Literature Review of Consequential Life Cycle Assessment Research of Grain and Oilseed Crops

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EXECUTIVE SUMMARY

While the economic benefits of the Canadian field crop industry are clear, there are also potential environmental costs associated with field crop production (see for example Pelletier et al. 2008; MacWilliam et al. 2014, 2016). These include land and energy use, as well as direct greenhouse gas (GHG) and other emissions at the field level (Ma et al. 2010; Ali et al. 2014; Van Zandvoort et al. 2017; Guzman-Bustamante et al. 2019). In addition to these direct environmental impacts, resource use and emissions are also embedded within the products originating upstream of the field in the product supply chain, such as those associated with production of the fertilizers and pesticides applied to fields (Schmidt Rivera et al. 2017). For this reason, assessing and seeking to mitigate the environmental costs of field crop production requires “life cycle thinking” - a holistic, systems-level perspective supported by analytical tools of commensurate scope (Zamagni 2012).

Life cycle assessment (LCA) has become the leading methodological approach based on life cycle thinking. LCA supports systematic analysis of all aspects of the life cycle of a product (i.e. including raw material extraction, processing, transportation, use and end-of-life phases) in order to quantify the cumulative resource demand and emissions associated with a product over its entire life cycle (ISO 2006). There are currently two principal types of environmental LCA: attributional LCA (ALCA) and consequential LCA (CLCA). ALCA is a retrospective methodology that aims to present a snapshot of average, “status quo” conditions along a product supply chain at a specific point in time. CLCA is a prospective methodology for evaluating the environmental implications of potential changes in a product system of interest, including any associated market-mediated product substitution effects that may arise (Weidema 2003). In the context of Canadian field crop production, CLCAs are well suited (and, indeed, even necessary) for accurate assessment of any foreseen large-scale changes in the industry, due to its linkages with other sectors and processes, including the production of biofuel and food for both human and animal consumption.

The utility of CLCA in bringing additional nuance to environmental impact assessment is clear, but its application remains quite limited to date. In contrast, use of ALCA (or related assessments, such as carbon footprinting) is quite common globally, including for assessment of grain and oilseed crops (see for example Kim and Dale 2008; Kim et al. 2009; Boone et al. 2016, etc.). Attributional LCA and carbon footprint studies have been reported for a wide variety of Canadian field crop products in recent years (for a review of these studies, see Turner et al. (2019). While this is a very useful type of assessment, it does not enable providing recommendations with respect to alternative practices to adopt at broad scale in the future in order to reduce impacts. Instead, such questions must be answered through application of CLCA.

The aim of this report is to review consequential LCA studies that assess the impacts of farm practices on the life cycle greenhouse gas (GHG) emissions associated with agricultural crop production. The following questions are addressed:

1) For what agricultural crops and associated farm practices have consequential LCA studies been reported to date? What proportion have specifically addressed field crops, and which among these are specific to Canada?

2) Among these studies, how were the system boundaries defined, including the definition of assumed market-mediated substitutions? Which production systems were included? What were the affected technologies? What modelling approaches were employed, and what commonalities and differences can be observed across studies?

3) What were the reported influences of specific farm practices on estimated GHG emissions for the field crops considered, as modelled using CLCA? Can any recommendations be made for sustainability best practices in field crop production on the basis of these studies?

4) What were the reported influences of assumed market-mediated substitutions and other methodological choices on estimated GHG emissions for the field crops?

5) What research gaps can be identified with respect to CLCA research of field crops, in particular for Canadian conditions? Are there obvious opportunities to build on prior, related research – for example, ALCA or other studies that investigate the GHG mitigation potential of alternative technologies and management strategies for grain production?

CLCA studies were selected for detailed review if they (1) reported a consequential LCA (or carbon footprint) of an agricultural crop and (2) were published from 2010 to 2019. For each CLCA study, information was extracted and tabulated regarding the type of agricultural crop, farm practices modelled, and geographical area represented. The total number of CLCAs for each crop type were calculated, as well as the number of Canadian-specific crop CLCAs for each crop type. The types of farm practices (i.e., prevalent and crop/region-specific strategies and technologies for cultivation, seeding, pesticide application, fertilizing, harvesting and storage) were tabulated in the same way. Information was also extracted from each study regarding the system boundaries, affected product systems, marginal data used (processes assumed to change as a result of the intervention assessed), and use of different modelling approaches (e.g., partial equilibrium, simplified, general equilibrium models) to determine market-mediated substitutions. The impact assessment results of each CLCA were summarized in a table, highlighting the impact of the farm practice assessed (fertilizing strategies, tillage operation, using of precision agriculture, etc.) on the GHG emissions of the crop in each study.

A total of 30 CLCA studies published within the past 10 years were identified that met the specified criteria. Only one (Li and Mupondwa 2014) addressed a Canadian crop - in this case, the use of camelina oil as biodiesel or jet fuel. Other studies were representative of crop production in the United States, Europe, Asia or South America.

A total of 22 different crop types were included in the CLCA studies identified. Wheat, corn and grasses were the most highly represented crops with 9, 7 and 7 studies, respectively. All other crops were assessed in 3 or fewer studies. The prevalence of wheat and corn studies is in line with the prevalence of grain crops grown in Canada, however there is not as extensive a representation of oilseed crops, which are also prevalent in Canada. Therefore, more CLCA studies should be performed on the major Canadian field crops, which include wheat, canola, barley, corn and soy.

Of the 30 crop CLCA studies, 22 assessed crop use in some form of bioenergy production (electricity, heat or fuel), and included the product system(s) for the bioenergy produced in addition to the crop cultivation system(s). In general, this increase in energy from crop biomass would replace energy from conventional sources (generally fossil fuels). After crop use for bioenergy, crop use for animal feed was the second most commonly studied scenario (4 studies), highlighting the interconnection of crop production, animal feed, bioenergy and agri-food product systems.

Common modelling approaches to identify the marginal technologies and products to be included in the CLCA models included economic optimization models such as general or partial equilibrium models, or more simply designing likely scenarios based on published literature and reports on country or product specific economic trends. There were also a small number of studies that did not indicate how marginal technologies were identified. In general, bioenergy studies represented the majority of identified CLCA studies, and employed each of the methods identified above for predicting marginal substitutions. There were no clear trends with any of the methods for identifying marginal substitutions in terms of the modelled GHG mitigation potential of using crops for bioenergy. Overall, the changes in GHG emissions associated with the use of crops for different types of bioenergy ranged from -209% to +369.5% of the impacts of conventional energy production.

There have been no Canadian CLCA studies to date that assess changes in farm management practices, hence representing a substantial a research gap. However, there have been many assessments (field-level or ALCA) and recommendations for farm management practices that may reduce GHG emissions from crop production in Canada and elsewhere which can inform future Canadian crop CLCA studies. Farm management practices considered include fertilizer application management, crop rotation, reduced tillage, etc. These previous studies can be transformed into CLCA studies by adhering to the ISO standards for life cycle assessment, identifying the marginal technologies that would be impacted by the farm practices being assessed, including multiple relevant environmental impact categories, and performing a robust uncertainty analysis.

Given the current lack of Canadian crop CLCA studies, it is highly recommended that a broad suite of Canadian crops and alternative crop production practices should be assessed using CLCA to determine their potential environmental benefits and trade-offs. This would do much to fill the current gap in terms of CLCA studies of Canadian field crops, and provide useful insight to farmers in support of determining the most sustainable farm practices.

TABLE OF CONTENTS

INTRODUCTION

Grains and oilseeds such as wheat, canola, corn, barley and soy are important staple crops grown in Canada. Current estimates for the 2018-2019 crop year predict a total yield of 93.2 million tonnes for the Canadian field crop industry, with grains and oilseeds accounting for 92% of this production (Statistics Canada 2019). Moreover, it is estimated that total yields will further expand in 2020 to 95.6 million tonnes, with associated increases in yield/hectare for both grains and oilseeds, along with pulses and other crops (Statistics Canada 2019). Together, these estimates fall in line with a general trend of growth in the Canadian field crop industry. Taken together, GDP in the agriculture and agri-food industries increased at a rate almost double that of total Canadian GDP for the years 2012-2016 (Statistics Canada 2017).

While the economic benefits of the Canadian field crop industry are clear, there are also potential environmental costs associated with field crop production (see for example Pelletier et al. 2008; MacWilliam et al. 2014, 2016). Field crop production contributes significantly to land and energy use, while also producing greenhouse gasses (GHGs) and other emissions at the field level, including carbon dioxide (CO_2), and nitrous oxide (N_2O) (Ma et al. 2010; Ali et al. 2014; Van Zandvoort et al. 2017; Guzman-Bustamante et al. 2019). Rising nitrous oxide emissions are particularly concerning, due to their high radiative forcing effect relative to carbon dioxide (Skiba et al. 2012; Mikaloff Fletcher and Schaefer 2019). In addition, these direct environmental costs of field crop production may be further exacerbated by resource use and emissions embedded within the products originating upstream of the field in the product supply chain, such as those associated with production of the fertilizers and pesticides applied to fields (Schmidt Rivera et al. 2017). For this reason, assessing and seeking to mitigate the environmental costs of field crop production requires a holistic, systems-level perspective supported by analytical tools of commensurate scope (Zamagni 2012).

The first use of life cycle approaches to analyze sustainability questions date back to the 1960s, when they were used to look at aspects of food supply chains (Darnay and Nuss 1971; Pimentel et al. 1973). Increasingly widespread use of such eventually resulted in the need for standardization of methodologies. Standardization efforts took place throughout the 1990s and 2000s, culminating in the publication of the current International Organization for Standardization (ISO) 14040-14044 series of standards governing applications of life cycle assessment (ISO 2006). Life cycle assessment (LCA) has become the leading methodological approach based on life cycle thinking. LCA supports systematic analysis of all aspects of the life cycle of a product (i.e. including raw material extraction, processing, transportation, use and end-of-life phases) in order to quantify the cumulative resource demands and emissions over its entire life cycle.

A key benefit obtained from the use of standardized LCA methodology for environmental impact assessment is the avoidance of potential burden shifting from one phase of the life cycle, one region, or one environmental problem to another (Finnveden et al. 2009). By taking a systems-level, multi-criteria approach, LCA studies are effectively able to identify potential environmental trade-offs that may occur as a result of technology or management changes, as well as identify "hot-spots" – that is, areas of relatively large impact – throughout a products complete supply chain (Guinee et al. 2002). For example, fertilizer production has been identified as a hot-spot for environmental impacts in the Canadian field crop industry (Pelletier et al. 2008; MacWilliam et al. 2014). Likewise, recent work studying the impacts of genetically modified soy demonstrates the utility of the multi-criteria nature of LCA. Eriksson et al. (2018) reported decreases in greenhouse gas (GHG) emissions, but increases in other kinds of environmental impacts resulting from the introduction of GMO soy. Together, these two key features allow LCA studies to present a big picture look at all potential impacts of a product, and interventions in the production supply chain.

There are currently two principal types of environmental LCA: attributional LCA (ALCA) and consequential LCA (CLCA). Use of one or the other of these two types is largely dependent on the goals of a given study. ALCA is a retrospective methodology that aims to present a snapshot of average, "status quo" conditions along a product supply chain at a specific point in time. CLCA is a prospective methodology for evaluating the environmental implications of potential changes in a product system of interest, including any associated market-mediated product substitution effects that may arise (Weidema 2003). For example, an ALCA study might be applied to characterize the current average life cycle impacts of wheat production in the Canadian prairies, while a CLCA study might be used to evaluate the potential environmental effects of a large-scale expansion of wheat production, taking into account the reduced production of displaced crops and related market adjustments to otherwise provide the displaced crop products.

This fundamental difference in scope between ALCA and CLCA studies necessitates different "system boundaries" (i.e. the portion of the product supply chain covered by the LCA study for the analysis (Guinee et al. 2002). Attributional LCAs include all inputs and outputs in the product system for the product being studied. In contrast, the system boundaries in CLCAs are expanded to include the inputs and outputs in other product systems that would be affected given a change in the product being studied. It is through the inclusion of these market-mediated substitutions that CLCA is able to assess potential additional impacts not normally considered in an ALCA. For example, in their study investigating the impacts of camelina-derived jet fuel production in Canada, Li and Mupondwa (Li and Mupondwa 2014) were able to take into account reductions in impacts from decreased production of conventional jet fuel as a consequence of increased camelina cultivation and processing; in an ALCA study, these associated reductions would not be captured.

In the context of Canadian field crop production, CLCAs are well suited (and, indeed, even necessary) for accurate assessment of any foreseen large-scale changes in the industry, due to its linkages with other sectors and processes, including the production of biofuel and food for both human and animal consumption. For example, if more of a grain was used for biofuel then less may be available for animal feed. In this case, increased production of some other feed product would be necessary to keep the supply of animal feed constant.

While the utility of CLCA in bringing additional nuance to environmental impact assessment is clear, its application remains quite limited to date. A recent review of 2687 LCA studies published over the past five indicated that only 6% were CLCAs (Bamber et al. 2019c). In contrast, use of ALCA (or related assessments, such as carbon footprinting) is quite common globally, including for assessment of grain and oilseed crops (see for example Kim and Dale 2008; Kim et al. 2009; Boone et al. 2016, etc.).

Attributional LCA and carbon footprint studies have been reported for a wide variety of Canadian field crop products in recent years (for a review of these studies, see Turner et al. 2019). For example, the Canadian Roundtable for Sustainable Crops has produced a series of reports estimating the carbon footprints of ten major field crops in Canada on a regional basis. For these and other attributional studies, the system boundaries included the direct inputs and emissions of agricultural operations, as well as those associated with the upstream activities that provide inputs to grain crop production, such as fuels, fertilizers, and plant protection products. As such, these studies typically focus on estimating the impacts of current farm practices (ex. (S&T)2 Consultants Inc. 2017). While this is a very useful type of assessment, it does not enable providing recommendations with respect to alternative practices to adopt at a broad scale in the future in order to reduce impacts. Instead, such questions must be answered through application of CLCA.

Indeed, there are many potential strategies to reduce GHG emissions and other impacts in from grain crops production, including crop rotation (Carvalho et al. 2014), reducing nitrogen fertilizer inputs (Linquist et al. 2012), adding biochar as a soil amendment (Xu et al. 2019), etc. CLCA is therefore a useful tool in assessing the changes in cumulative impacts across multiple linked industries that may result from the widespread uptake of these different management strategies. For example, Bamber et al. (2019a) performed an attributional LCA comparing apple production with and without the application of wood/bark mulch as a soil amendment on Okanagan apple orchards. They found that, despite the experimentally measured field-level reduction in emissions, the increase in upstream emissions and resource use associated with the production and application of the mulch outweighed those benefits. However, when a consequential approach was undertaken (i.e., including substituted alternative uses for the wood and bark chips – specifically, for paper and bioenergy production), they found lower impacts in many impact categories when mulch use was increased on orchards (and thus unavailable for the production of the alternative products which were then produced in other ways) (Bamber et al. 2019b). This was due to the higher impacts of producing paper and energy in the alternative ways without the use of wood or bark chips. This example clearly illustrates the utility of CLCA in assessment of changing management strategies, as may be applied in the Canadian field crop industry.

On this basis, the aim of this report is to review consequential LCA studies that assess the impacts of farm practices on the life cycle greenhouse gas (GHG) emissions associated with agricultural crop production. The focus is on cereals, oilseeds and specialty crops produced in Canada, specifically. However, due to the small number of Canadian agri-food consequential CLCA studies that have been published to date (Turner et al. 2019), similar studies from other geographical regions are also included in the review. The following questions are addressed:

1) For what agricultural crops and associated farm practices have consequential LCA studies been reported to date? What proportion have specifically addressed field crops, and which among these are specific to Canada?

2) Among these studies, how were the system boundaries defined, including the definition of assumed market-mediated substitutions? Which production systems were included? What were the affected technologies? What modelling approaches were employed, and what commonalities and differences can be observed across studies?

3) What were the reported influences of specific farm practices on estimated GHG emissions for the field crops considered, as modelled using CLCA? Can any recommendations be made for sustainability best practices in field crop production on the basis of these studies?

4) What were the reported influences of assumed market-mediated substitutions and other methodological choices on estimated GHG emissions for the field crops?

5) What research gaps can be identified with respect to CLCA research of field crops, in particular for Canadian conditions? Are there obvious opportunities to build on prior, related research – for example, ALCA or other studies that investigate the GHG mitigation potential of alternative technologies and management strategies for grain production?

METHODS

The Web of Science Core Collection was used to search for peer-reviewed journal articles using the keywords “consequential life cycle assessment” OR “consequential LCA” AND “crop” OR “grain” OR “cereal” OR “oilseed” OR “wheat” OR “canola” OR “corn” OR “maize” OR “barley” OR “soy”. Relevant industry and government websites such as Fertilizer Canada and Agriculture and Agri-Food Canada were also searched using the same keywords. In addition, the advanced search function of the Google search engine was used (with the same search terms) to identify any remaining non-academic LCA studies. Studies were selected for detailed review if they (1) reported a consequential LCA (or carbon footprint) of an agricultural crop and (2) were published from 2010 to 2019. This timeframe was selected because CLCA modelling is relatively new in terms of widespread adoption as an LCA methodology, as well as to ensure the relevance of the studies to modern conditions.

For each CLCA study, information was extracted and tabulated regarding the type of agricultural crop, farm practices modelled, and geographical area represented. The total number of CLCAs for each crop type were calculated, as well as the number of Canadian-specific crop CLCAs for each crop type. The types of farm practices (i.e., prevalent and crop/region-specific strategies and technologies for cultivation, seeding, pesticide application, fertilizing, harvesting and storage) were tabulated in the same way.

Information was also extracted from each study regarding the system boundaries, affected product systems, marginal data used (processes assumed to change as a result of the intervention assessed), and use of different modelling approaches (e.g., partial equilibrium, simplified, general equilibrium models) to determine market-mediated substitutions. For each type of methodological choice, the choices were tabulated and conclusions were made about any similarities and differences with respect to the crops assessed and the results of the studies.

The impact assessment results of each CLCA were summarized in a table, highlighting the impact of the farm practice assessed (fertilizing strategies, tillage operation, using of precision agriculture, etc.) on the GHG emissions of the crop in each study. These results were grouped by intervention type (farm practices, different uses of crops, etc.), and conclusions were drawn about the environmental benefits of these interventions.

Based on the information resulting from this review, data gaps were identified with respect to current CLCAs of field crops, including selection of the system boundaries, identification of marginal data, etc. Major crops or farm practices with few or no CLCA studies were identified. Similarly, research gaps specific to CLCA studies of Canadian field crops were identified.

RESULTS AND DISCUSSION

Representation of crops and geographical regions in CLCA studies

A total of 30 CLCA studies from the past 10 years were identified that met the criteria of (1) being a consequential LCA study of an agricultural crop and (2) reported the life cycle GHG emissions (CO_2 equivalent) associated with a change in the supply chain of that crop (Table 1). However, of all the studies identified, only one (Li and Mupondwa 2014) addressed a Canadian crop, in this case the use of camelina oil as biodiesel or jet fuel. There were two studies from the United States: one referring to a corn bioenergy policy change (Bento and Klotz 2014) and the other evaluating the integration of grass-clover and livestock production with a biorefinery (Parajuli et al. 2018). The majority of studies (21) focused on European crop production systems. Of these studies, 16 assessed the use of crops (miscanthus, maize, grass, canola, wheat, barley, beet, beans, oats, rye, willow, ryegrass, oilseed radish, alfalfa, banana, flax and sunflower) for bioenergy production (Reinhard and Zah 2008; Abiola et al. 2010; Kimming et al. 2011; Tonini et al. 2012, 2016b, a; Van Zanten et al. 2014; Styles et al. 2015a, b, 2016b; Deng and Tian 2015; Karlsson et al. 2015; Van Stappen et al. 2016; Kloverpris et al. 2016; Escobar et al. 2017; Parajuli et al. 2017; Buchspies and Kaltschmitt 2018; Vadenbo et al. 2018; Sacchi 2018). Other than bioenergy production, the remaining European studies variously addressed the use of peas for gin (Lienhardt et al. 2019), the introduction of genetically modified soy (Eriksson et al. 2018), the planting of willows as riparian buffers on cropland (Styles et al. 2016a), an increase in demand for bananas (Sacchi 2018), and the use of flax for polymers (Deng and Tian 2015). Two studies were specific to Asia, respectively addressing flax production for use in polymer formation (Deng and Tian 2015), and cassava production for bioenergy (Prapaspongsa and Gheewala 2016). Three studies focused on in South American systems – specifically, sorghum production for bioenergy (Adler et al. 2018), an increase in grape production for pisco (Larrea-Gallegos et al. 2018), and the use of bioethanol residue as fertilizer in sugarcane production (Moore et al. 2017).

There is clearly a large gap with respect to Canadian-specific consequential life cycle assessment research of field crops. Not only are other countries not representative of Canadian agricultural and economic conditions, but the single location within Canada considered by a crop CLCA study to date is clearly not representative of all of Canada, not is the single crop addressed representative of all crops grown in Canada. New, regionalised CLCA studies of all major crops grown in Canada will be necessary to bridge this gap.

A total of 22 different crop types were included in the CLCA studies identified. Wheat, corn and grasses were the most highly represented crops with 9 (Styles et al. 2015b, Van Zanten et al. 2014, Buchspies and Kaltschmitt 2018, Kimming et al. 2011, Tonini et al. 2016a, Tonini et al 2016b, Kloverpris et al. 2016, Parajuli et al. 2017, Vadenbo et al. 2018), 7 (Bento and Klotz 2014, Styles et al. 2015b, Styles et al. 2015b, Styles et al. 2016a, Abiola et al. 2010, Tonini et al. 2016a, Van Stappen et al. 2016), and 7 studies (Parajuli et al. 2018, Styles et al. 2015a, Styles et al. 2016a, Tonini et al. 2012, Tonini et al. 2016a, Tonini et al 2016b, Parajuli et al. 2017), respectively. There were 3 studies for each of beets (Van Zanten et al. 2014, Styles et al. 2016a, Tonini et al. 2016a), canola (Styles et al. 2015b, Kimming et al. 2011, Reinhard and Zah 2011) and willow crops (Styles et al. 2016b, Tonini et al. 2012, Tonini et al. 2016a), and 2 studies for beans (Karlsson et al. 2015, Kimming et al. 2011). Camelina (Li and Mupondwa 2014), peas (Lienhardt et al. 2019), soy (Eriksson et al. 2018), oats (Kimming et al. 2011), rye (Kimming et al. 2011), oilseed radish (Kloverpris et al. 2016), banana (Sacchi 2018), sunflower (Escobar et al. 2017), flax (Deng and Tian 2015), cassava (Prapaspongsa and Gheewala 2016), sorghum (Adler et al. 2018), grape (Larrea-Gallegos et al. 2018) and sugarcane crops (Moore et al. 2017) were only assessed in 1 study each. The prevalence of wheat and corn studies is in line with the prevalence of grain crops grown in Canada, however there is not as extensive a representation of oilseed crops which are also prevalent in Canada. Therefore, more studies should be performed on the major Canadian field crops, which include wheat, canola, barley, corn and soy.

Table 1. List of consequential life cycle assessments of agricultural crops from 2010-2019 and the farm practices assessed and geographical location of each study.

Geographical location	Crop	Farm/processing practice or policy	Citation
Canadian prairies	Camelina oil	Used for biodiesel or jet fuel	Li and Mupondwa 2014
United States	Corn	Policy change: Renewable Fuel Standard and Volumetric Ethanol Excise Tax Credit	Bento and Klotz 2014
United States	Grass-clover	Integrated crop-livestock system with biorefinery	Parajuli et al. 2018
Europe	Miscanthus, maize, grass	Production of biogas with different crops	Styles et al. 2015a
Europe	Maize, canola, wheat, barley	Production of biogas with different crops	Styles et al. 2015b
Europe	Wheat, barley, beet	Bioenergy or animal feed from different crops	Van Zanten et al. 2014
United Kingdom	Beet, grass, maize	Anaerobic digestion for bioenergy	Styles et al. 2016a
United Kingdom	Pea	1 litre of gin produced from peas instead of wheat	Lienhardt et al. 2019
England	Corn	Different processing technologies for bioethanol production	Abiola et al. 2010
Germany	Wheat grains and straw	Different processing technologies for bioethanol production	Buchspies and Kaltschmitt 2018
Sweden	Soy	Introducing of genetically modified soy meal for feed	Eriksson et al. 2018
Sweden	Faba beans	Switch from protein feed to either bioethanol or roughage feed	Karlsson et al. 2015
Sweden	Beans, oats, canola, wheat, rye	Self-sufficient bioenergy for farms compared to fossil fuel reference	Kimming et al. 2011
Sweden	Willow	Addition of fertilised and unfertilised willow on riparian buffer strips and drainage filtration zones of cropland	Styles et al. 2016b
Denmark	Ryegrass, willow, miscanthus	Heat and electricity production using different technologies, replacing fossil fuels	Tonini et al. 2012
Denmark	Willow, miscanthus, ryegrass, sugar beet, maize, wheat, barley	Production of bioelectricity, biomethane and bioethanol from different crops or residues	Tonini et al. 2016a
Denmark	Wheat, natural grass	Bioethanol and biogas production from different crops and residues	Tonini et al 2016b
Denmark	Barley, oilseed radish, wheat	Different combinations of crop residue for bioenergy	Kloverpris et al. 2016
Denmark	Winter wheat straw, alfalfa	Bioenergy produced from standalone wheat, standalone alfalfa, and both integrated	Parajuli et al. 2017
Denmark	Banana	Increase in demand for bananas	Sacchi 2018
Switzerland	Canola	Bioenergy production replaces human or animal consumption	Reinhard and Zah 2011
Switzerland	Residues from cereals	Bioenergy from different crops, residues and waste based on different policies	Vadenbo et al. 2018

Belgium	Maize	Bioenergy produced from different crops, residues and waste	Van Stappen et al. 2016
Spain	Sunflower and canola	Optimize feedstock combination for biodiesel according to policy objectives to increase 2.58 Mt demand	Escobar et al. 2017
China and France	Flax	Switch from glass to flax fibres for polymers	Deng and Tian 2015
Thailand	Cassava	Different ratios of cassava and molasses for bioethanol	Prapaspongsa and Gheewala 2016
Western and Northern Uruguay	Grain sorghum and sweet sorghum	Introduction in multi-crop system for bioethanol compared to gasoline	Adler et al. 2018
Peru	Grapes	Increase in pisco demand	Larrea-Gallegos et al. 2018
Brazil	Sugarcane	Residues from bioethanol replace chemical fertilizer for sugarcane production	Moore et al. 2017

Definition of system boundaries and marginal technologies in crop CLCA studies

One of the most important methodological aspects of consequential life cycle modelling is identifying the product systems to include in the study. As defined by Weidema (2003), a consequential LCA should include all products (and associated flows and environmental impacts) that would be affected by the change being assessed (e.g. the use of a crop for bioenergy instead of animal feed). This is clearly an important choice to make, since different product systems have different impacts, thus influencing the overall impacts and conclusions of the CLCA study. The technologies that would change as a result of a change in supply or demand of a product or service are called the marginal technologies in CLCA modelling. There are several ways to identify the marginal technologies in a CLCA study, including economic models of markets, and using regionally specific industry data.

Almost all of the crop CLCA studies identified assessed the use of crops for bioenergy, therefore most studies included the product systems for the agricultural cultivation of the specific crop assessed, as well as the production of bioenergy from that crop (Table 2). Of the 30 crop CLCA studies identified, 22 assessed crop use in some form of bioenergy (electricity, heat or fuel), and included the product system(s) for the bioenergy produced in addition to the crop cultivation system(s). In general, this increase in energy from crop biomass would replace energy from conventional sources (generally fossil fuels). Many studies specified what conventional energy source was replaced, and these included gasoline, natural gas, diesel, jet fuel, fossil fuels in general, and the local electricity grid mix (Bento and Klotz 2014, Adler et al. 2018, Buchspies and Kaltschmitt 2018, Tonini et al 2016b, Van Zanten et al. 2014, Kloverpris et al. 2016, Li and Mupondwa 2014, Parajuli et al. 2018, Styles et al. 2016a, Styles et al. 2015b, Van Stappen et al. 2016, Parajuli et al. 2017, Styles et al. 2015a, Tonini et al. 2012, Tonini et al 2016a, Prapaspongsa and Gheewala 2016). Co-products of bioenergy production can be returned to the field as fertilizer, thus replacing synthetic fertilizer inputs to crop production. These product systems were included in 6 CLCA studies of crops used for bioenergy (Van Stappen et al. 2016, Parajuli et al. 2017, Van Zanten et al. 2014, Parajuli et al. 2018, Moore et al. 2017, Tonini et al. 2012) as well as one of peas used for gin, in which the co-products of distillation could similarly be used for fertilizer (Leinhardt et al. 2019).

After crop use for bioenergy, crop use for animal feed was the second most commonly studied CLCA change (4 studies). In these CLCA models, the product systems for animal feed from the studied crops, and the displaced marginal animal feed product systems, were included in addition to the cultivation of the crop itself (Table 2). Even in some studies that did not focus on a change in crop use for animal feed, these product systems were included since they would be impacted by a change in use or production of the crop being assessed, highlighting the interconnection of crop production, animal feed, bioenergy and agri-food product systems. The most common marginal animal feed products were barley, soy and maize

(Parajuli et al. 2017, Tonini et al 2016b, Vadenbo et al. 2018, Leinhardt et al. 2019, Parajuli et al. 2018, Reinhard and Zah 2011).

Common modelling approaches to identify the marginal technologies and products to be included in the CLCA models included economic optimization models such as general or partial equilibrium models, or more simply designing likely scenarios based on published literature and reports on country or product specific economic trends (Table 2). Ten studies used either an economic model, or economic trend data to predict the marginal product affected. These studies assessed a variety of changes in crop use or production including different bioenergy policies (Bento and Klotz 2014), optimization of biodiesel production (Escobar et al. 2017), different bioethanol technologies (Buchspies and Kaltschmitt 2018, Abiola et al. 2010, Tonini et al. 2012), different ratios of feedstock for bioethanol production (Prapaspongsa and Gheewala 2016), the use of flax in polymer production (Deng and Tian 2015), an increase in the use of crops for bioenergy, taken away from other uses (Reinhard and Zah 2011), genetically modified soy for animal feed (Eriksson et al. 2018), and an increase in the demand for bananas (Sacchi 2018). The economic model types used were general equilibrium, which takes into account an entire market (Bento and Klotz 2014), and partial equilibrium which only accounts for some aspects of a market (Escobar et al. 2017). Of the studies that used economic models and assessed the use of crops for bioenergy, the majority found either an increase or decrease in overall GHG emissions depending on the specific scenarios modelled (Bento and Klotz 2014, Buchspies and Kaltschmitt 2018, Reinhard and Zah 2011, Tonini et al. 2012) (Table 3). Two studies found an overall increase in GHG emissions with the use of crops for bioenergy (Escobar et al. 2017, Prapaspongsa and Gheewala 2016), and one found an overall decrease (Abiola et al. 2010).

Five studies used published scientific literature on similar systems or industry/country reports on market trends to inform the choice of marginal technologies. The topics of these studies were all related to bioenergy production, including the use of beans for either bioethanol or roughage feed (Karlsson et al. 2015), the production of bioethanol from a multi-crop system (Adler et al. 2018), and bioenergy produced from different crops (Tonini et al. 2016a, Tonini et al. 2016b, Van Zanten et al. 2014). Two studies defined the marginal crops substituted for animal feed based on the nutritional profiles of the crops. These studies assessed the use of camelina oil for biodiesel or jet fuel (Li and Mupondwa 2014), and the integration of a biorefinery into a crop-livestock system (Parajuli et al. 2018). Of the studies that used literature to inform the choice of marginal processes, three found either an increase or decrease in GHG emissions depending on scenarios (Adler et al. 2018, Tonini et al. 2016a, Tonini et al. 2016b), three found an overall increase (Karlsson et al. 2015, Li and Mupondwa 2014, Parajuli et al. 2018) and one found an overall decrease (Van Zanten et al. 2014).

Three studies, which assessed an increase in pisco production (Larrea-Gallegos et al. 2018), different crops for use in bioenergy production (Kloverpris et al. 2016), and the addition of willows to crop land (Styles et al. 2016b), used assumptions about land use and availability to define the system boundaries and inform the choice of marginal substitutions. Four studies did not indicate how marginal products and technologies were identified, but did list processes that were excluded from the product system, namely co-products that were considered waste (Moore et al. 2017), manufacturing of capital goods and infrastructure that had been shown by previous literature not to influence LCA results (Kimming et al. 2011, Leinhardt et al. 2019), and domestic production of dedicated energy crops and imported liquid biofuels due to policy objectives to avoid these products (Vadenbo et al. 2018). The rest of the studies (5 studies) either did not give an indication of how marginal processes and system boundaries were defined, or simply stated that the system boundaries included all processes that were affected by the change assessed, which is in the definition of a CLCA (Weidema 2003). Of the studies that did not indicate any method of identifying marginal technologies, four found a net reduction in GHG emissions with the use of crops for bioenergy (Moore et al. 2017, Kimming et al. 2011, Vadenbo et al 2018, Styles et al. 2016a), three found either an increase or reduction (Van Stappen et al. 2016, Styles et al. 2015b, Styles et al. 2015a), and one found an overall increase (Parajuli et al. 2017).

In general, bioenergy studies represented the majority of identified CLCA studies, and employed each of the methods described above for identifying marginal substitutions. There were no clear trends with any of the methods of identifying marginal substitutions in terms of the modelled GHG mitigation potential of using crops for bioenergy. With complex economic modelling, or marginal substitutions identified using the literature, the results were mostly inconclusive, with a slight indication of increased GHG emissions. Of the other studies that did not indicate a method of identification of marginal substitutions, there was a slight trend toward decreased GHG emissions from crop use in bioenergy, although many studies were also inconclusive.

Table 2. Definition of system boundaries, market-mediated substitutions and product systems included in consequential life cycle assessments of agricultural crops.

Product systems studied	Definition of system boundaries and market-mediated substitutions	Assumed substitutions	Citation
Corn, bioethanol	Economic framework from policy change. Multi-market general equilibrium model.	Other crops, gasoline	Bento and Klotz 2014
Sunflower, canola, sugarbeet, biodiesel	Land use assumed to be the same, so only crop rotations change, increases from intensification. Partial equilibrium model, demand for non-energy crops assumed stable.	Domestic vegetable oil production, diesel	Escobar et al. 2017
Wheat, biofues	Inputs, outputs and substitutions based on literature and industry reports. Deterministic model for marginal suppliers, based on changes in demand of co-products.	Fossil fuels, electricity, animal feed, vegetable oil	Buchspies and Kaltschmitt 2018
Molasses, cassava, bioethanol, use in vehicles	Based on which product is the determining or dependent co-product – sugarcane not included because not driven by demand for molasses. Marginal substitutions based on trading conditions, countries imports/exports – electricity delimited within regional boundaries, agricultural products traded internationally – capacity for increased production, cheapest sources, countries with largest increasing production trend.	Fossil fuel, barley	Prapaspongsa and Gheewala 2016
Corn, ethanol	Mixed integer nonlinear programming, general algebraic modelling system, multi-objective design operation framework.	Fossil fuels	Abiola et al. 2010
Flax, composite manufacturing	System expansion to include all co-products. Global supply market determined.	Glass composite manufacturing	Deng and Tian 2015
Canola, barley, biofuel,	Economic value criteria, constrained or linked markets.	Soy, sunflower animal feed, fuel	Reinhard and Zah 2011
Soy	Proportions of types of soy based on publications of country market.	Palm oil, canola	Eriksson et al. 2018
Banana	Market trends of countries and specific products.	Agricultural and food products from a trade matrix	Sacchi 2018
Ryegrass, willow, miscanthus, bioenergy,	Substitutions based on the literature, rebound effects based on changes in market prices.	Fertilizer, electricity, heat, barley	Tonini et al. 2012
Bean, bioenergy, animal feed	Marginal fuel technologies from literature, market information on products/countries. Excess arable land assumed to be available. Marginal protein feed assumed to be soymeal based on country with largest increase in exports. Marginal effects of changes in demand for feed grain from Schmidt (2008).	Soymeal	Karlsson et al. 2015
Biothanol	System expansion for co-products, included use phase of bioethanol, experts define crop rotations (not economic models), bioenergy crops did not affect pasture – only prices and location influenced rotations. Marginal products based on evidence from similar systems.	Soy, gasoline	Adler et al. 2018

Wheat, grass, Brewer's grain, beet, potato, whey, bioenergy	Products defined as waste, co-products or products – to determine if substituted by another product or decay. Substitutions based on demand trends/projections in literature.	Waste disposal, animal feed (maize, soy), fossil energy	Tonini et al. 2016b
Wheat, barley, beet, bioenergy	Includes alternative processes for which co-products could be used. Assumed stable market (demands for products equal), co-products not the determining product, products to substitute displaced co-products determined from literature, feed products substituted based on energy content.	Fossil energy, artificial fertilizer	Van Zanten et al. 2014
Miscanthus, willow, ryegrass, sugar beet, maize, wheat, barley, agro-industrial residues, other waste/residues, bioenergy, animal feed	Substitutions from literature.	Electricity, heat, animal feed	Tonini et al. 2016a
Camelina, bioenergy	Substituted animal feed soy selected based on similar nutrient profile.	Soy, diesel, jet fuel	Li and Mupondwa 2014
Grass-clover, livestock, bioenergy	Feed substitutions based on nutrient contents.	Feed (soy, barley), natural gas, fertilizer	Parajuli et al. 2018
Grape, pisco	Water other than irrigation excluded because irrigation shown to be 99% of total. To be called pisco, it must be grown in a certain region so available land constrained.	Cotton, corn, onion, watermelon, potato, tomato	Larrea-Gallegos et al. 2018
Barley, bioenergy	Available Danish cropland assumed not to change.	Natural gas, gasoline, electricity	Kloverpris et al. 2016
Willow	Based on current land capacity.	Displaced food crops	Styles et al. 2016b
Sugarcane, bioethanol, fertilizer	Co-products of sugarcane considered waste. System expansion for co-products of fertilizer production and substituted alternatives.	Synthetic fertilizer and substitutable chemicals for fertilizer co-products	Moore et al. 2017
Rotation of: wheat, ley, rye, beans, oats, canola; bioenergy, liquid CO_2 refrigerant	Manufacturing of capital goods/infrastructure excluded because previously shown to have minor impact	Fossil fuel, HFC refrigerant	Kimming et al. 2011
Agricultural residues (cereal, other), woody biomass, municipal waste, bioenergy	Domestic production of dedicated energy crops and imported liquid biofuels omitted due to policy objectives to avoid these products.	Animal feed (maize, soy), waste treatment	Vadenbo et al. 2018
Peas, gin	Infrastructure excluded from system boundaries.	Wheat, fertilizer, animal feed (barley, soy)	Leinhardt et al. 2019
Maize, manure, other agricultural by-products, bioenergy	System expansion for alternative product systems impacted.	Animal feed, fertilizer, electricity, heat	Van Stappen et al. 2016

Wheat, canola, barley, maize, heat, bioenergy	Not indicated.	Food crops, UK electricity grid, heat from boilers, petrol, diesel, food waste management, animal feed, fertilizer	Styles et al. 2015b
Wheat, alfalfa, lactic acid, bioethanol	Not indicated.	Ethanol, electricity, fertilizer, animal feed (barley, soy)	Parajuli et al. 2017
Grass, maize, wheat, biogas, electricity	Not indicated.	Food waste in landfill, electricity grid, heat, soy, palm oil	Styles et al. 2015a
Beet, grass, maize, biogas, waste disposal, bioheat, bioelectricity	Not indicated.	Fossil heat, fossil electricity, diesel	Styles et al. 2016a

Impacts of changes on GHG emissions

A total of 22 studies assessed the impacts, in terms of GHG emissions, as well as resource use and other emissions in some cases, of replacing conventional energy sources with bioenergy. For bioethanol production, almost all studies found both an increase and or decrease in overall life cycle GHG emissions, depending on the specific scenario or modelling choice assessed (Adler et al. 2018, Buchspies and Kaltschmitt 2018, Parajuli et al. 2017, Tonini et al. 2016a, Tonini et al. 2016b) (Table 3). For example, Buchspies and Kaltschmitt (2018) estimated the change in GHG emissions from the substitution of gasoline with bioethanol to range from -13% to +17.5%. Only one study found a definitive decrease in GHG emissions associated with the production of bioethanol from crops (Abiola et al. 2010), and one found an increase in emissions (Karlsson et al. 2015). For other biogas and biofuel production systems, three studies found either an increase or decrease in GHG emissions with the use of crops, depending on the scenarios modelled (Tonini et al. 2016a, Styles et al. 2015a, Styles et al. 2015b), and two found an overall increase (Escobar et al. 2017, Li and Mupondwa 2014). For heat and electricity production, five studies found either an increase or decrease in GHG emissions associated with the use of crops, depending on the scenarios modelled (Tonini et al. 2012, Van Stappen et al. 2016, Tonini et al 2016, Reinhard and Zah 2011, Bento and Klotz 2014), five found an overall decrease (Kimming et al. 2011, Van Zanten et al. 2014, Kloverpris et al. 2016, Styles et al. 2016a, Vadenbo et al. 2018), and one found an overall increase (Parajuli et al. 2018). Overall, the changes in GHG emissions with the use of crops for different types of bioenergy ranged from -209% to +369.5% of the impacts of conventional energy production, with many smaller impacts in between.

Three studies assessed the use of crops for animal feed (Table 3). Eriksson et al. (2018) assessed the difference in emissions from genetically modified (GM) and non-GM soy used for animal feed. They found that the production of GM soy emitted 5.5 times more life cycle GHG emissions (including all marginal product systems) than non-GM soy. Karlsson et al. (2015) assessed the change from crops used as protein feed for livestock to roughage feed. They found an overall increase in GHG emissions of 164% if used for roughage feed, compared to protein feed. Van Zanten et al. (2014) performed an optimization model for crop use in animal feed, and found that the optimal scenario yielded 0.24 kg fewer GHG emissions per kg biomass. Deng and Tian (2015) found an 80-200% increase in GHG emissions from the use of flax crops for polymers (replacing glass).

Three studies assessed an increase in demand for crops, or products made from crops, for human consumption (Table 3). An increase of 1 L of pisco production from grapes would result in an increase of up to 9.23 kg CO_2 equivalent emissions from the indirect land use change effects (Larrea-Gallegos et al. 2018), an production of 1 L of gin from with peas result in a reduction of 2.2 kg CO_2e due to the substitution of soybean animal feed with the co-products of pea-gin production (Lienhardt et al. 2019), and an increase in production of 1 kg of bananas would result in an increase of up to 0.34 kg CO_2e from the production and transportation of the bananas (Sacchi 2018).

Only two of the identified studies assessed the GHG implications of changes in farm management practices for crop production (Table 3). Moore et al. (2017) evaluated the replacement of synthetic fertilizer with bioethanol residues as fertilizer, and found that sugarcane produced with the bioethanol residues produced 384 fewer kg CO_2e per 10.8t ethanol than those produced with synthetic fertilizers. Styles et al. (2016b) assessed the addition of willow crops to cropland either on riparian buffer strips or cropland drainage filtration zones, and found an overall reduction of 9.5 to 14.8 t CO_2e per ha per year.

Table 3. Impacts of modelled changes on the estimated GHG emissions of the production of crops in consequential life cycle assessment studies.

Farm/processing practice or policy	Impact on GHG emissions	Citation
Crops for bioenergy		
Different processing technologies for bioethanol production	Conventional: 1.03 kg CO_2e per kg ethanol Bioethanol: 0.66 kg CO_2e per kg ethanol (-35%)	Abiola et al. 2010
Introduction in multi-crop system for bioethanol compared to gasoline	Gasoline (conventional): 93 g CO2e per MJ energy Bioenergy: ranged from -2.9 g CO_2e (-3%) to +44.8 g CO_2e per MJ (+48%), compared to conventional, depending on methods	Adler et al. 2018
Different processing technologies for bioethanol production	Gasoline (conventional): 94.1 g CO_2e per MJ energy Bioethanol: ranged from -12.1 g CO_2e (-13%) to +16.5 g CO_2e per MJ (+17.5%), compared to conventional, depending on methods	Buchspies and Kaltschmitt 2018
Different ratios of cassava and molasses for bioethanol	Gasoline (conventional): 1.8 kg CO_2e per L bioethanol Bioenergy: range from 2.2 (+18%) to 4.8 kg CO_2e (+62.5%) per L bioethanol	Prapaspongsa and Gheewala 2016
Bioethanol produced from standalone wheat, standalone alfalfa, and both integrated	Standalone wheat: 0.13 kg CO_2e per MJ bioethanol Standalone alfalfa: 0.39 kg CO_2e per MJ Integrated: 0.05 kg CO_2e per MJ (-87% from standalone alfalfa)	Parajuli et al. 2017
Switch from protein feed to either bioethanol or roughage feed	For bioethanol: +370 kg CO_2e per ha*yr (+25%) For roughage: +2420 kg CO_2e per ha*yr (+164%)	Karlsson et al. 2015
Production of bioelectricity, biomethane and bioethanol from different crops or residues	Bioelectricity: ranged from -400 g CO_2e to +4000 g CO_2e per kWh Biomethane: ranged from -100 g CO_2e to +600 g CO_2e per MJ Bioethanol: ranged from -600 g CO_2e to +620 g CO_2e per MJ	Tonini et al. 2016a
Bioethanol and biogas production from different crops and residues	Ranged from -2.5 kg CO_2e to +2.0 kg CO_2e per kg biomass, compared to conventional, depending on methods	Tonini et al 2016b
Production of biogas with different crops	Ranged from -209% to +359%, compared to conventional, depending on methods	Styles et al. 2015b
Production of biogas with different crops	Ranged from -637 g CO_2e to +509 g CO_2e per kg dry matter	Styles et al. 2015a
Optimize feedstock combination for biodiesel according to policy	Ranged from 2 Tg CO_2e per 2.58 Mt biodiesel to 4Tg, with one scenario at 29Tg	Escobar et al. 2017
Used for biodiesel or jet fuel	For biodiesel: 7.61-24.72 g CO_2e per MJ For jet fuel: 3.06-31.01 g CO_2e per MJ	Li and Mupondwa 2014
Bioenergy produced from different crops, residues and waste	Ranged from -0.222 kg CO_2e to +0.096 kg CO_2e per MJ electricity, compared to conventional, depending on methods	Van Stappen et al. 2016
Heat and electricity production using different technologies, replacing fossil fuels	Ranged from -45 t CO_2e to +250 t CO_2e per ha, depending on scenario	Tonini et al. 2012
Self-sufficient bioenergy for farms compared to fossil fuel reference	Wheat straw: reduced 9% compared to fossil fuel Ley: reduced 35% compared to fossil fuel	Kimming et al. 2011
Bioenergy or animal feed from different crops	-329 g CO_2e or -239 g CO_2e per kg biomass	Van Zanten et al. 2014

Different combinations of crop residue for bioenergy	Conventional: 590 g CO_2e per kg biomass Bioenergy: ranged from 35 g CO_2e (-94%) to 470 g CO_2e (-20.5%) per kg biomass	Kloverpris et al. 2016
Integrated crop-livestock system with biorefinery	19.6 kg CO_2e per kg live weight cows + kg live weight pigs	Parajuli et al. 2018
Bioenergy production replaces human or animal consumption	Conventional: 89 g CO_2e Replaces edible oil: ranged from 58 (+65%) to 329 g CO_2e (+369.5%) Replaces animal feed: ranged from -175 (-196.5%) to 197 g CO_2e (+221%)	Reinhard and Zah 2011
Anaerobic digestion for bioenergy	Reduced 551-775 Gg CO_2e for entire sector	Styles et al. 2016a
Bioenergy from different crops, residues and waste based on different policies	Optimized bioenergy scenario: -47%	Vadenbo et al. 2018
Policy change: Renewable Fuel Standard and Volumetric Ethanol Excise Tax Credit	Ranged from -16.1 g CO_2e to +24.0 g CO_2e per MJ bioenergy, compared to conventional, depending on methods	Bento and Klotz 2014
Crops for animal feed		
Introducing 1 tonne of genetically modified soy meal for feed	non-GM: 1.3 kg CO_2e per kg soy GM: 8.3 kg CO_2e per kg soy (+538%)	Eriksson et al. 2018
Switch from protein feed to either bioethanol or roughage feed	For bioethanol: +370 kg CO_2e per ha*yr (+25%) For roughage: +2420 kg CO_2e per ha*yr (+164%)	Karlsson et al. 2015
Bioenergy or animal feed from different crops	-329 g CO_2e or -239 g CO_2e per kg biomass	Van Zanten et al. 2014
Crops for polymers		
Switch from glass to flax fibres for polymers	Flax 80% to 200% higher than glass, depending on scenario	Deng and Tian 2015
Increase in human consumption of crops		
Increase in pisco demand	Up to 9.23 kg CO_2e per L pisco, depending on scenario	Larrea-Gallegos et al. 2018
1 litre of gin produced from peas instead of wheat	Wheat (conventional): 2.0 kg CO_2e per L gin Pea: -2.2 kg CO_2e per L gin (-110%)	Lienhardt et al. 2019
Increase in demand of 100 kg bananas	Up to 0.34 kg CO_2e per kg bananas	Sacchi 2018
Changes in farm practices for crops		
Residues from bioethanol replace chemical fertilizer for sugarcane production	-384 kg CO_2e compared to conventional per 10.8 t ethanol	Moore et al. 2017
Addition of fertilised and unfertilised willow on riparian buffer strips and drainage filtration zones of cropland	Reduced 9.5 to 14.8 Mg CO_2e per ha per yr	Styles et al. 2016b

Environmental impact categories included in crop CLCA studies

As defined in the review criteria for this literature review, all CLCA studies identified included GHG emissions (scaled to CO_2 equivalent emissions) in their environmental impact assessment. However, one of the benefits of LCA is that it is a multi-criteria analysis. This means that within the LCA framework, it is possible to include a broad suite of environmental impact categories, thus distinguishing it from a footprint study such as a carbon footprint that only assesses GHG emissions. Indeed, compliance with the ISO 14044 (2006) standard for LCA specifically requires that all relevant impact types be included in the analysis. Land use, acidification, ecotoxicity, eutrophication, ionising radiation, ozone depletion, photochemical oxidation, particulate matter formation, mineral resource use, energy use, fossil resource use, and human toxicity were additional impact categories included in the CLCA studies that assessed more than just GHG emissions (Abiola et al. 2010, Eriksson et al. 2018, Escobar et al. 2017, Karlsson et al. 2015, Kimming et al. 2011, Kloverpris et al. 2016, Li and Mupondwa 2014, Lienhardt et al. 2019, Moore et al. 2017, Parajuli et al. 2017, Parajuli et al. 2018, Reinhard and Zah 2011, Styles et al. 2015a, Styles et al. 2015b, Styles et al. 2016a, Styles et al. 2016b, Tonini et al. 2012, Van Stappen et al. 2016, van Zanten et al. 2014). The most commonly included impact categories were GHG emissions, acidification, eutrophication, ecotoxicity, land use and energy use. By including these multiple impact categories, more information about the environmental impacts of the changes assessed in the CLCA studies was revealed. For example, Eriksson et al. (2018) assessed the impacts of a change from non-GM to GM soy for animal feed. They found a 543% increase in GHG emissions from non-GM to GM soy. They also found a 165% increase in acidification, an 11% increase in eutrophication, and a 36% decrease in ecotoxicity. Based on GHG emissions alone, the conclusions would have been that GM soy clearly had higher impact than non-GM soy. However, when taking the other impact categories into account, that conclusion becomes less clear. Other categories had a much smaller increase in emissions with the switch to GM soy, and toxic emissions were actually reduced. This underscores why it is important to consider all relevant impact categories when using LCA as a decision support tool for farm practices and policies.

Canadian crop CLCA research gaps

Of all the CLCA studies included in this report, only one (Li and Mupondwa 2014) was representative of a Canadian crop – camelina oil grown in the Canadian prairies, assessed for use as biodiesel or jet fuel. Only three studies (Eriksson et al. 2018 and Moore et al. 2017, Styles et al. 2016b) assessed a change in the cultivation of crops, and none of these studies were representative of a region of Canada. Based on these results, there have been no Canadian CLCA studies to date that assess changes in farm management practices, hence representing a substantial research gap. However, there have been many assessments (field-level or ALCA) and recommendations for farm management practices that may reduce GHG emissions from crop production in Canada and elsewhere which can inform future Canadian crop CLCA studies.

Transformation of non-CLCA assessments of crop management practices into CLCA studies

In order to transform current ALCA and other field-level experimental studies investigating reductions in GHG emissions through the use of different farm management strategies into CLCA studies, a number of methodological choices must be made. First and foremost, it will be necessary to identify the marginal markets affected by changes in farm management practices in the field crop industry. This challenge may pose considerable difficulty, due to the numerous other industries linked to crop production. Additionally, the marginal market affected may differ depending on the intervention studied, and the effects of the intervention on the crop. For example, Paré et al. (Paré et al. 2015) performed a long term study to identify best management practices with respect to crop rotation and tillage for northern agriculture. In other studies, both of these management strategies have been shown to reduce GHG emissions at field level (Regina and Alakukku 2010; Jeuffroy et al. 2013). However, Paré et al. (Paré et al. 2015) found that crop rotation resulted in increased yields, while tillage practices did not affect yield. As such, a CLCA of these two management practices, though both resulting in decreased GHG emissions at farm level, would have different affected marginal markets. In the case of crop rotation, marginal markets would include those affected by an increase in grain supply, and any changes in the crops included in the rotation. In the case of tillage practices, marginal markets would include those affected by a decrease in tillage practices, for example fuel and machinery markets, but would not include an increase in grain supply since yield was not affected. Proper identification of marginal markets is absolutely essential to performance of a robust CLCA.

Currently, few detailed guidelines exist on how to identify marginal markets. The International Reference Life Cycle Data System (ILCD) provides a set of guidelines for identification of associated market processes (JRC2010); however, these guidelines suggest that the inclusion of experts in many fields, including technology cost, development, and forecasting, scenario development, market cost and forecasting, and general and partial equilibrium modelling is necessary for proper identification. In order to decrease the financial and temporal burden of identifying marginal markets, Bamber et al. (2019b) instead chose to identify marginal markets through interviews with experts in the field. This may be a viable alternative to increase ease in identification of marginal markets. Regardless of the method used however, the ILCD guidelines are still useful in demonstrating the scope of the market effects needing to be considered, including market directions, secondary markets, as well as potential market constraints (JRC2010). Further investigation into the nature of the substitutions taking place may also be necessary, as the assumption of one-to-one substitution of marginal market equivalents with product may not be valid (Zamagni et al. 2012).

In addition to the identification of marginal markets, any future CLCAs performed for the Canadian field crop industry should follow the guidelines for LCA outlined in the ISO14040-14044 standards. According to these guidelines, there are four phases of an LCA study, each with their own requirements (ISO 2006). The first phase, the goal and scope phase, describes the study being carried out in terms of the reasons for carrying out the study, the intended audience and intended application of the results, and if the study results will be used to support any comparative assertions made to the public. It is also at this point that the functional characteristics of the study are described, including the product system to be studied and its functions, the functional unit (product or service provided) that the study is to be scaled to, the system boundaries and allocation procedures, the impact assessment methodology and the types of impacts studied, etc. The second phase of the study is the life cycle inventory phase, in which LCA practitioners undertake the collection of data characterizing the material and energy inputs and emissions associated with the product system(s) of interest. The third phase of the study is the life cycle impact assessment phase, in which the results from the life cycle inventory phase are classified according to the impacts to which they contribute, and are converted into a common unit and aggregated to obtain the final score for each impact study. The fourth and final phase is then the interpretation phase, in which a number of different analyses may be performed, such as uncertainty analyses to determine the level of uncertainty associated with the results, and contribution analyses to identify hot spots in the product supply chain (ISO 2006). Adherence to the ISO guidelines for LCA ensures consistent application of methodologies, allowing for comparison between studies of consisted methods.

Previous ALCA studies that assessed field crop production in Canada are largely in compliance with the standards outlined by the ISO14040-14044 series (Pelletier et al. 2008; MacWilliam et al. 2014; MacWilliam et al. 2016; Jayasundara et al. 2014; Courchesne and Saad 2014), including all four phases. The same cannot be said of the CRSC field crop carbon footprint studies, since these focused exclusively on GHG emissions. That being said, much of the information necessary for bringing those reports into compliance with the ISO standards is available, and would only require some additional data collection along with formalization into the format given by ISO. A common downfall of all the aforementioned studies is the lack of quantitative uncertainty assessment. While many did make note of uncertainty in their life cycle inventory data, efforts were not made to propagate this uncertainty throughout the model in a formal uncertainty assessment. Additionally, data quality assessment was not undertaken in these studies to assess the fitness of the models produced for the intended purposes. The lack of these additional uncertainty assessments reduces their robustness. Recent work by Bamber et al. (2019c) includes significant detail regarding best practices for uncertainty assessment in CLCA studies, along with best practice guidelines for uncertainty assessment in CLCA. In addition, ongoing research in the Food Systems PRISM Lab at the University of British Columbia Okanagan is investigating the development of regionalised, context-specific data quality assessment for LCA studies in the Canadian field crop industry, which may, in the future, add an additional level of robustness.

Crop production recommendations for inclusion into CLCA studies

The aforementioned ISO-compliant ALCA studies of Canadian crop production could potentially be transformed into CLCA studies by expanding the system boundaries to include likely market-mediated substitutions. For example, Pelletier et al. (2008) assessed the implications of transitioning to organic production of canola, corn, soy and wheat. In this case, marginal products would need to be considered for any changes in yield and inputs associated with the transformation of conventional to organic farming for these crops. MacWilliam et al. 2014 assessed the inclusion of pulses into crop rotations. For a CLCA, the alternative uses of those pulses should be considered, as well as the decrease in production of the crops that were substituted by the pulses in the rotation. Additionally, any changes in yield and inputs would also need to be included.

In addition to previously conducted ALCA studies, there are currently diverse recommendations that might potentially support more sustainable crop production, which can be assessed using CLCA to determine their sustainability at a larger scale, including the life cycle of all product systems affected by a change in farm management. The 4R Nutrient Stewardship framework from Fertilizer Canada (Fertilizer Canada 2019) refers to applying fertilizer to crops from the Right source, at the Right rate, the Right time and the Right place. The framework is currently practiced in many different regions of Canada (including Alberta, Manitoba, Ontario, New Brunswick and Prince Edward Island), making it an ideal candidate to assess using CLCA at a regionally-relevant scale within Canada. Nitrogen fertilizer best management practices under the 4R framework have been shown to reduce GHG emissions by at least 25%, while increasing yields up to 20% (Fertilizer Canada 2018). The 4R Research Network has identified 10 best management practices for Canadian wheat, canola, soybean and potato production. These are 1) applying nitrogen fertilizer as a band close to the seed row for wheat and canola in Alberta, 2) optimizing the rate of nitrogen application during seeding in wheat production in Alberta, 3) integrating sulphur fertilizer using Fertigation for wheat production in Alberta, 4) applying phosphorus fertilizer as an in-soil placement to reduce runoff and waste for wheat, canola and soybean production in Saskatchewan, 5) applying nitrification inhibitors in wheat production in Manitoba, 6) applying urea at the time of planting in wheat production in Manitoba, 7) applying urea/urea ammonium nitrate with nitrification and urease inhibitor at the eighth leaf growth stage in corn production in Ontario, 8) applying nitrification and urease inhibitors with nitrogen fertilizer as a soil injection in corn production in Ontario, 9) applying phosphorus fertilizer as a sub-surface band in corn production in Ontario, and 10) applying nitrogen fertilizer at an optimized rate in potato production on Prince Edward Island. These best management practices could be assessed using CLCA to determine the broader market impacts of differing yield, land use or agricultural inputs.

Alberta's Agricultural Carbon Offsets program gives recommendations for ways to decrease the carbon footprint of crop production (Government of Alberta 2019). These recommendations include aerobic composting to reduce methane emissions, aerobic landfill bioreactors to reduce methane emissions, implementing the 4Rs framework mentioned above, creating biofuels from crops/residues to avoid GHG emissions from petroleum based fuel, carbon capture and storage to remove carbon from the atmosphere, conservation tillage to increase soil carbon sequestration, generating renewable energy (wind, water and solar) to offset fossil fuel sources, implementing energy efficient technologies, improving the fuel efficiency of combustion engines and capture of methane, using air rather than natural gas in pneumatic power tools, landfill gas capture and combustion to covert methane to carbon dioxide for an overall reduction in GHG emissions, and waste heat recovery. These recommendations could similarly be assessed using CLCA to determine the impacts of their implementation, including an increased or decreased demand for certain products used on farms, displaced alternative sources of energy, crops, or other products produced, changes in yield, emissions, land use, agricultural inputs, etc. This would do much to resolve the current gap in terms of CLCA studies of Canadian field crops, and provide useful insight to farmers in support of determining the most sustainable farm practices.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this literature review, the majority of consequential LCA studies on agricultural crops published in the past 10 years have assessed the use of crops in bioenergy production. Despite the relatively large sample size of 22 studies, there was no consensus on the GHG mitigation potential of bioenergy. Most studies found there to be either an increase or a decrease in GHG emissions with the increase in production of bioenergy from crops, depending on the specific scenario assessed. There were also some studies that found an overall increase in emissions in all scenarios assessed, and some that found an overall decrease. Therefore, it can be concluded that some specific scenarios may be beneficial or detrimental in terms of GHG mitigation, but overall there is a large amount of uncertainty and variability in the mitigation potential of bioenergy production.

There were also a small number of studies of crop use for animal feed. Two of the CLCA studies that assessed crop use for animal feed found increased GHG emissions, but one study performed an optimization to determine the best scenario, which resulted in decreased GHG emissions. Similarly to crop use in bioenergy production, there is uncertainty and variability in the mitigation potential of crop use as animal feed. There were three CLCA studies that assessed different crop management practices. Eriksson et al. 2018 found that GM soy produced 5.5 times higher GHG emissions than non-GM soy for use as animal feed. Moore et al. 2017 found that the replacement of synthetic fertilizer with residue from bioethanol production reduced GHG emissions by 384 kg CO_2e per 10.8 t of ethanol production, and Styles et al. 2016b found that adding willow crops to crop fields can reduce GHG emissions by 9.5 to 14.8 t CO_2e per ha per year, depending on the location of willow planting. However, none of those crop management CLCAs was geographically representative of Canada. In fact, there was only one CLCA out of all studies assessed that was representative of a Canadian field crop (camelina oil for biofuel). This clearly indicates the need for further research in the field of consequential life cycle assessment of farm management practices for Canadian crops.

There have been a variety of ALCA studies of Canadian crop management practices that can be used as a basis to perform CLCA studies. In order to transform these previous studies into CLCAs, the most important step is to identify the potential market-mediated marginal substitutions, or the processes that would be affected by the crop production intervention being assessed. This can be done using economic optimization models, or interviews with experts and local producers. Data on changes in crop yield, inputs, and alternative uses of products and co-products are necessary to determine these marginal processes.

In order to avoid burden shifting between different types of environmental impacts, it is recommended to perform a full multi-criteria CLCA of any potential broad-scale change in crop management practice. This involves including all relevant environmental impact categories in the impact assessment. Common impact categories included in agricultural LCA studies are climate change (GHG emissions), acidification, eutrophication, ecotoxicity, land use and energy use.

Due to the lack of Canadian crop management CLCA studies, it is strongly recommended to conduct a representative suite of CLCAs to inform best management practices for sustainable crop production in Canada. The information gathered in this literature review can support the development of CLCA methodology with respect to the identification of potential crop management strategies, definition of system boundaries, identification of market-mediated substitutions, and inclusion of impact categories.

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