethanol, whereas when DDGs are used as fertilizer the emission savings were 1.72 to 8.61 g CO_2eq/MJ of ethanol. Table 3 shows the percentage of use, amount of products displaced by coproducts, and associated GHG emissions saved for the three DDG applications.

We developed a number of scenarios that consider different potential uses of biofuel coproducts. Fig. 4 shows the GHG emissions savings from combining different DDGs uses. Since DDGs are primarily used as animal feed, this use is considered to be the main use when we developed the combined scenarios. The coproduct credit increases with increasing percentages of coproduct use as fuel in combinations. Unlike coal displacement, comparatively fewer GHG emissions were saved when DDGs displace animal feed and/or urea.

Table 4 shows the coproduct credits from the use of canola meal and glycerine from biodiesel. The coproduct credit ranges from 2.23 to 11.14 g CO_2eq/MJ of biodiesel based on canola meal's use percentage. For glycerine, the highest credit was earned when the crude glycerine produced in biodiesel production replaces synthetic glycerine. The GHG emissions savings ranged from 17.13 to 3.95 g CO_2eq/MJ when crude

Table 3
GHG emissions savings per MJ of ethanol from different uses of DDGs.

GHG emissions savings when DDGs displaces animal feed (wheat and soybean meal)						
% of quantity of DDGs displacing animal feed	%	100	80	60	40	20
Amount of animal feed displaced by DDGs	tonne	112.23	89.78	67.34	44.89	22.45
GHG emissions savings from the use of DDGs as animal feed	g CO_2eq/MJ	17.29	15.79	12.80	9.80	8.31
GHG emissions savings when DDGs displaces fertilizer (urea)						
% of quantity of DDGs displacing fertilizer	%	100	80	60	40	20
Amount of fertilizer displaced by DDGs	tonne	8610	6888	5166	3444	1722
GHG emissions savings from the use of DDG as fertilizer	g CO_2eq/MJ	5.18	4.15	3.11	2.20	1.04
GHG emissions savings when DDGs displace fossil fuel (coal)						
% of quantity of DDGs displacing fossil fuel	%	100	80	60	40	20
Amount of fossil fuel displaced by DDGs	tonne	74,272	59,417	44,563	29,709	14,854
GHG emissions savings from the use of DDGs as fuel	g CO_2eq/MJ	67.14	53.71	40.28	26.86	13.43

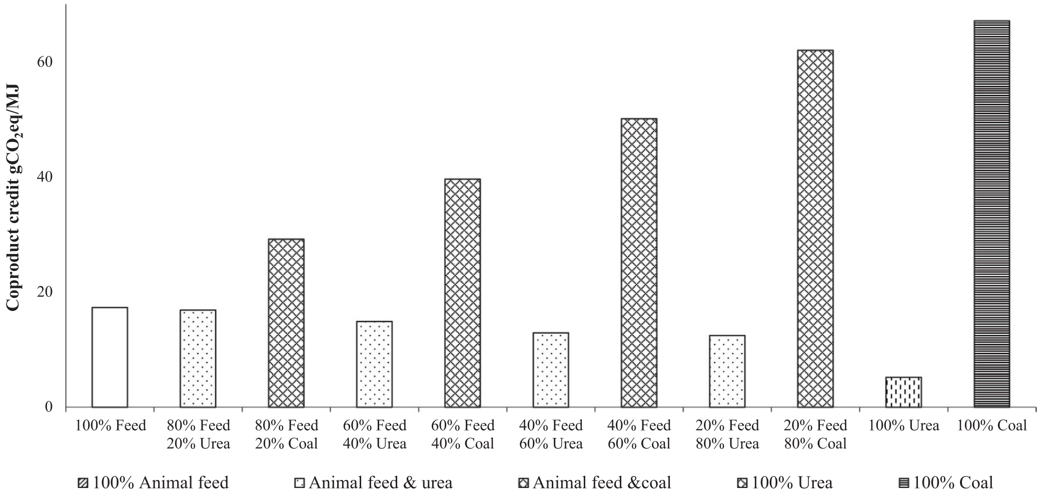

Fig. 4. Coproduct credit or GHG emissions savings from different combinations (by mass percentage) of DDGs used in the wheat to ethanol pathway.

glycerine was processed into synthetic glycerine based on its percentage use. The displaced emissions value of synthetic glycerine (6590 g CO_2eq/kg glycerine) is the largest, due to the higher energy consumption and higher emissions associated with synthetic glycerine production from crude glycerine compared to the other glycerine uses such as animal feed (0.40 g CO_2eq/MJ of biodiesel) or fuel (0.30 g CO_2eq/MJ of biodiesel) [25]. The GHG emission savings ranged from 1.04 to 0.21 g CO_2eq/MJ and 0.78 to 0.16 g CO_2eq/MJ of biodiesel when glycerine replaces corn in the cattle feed rations and petroleum-based natural gas as an energy source, respectively.

Fig. 5 compares different combinations of glycerine use. Because synthetic glycerine has the highest displaced emissions factor, we found that the coproduct credit gradually decreases with deceases in the percentage of glycerine replacing synthetic glycerine. The lowest coproduct credit was earned from the use of glycerine as an energy source.

Impact of coproduct credit on overall life cycle GHG emissions of biofuels

Life cycle GHG emissions decrease significantly when biofuel pathways are credited for coproduct production and use. Falano et al. assessed the cradle-to-gate GHG emissions of ethanol production from wheat in a bio refinery. 1 MJ ethanol production is responsible for 82.70 g CO_2eq [26]. The system boundary in Falano et al.'s study included the production of coproducts like acetic acid, lactic acid, and electricity along with the main product, and emissions savings from the use of coproducts were evaluated using the system expansion approach [26]. However, that study did not consider the transportation and use of the main product and the coproducts within the system boundary [26]. The wheat to ethanol life cycle GHG emissions reported by Falano et al. were used as a reference in our study to assess the percentage reduction in the total life cycle GHG emissions for different applications of DDGs (shown in Table 5). The life cycle GHG emissions can be decreased by 16–81%, 10–21%, and 1–6% when DDGs replace fuel, animal feed, and fertilizer, respectively, based on uses of 20–100% (by mass). The life cycle GHG emissions reductions from combined applications of DDGs were also determined (Table 6). Because of coal's higher emissions intensity, GHG emissions can be reduced by 35–75% when DDGs replace fuel and animal feed in combination. On the other hand, the GHG emission reductions ranged from 15 to 20% when DDGs replace animal feed and fertilizer in combination depending on the use percentage.

Table 7 shows the impact of canola meal and glycerine uses on the overall life cycle GHG emissions in the canola to biodiesel pathway. A study by (S & T)^2 Consultants for Alberta Innovates – Energy and Environment Solutions that evaluates the cradle-to-grave GHG emissions of biodiesel production from canola in Alberta was our source [25]. The study shows that the production of 1 MJ biodiesel from canola in

Table 4
GHG emissions savings per MJ of biodiesel from different uses of the biodiesel coproducts canola meal and glycerine.

GHG emissions savings when canola meal displaces animal feed						
% of quantity of canola meal displacing animal feed	%	100	80	60	40	20
GHG emissions savings from the use of canola meal as animal feed per kg of canola meal	g CO_2eq/kg canola	335	268	201	134	67
GHG emissions savings from the use of canola meal as animal feed per MJ of biodiesel	g CO_2eq/MJ	11.14	8.92	6.69	4.46	2.23
GHG emissions savings when crude glycerine displaces synthetic glycerine						
% of quantity of crude glycerine displacing synthetic glycerine	%	100	80	60	40	20
Amount of synthetic glycerine displaced by crude glycerine	kg/L biodiesel	0.092	0.074	0.055	0.037	0.018
GHG emissions savings from the use of crude glycerine	g CO_2eq/MJ	17.13	13.70	10.28	6.85	3.43
GHG emissions savings when crude glycerine displaces fuel (natural gas)						
% of quantity of crude glycerine displacing fossil fuel	%	100	80	60	40	20
Amount of fossil fuel displaced by crude glycerine	kg/L biodiesel	0.092	0.074	0.055	0.037	0.018
GHG emissions savings from the use of crude glycerine	g CO_2eq/MJ	0.78	0.62	0.47	0.31	0.16
GHG emissions savings when crude glycerine displaces animal feed						
% of quantity of crude glycerine displacing animal feed	%	100	80	60	40	20
Amount of animal feed displaced by crude glycerine	kg/L biodiesel	0.092	0.074	0.055	0.037	0.018
GHG emissions savings from the use of crude glycerine	g CO_2eq/MJ	1.04	0.83	0.62	0.42	0.21

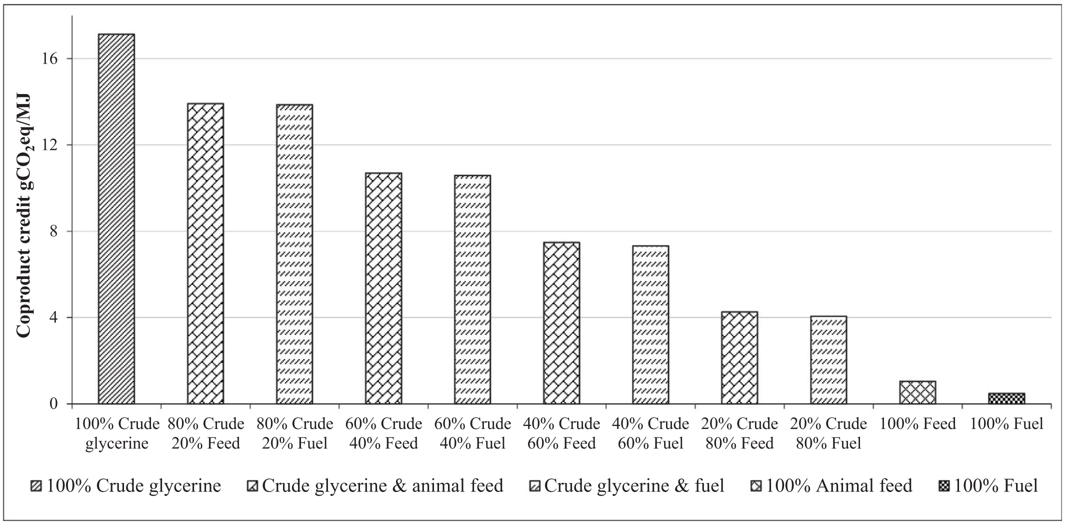

Fig. 5. Coproduct credit or GHG emissions savings from different combinations (by mass percentage) of crude glycerine use in the canola to biodiesel pathway.

Alberta emits around 42.28 g CO_2eq [25] when the pathway is not credited for any coproduct production and use. GHG emissions decreased by 5–26% from the use of canola meal as animal feed and by 8–41% when crude glycerine replaced synthetic glycerine in the market. However, due to very low emissions intensity, the GHG emissions reduction was quite small (around 1–2%) when crude glycerine replaced either fuel or fertilizer in the market. Similarly, because of the higher emissions intensity of synthetic glycerine, the combined GHG emissions reductions ranged from 10 to 33% for either combination (Table 8).

Sensitivity and uncertainty analyses

The applications from both pathways with the largest GHG emissions savings are presented in this paper. In the wheat to ethanol pathway, when DDGs replace fossil coal, the combustion energy of coal and the quantity of DDGs were found to be the parameters with high uncertainty input parameters (Fig. 6).

Similarly, in the canola to biodiesel pathway, when crude glycerine replaces synthetic glycerine, the quantity of glycerine produced per litre of biodiesel was found to be the parameter with high uncertainty and needs further investigation (Fig. 7).

Discussion

The study results highlight that the overall environmental performances of biofuel production are highly affected by making use of coproducts. The importance of considering coproduct uses in evaluating the life cycle environmental impacts of biofuel has been highlighted by different authors [75–77]. Biofuel use has been practiced as a potential solution to climate change mitigation. The U.S., one of the largest global biofuel producers, has mandated biofuel production and its blending with conventional transportation fuels under the RFS federal program. With increasing biofuel production, industries are also producing unavoidably huge amount of coproducts every year that are often overlooked in environmental assessments of the main products. Biofuel coproducts have the potential to be used as animal feed and fertilizer and also replace fossil-based energy products in the market, thereby reducing GHG emissions. Globally, the biofuel industry produces around 52 million tonnes of byproducts that can be used for animal feed, mainly from ethanol production [78]. Coproducts from corn to ethanol conversion are widely applied in feeding dairy and beef cattle, but with the substantial increase in the ethanol market and associated coproducts, the applications of these coproducts have expanded to swine, poultry, and aquaculture feed [78,79]. Other application areas include the substitution of fertilizer and fuel energy with biofuel coproducts. The net environmental benefit from bioenergy production thus highly depends on the applications of its coproducts and the corresponding substitution ratio. When the coproduct substitutes a product with a high GHG emissions intensity, the overall biofuel life cycle emissions will decrease significantly.

Different types of coproducts such as DDGs, CO_2, acetic acid, electricity, and lactic acid simultaneously produced during ethanol production have been found to reduce total life cycle GHG emissions ranging from 4 to 87% [26,47,48]. This study also showed different uses of coproducts produced in the bioethanol and biodiesel pathways. The most common use of the ethanol coproduct DDGs is as animal feed, and this use reduces the life cycle GHG emissions from 8.31 to 17.29 g CO_2eq/GJ of ethanol based on the percentage of DDGs used (20–100%). However, the highest GHG emissions reductions were obtained from using DDG pellets for heating as an alternative to coal firing. The GHG emissions savings range from 13.43 (20% use) to 67.14 (100% use) g

Table 5
Impact of coproduct use on overall life cycle GHG emissions in the wheat to ethanol pathway.

Total life cycle GHG emissions in wheat to ethanol pathway [9]	% of quantity of DDGs displacing other products	Net GHG emissions when DDG replaces fuel (coal)	% of total life cycle emission reduced	Net GHG emissions when DDG replaces fertilizer (urea)	% of total life cycle GHG emission reduced	Net GHG emissions when DDG replaces animal feed-wheat and soymeal	% of total life cycle GHG emission reduced
g CO_2eq/MJ	%	g CO_2eq/MJ	%	g CO_2eq/MJ	%	g CO_2eq/MJ	%
82.70	100	15.56	81	77.52	6	65.41	21
82.70	80	28.99	65	78.55	5	66.91	19
82.70	60	42.42	49	79.59	4	69.90	15
82.70	40	55.84	32	80.63	3	72.90	12
82.70	20	69.27	16	81.66	1	74.40	10

Table 6
Impact of different types of coproduct (DDG) use in combination on overall life cycle GHG emissions in the wheat to ethanol pathway.

Total life cycle GHG emissions in the wheat to ethanol pathway [9] g CO_2eq/MJ	% of combined use when DDGs displacing other products %	Net GHG emissions when DDGs are used as animal feed and fertilizer in a combination g CO_2eq/MJ	% of total life cycle GHG emissions reduced %	Net GHG emissions when DDGs are used as animal feed and fuel in a combination g CO_2eq/MJ	% of total life cycle GHG emissions reduced %
82.70	80%–20%	65.87	20	53.48	35
82.70	60%–40%	67.83	18	43.05	48
82.70	40%–60%	69.80	16	32.61	61
82.70	20%–80%	70.25	15	20.68	75
82.70	0%–100%	77.52	6	15.56	81
82.70	100%–0%	65.41	21	65.41	21

Table 7
Impact of coproduct use on overall life cycle GHG emissions in the canola to biodiesel pathway.

Total life cycle GHG emissions in canola to biodiesel pathway [10]	g CO_2eq /MJ	42.28	42.28	42.28	42.28	42.28
Percentage of quantity of canola meal/glycerine displacing other products	%	100%	80%	60%	40%	20%
Net GHG emissions when canola meal replaces animal feed	g CO_2eq/MJ	31.14	33.37	35.59	37.82	40.05
Percentage of total life cycle emissions reduced	%	26	21	16	11	5
Net GHG emissions when glycerine replaces synthetic glycerine	g CO_2eq/MJ	25.15	28.58	32.00	35.43	38.86
Percentage of total life cycle GHG emissions reduced	%	41	32	24	16	8
Net GHG emissions when glycerine replaces fuel	g CO_2eq/MJ	41.50	41.66	41.81	41.97	42.12
Percentage of total life cycle GHG emissions reduced	%	2	1	1	1	0
Net GHG emissions when glycerine replaces animal feed	g CO_2eq/MJ	41.24	41.45	41.66	41.86	42.07
Percentage of total life cycle GHG emissions reduced	%	2	2	1	1	0

Table 8
Impact of different types of coproduct (glycerine) use in combination on overall life cycle GHG emissions in the canola to biodiesel pathway.

Total life cycle GHG emissions in the canola to biodiesel pathway [10] g CO_2eq/MJ	% of combined use when glycerine displaces other products %	Net GHG emissions when glycerine displaces synthetic glycerine and fuel in combination g CO_2eq/MJ	% of total life cycle GHG emissions reduced %	Net GHG emissions when glycerine displaces synthetic glycerine and animal feed in combination g CO_2eq/MJ	% of total life cycle GHG emissions reduced %
42.28	80%–20%	28.42	33	28.37	33
42.28	60%–40%	31.70	25	31.59	25
42.28	40%–60%	35.00	17	34.81	18
42.28	20%–80%	38.23	10	38.02	10
42.28	0%–100%	41.50	2	41.24	2
42.28	100%–0%	25.15	41	25.15	41

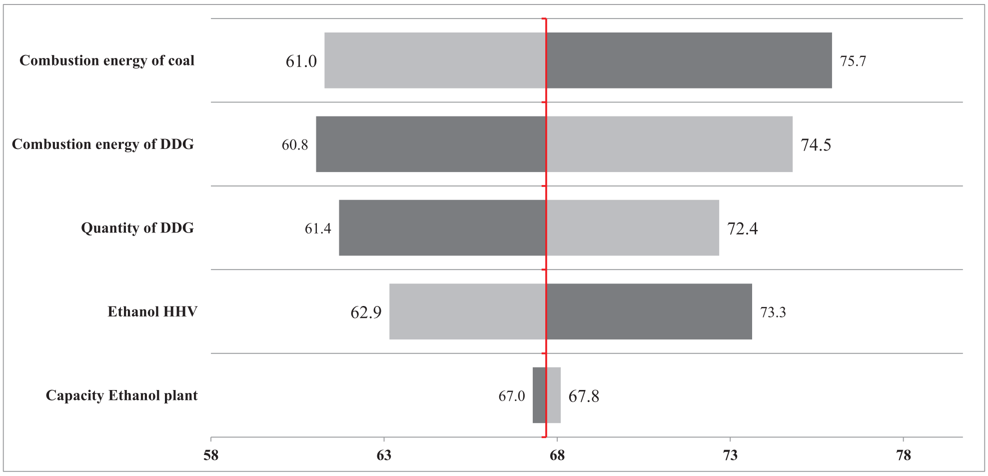

Fig. 6. Uncertainty analysis of coproduct credits in g CO_2eq/MJ when DDGs replace fuel (fossil coal).

CO_2eq/MJ of ethanol; the range is high because of the lower heating value and higher moisture level of DDG pellets than conventional coal. The GHG emissions savings were comparatively less from DDG's use as fertilizer and ranged from 1.72 to 8.61 g CO_2eq/MJ of ethanol. Several scenarios were also developed to determine the coproduct credit from different uses of coproducts in combination. We found that the emissions savings were higher with a higher percentage of DDG use as animal feed and fuel in combination. No other study has determined the combined impact of different coproduct use. The emissions factors for displaced products include all the life cycle stages.

For the canola to diesel pathway, two different coproducts were obtained in two different life cycle stages, namely canola meal and glycerine. The highest coproduct credits were obtained from crude glycerine displacing synthetic glycerine in the market. The GHG

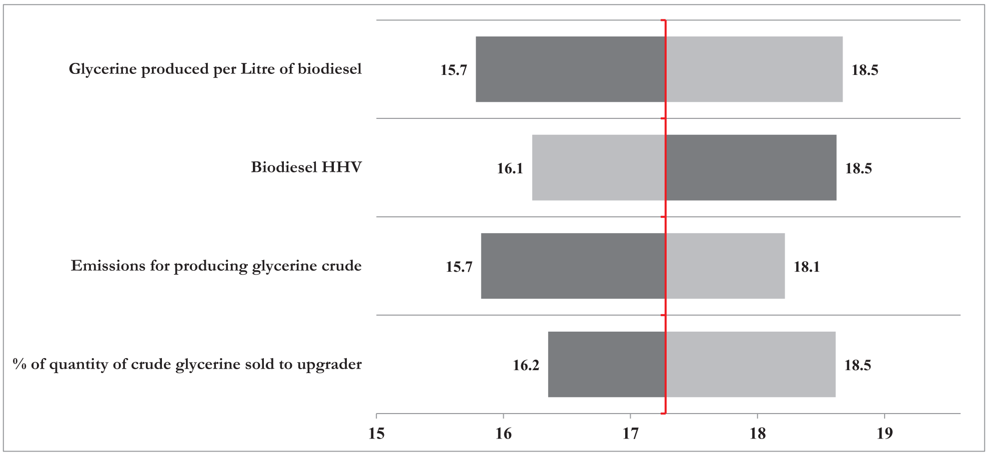

Fig. 7. Uncertainty analysis of coproduct credits in g CO_2eq/MJ when crude glycerine replaces synthetic glycerine.

emissions savings ranged from 3.95 to 17.13 g CO_2eq/MJ. The fewest GHG emissions – 0.16 to 0.78 g CO_2eq/MJ of biodiesel – were saved when glycerin replaces natural gas as a fuel source.

However, the actual impact could be affected by various factors, such as market availability, economic benefit, and environmental concerns, among others. For example, in the case of DDGs' use as animal feed, even though it has important features such as nutrient value, there are some concerns that could potentially affect its wide application. The high phosphorus concentration, poor digestibility due to high fiber concentration, high sulfur content, presence of carcinogenic toxins [80–85], and wide-ranging protein content (25–35%) [83] are issues that could have negative impacts on animal health. Further research is required to find ways to overcome these issues.

Evaluating the economic viability of biofuel coproduct use as animal feed, fertilizer, or fuel energy substitute is beyond the scope of this study. A detailed process-based techno-economic assessment is required to determine the impacts of coproducts on the overall cost competitiveness of biofuel development. The economic values of coproducts are other key elements that need to be investigated in detail. Due to very limited production and market supply, DDGs are very expensive when they are used to substitute animal feeds like corn grain, rice bran, and wheat bran. This is mainly due to their high protein content [86]. On the other hand, biofuel coproducts seemed to have less economic value as fertilizer than as feed, which discourages their application as fertilizers. Lory et al. showed that DDGs' market value as animal feed is 99 dollars per tonne more than as a fertilizer. DDGs are worth 39 dollars per tonne when used as fertilizer and around 172 dollars per tonne when used as animal feed [28]. Government initiatives and incentives are crucial to overcome economic barriers to the market penetration of a bioenergy coproduct and to ensure a viable GHG emissions reduction option. Short-term implications such as huge investment requirements and societal barriers might seem prohibitive; however, the long-term implications can help governments meet climate change mitigation targets, such as those issued in the Climate Leadership Plan, Renewable Fuels Regulations, Paris Agreement, and others.

The other important aspects is the long-term environmental and economic consequences of biofuel expansion in a given economy. This study highlights the role of coproduct use in reducing the environmental impacts of biofuel. The future renewable market outlook suggests considerable growth in biofuel production and associated coproducts. The agriculture, energy, and transportation sectors will be the most affected by the widespread development and use of biofuel. This study is limited to evaluating the share of GHG emissions from the use of coproducts; other environmental performance impacts are not covered. Hence, this study could be extended by assessing the economy-wide and global environmental and socio-economic consequences of coproducts from bioenergy.

Conclusion

This study identified potential applications of biofuel coproducts and analyzed the energy and emission impacts of coproduct use on the overall life cycle GHG emissions of the two most largely produced and commonly used biofuels, ethanol from wheat grain and biodiesel from canola. DDGs are produced as coproducts of ethanol from wheat grain, and canola meal and crude glycerine are produced along with biodiesel from canola. Three applications were considered for DDGs in the wheat to ethanol pathway: animal feed, fuel, and fertilizer. DDGs replace canola meal and soymeal as animal feed, coal as a fuel, and urea as a fertilizer. The results show that GHG emissions decrease by 181% from individual applications of DDGs and by 35–75% from different combined applications of DDGs. Similarly, in the canola biodiesel pathway, GHG emissions decrease by 5–26% when canola meal replaces animal feed and 8–41% when crude glycerine replaces synthetic glycerine. GHG emissions decrease by 10–33% when crude glycerine replaces synthetic glycerine and fuel or animal feed in combination. Hence, GHG emissions decrease significantly when coproduct use or its disposal is included in the system boundary of the biofuel life cycle. The biofuel pathways can also be credited for other applications of the identified coproducts or for other coproducts. The developed model can be used to determine the effects of coproduct use on the overall life cycle emissions for other biofuels as well. The model can be updated to include all the emissions factors associated with the life cycle stages of the alternative coproduct applications. This study will help inform stakeholders in the bioenergy sector of the environmental consequences of potential coproduct use. The model also provides insights for policy makers on the long-term perspective of biofuel coproduct use as a climate change mitigation option.

In general, the study provides a Canada-specific model for coproduct credit based on a comprehensive process-based LCA approach. Though the model was used here for coproducts of wheat to ethanol and canola to biodiesel production, with minor adjustments it could be used for other energy pathways. Finally, it is worth mentioning that there are some limitations that need to be considered when interpreting the results. For example, the carbon footprint of the replaced products can be updated to factorize all the stages involved in their life cycle (if needed). The model predominantly uses Alberta-specific assumptions and data, but it can be used for any region or country. More applications or coproduct disposal methods can be identified and embedded in the model for wider application.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2019.05.001.

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