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Review

Review of life-cycle assessment research for the Australian grain industries

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Abstract

This paper seeks to review the existing, published life-cycle assessment (LCA) analyses of the grain supply chain in Australia that have identified 'hot spots' requiring environmental improvement. This article also discusses the application of cleaner production strategies for reducing life-cycle ecological footprints, and achieving further economic and environmental benefits in the grain supply chain. In conclusion, some recommendations are made to overcome some existing drawbacks for LCA grain research.

Keywords: LCA, Grains, Cleaner production strategies

Introduction

Agricultural industries comprise a supply chain extending from the pre-farm inputs to post-farm processed products. Although the production of the crop is often the most visible aspect of the production chain, it may not be a major component in terms of the requirements for energy and fuel. Current practice is to assess the components of the production chain, sector by sector and to identify the environmental emissions in each sector in isolation. A more cost-effective approach may be to identify the major emission sources that are amenable to greenhouse gas (GHG) mitigation regardless of where they lie in the chain. This is the province of life-cycle assessment (LCA) in trying to highlight 'hot spots' that require in particular environmental management.

Grain production is one of the most important agricultural activities in Australia, given its use in food, fodder and industrial raw material applications. The Australian grain industry emits significant amounts of GHGs. The industry produces 30–40 million tonnes of grains per annum [1] including, wheat, coarse grain (barley, sorghum, oats), oilseeds (canola, cottonseed, sunflower seeds and soybeans) and pulses (field peas, faba beans, chickpeas, lupins and lentils). Approximately 65% of all grain produced is exported, earning around $6 billion per annum [1]. Furthermore, Australia's grain export production is expected to double in the next 10 years [1]. In addition, the production of ethanol for transport fuel is expected to create significant pressures on the grain industry [2].

Although the grain industry helps enhance Australia's economic growth, the environmental externalities produced also need to be addressed. The main GHGs emitted from agriculture are methane (CH_4) and nitrous oxide (N_2O). Both are powerful GHGs, with 21 and 310 times the global warming potential of carbon dioxide (CO_2), respectively. Nationally, agriculture is the dominant source of both methane (60%) and nitrous oxide (85%) [3]. Anthropogenic activities, including farm mechanization and the application of chemicals, are the main cause of these GHG emissions and other environmental impacts such as acidification, eco-toxicity, eutrophication and resource energy.

This paper discusses the use of LCA as an environmental management tool for reducing environmental emissions from the supply chain of grain production in Australia. Firstly, this paper discusses the methodology of the reviewing process. Secondly, it reviews the LCA methodology that applies a '*cradle to grave*' approach, in assessing the environmental impacts of the different stages of the supply chain of grain products. Thirdly, the paper discusses the application of cleaner production techniques for improving the ecological footprints of the product life cycle. Fourthly, recent grain LCA research is reviewed to identify gaps for the application of cleaner production strategies in improving the environmental performance of

Pre-farm	On-farm	Post-farm
Production of farm inputs ◇ Mining ◇ Extraction ◇ Processing ◇ Production	Management practices ◇ On-farm transport ◇ Lime application ◇ N-Fertilizer use ◇ Stubble burning ◇ Soil disturbance ◇ Transport to bin	Activities ◇ Grain storage ◇ Transport from bin to port

Figure 1 System boundary for GHG LCA on a paddock level

grain production. Discussion concludes with potential strategies for implementing cleaner production techniques to improve the ecological footprint of grain production and the grain supply chain in Australia.

Review Methodology

This literature review focuses on agricultural LCA literature that deals specifically with Australian grain production. Peer-reviewed articles from international journals and publicly available agricultural LCA reports developed by Australian industries that mainly focus on barley, canola, maize and wheat have been reviewed. While reviewing these reports, information has been analysed to synthesise key consensus and divergent points, including the goal and purpose of agricultural LCAs, LCA system boundaries, functional units, LCA modelling utilized, life cycle impact assessment methodology and impact categories. This review process has also identified 'hot spots' for some of the grain supply chain and discusses possible cleaner production strategies for treating the hot spots in order to improve the environmental performance of the grain supply chain.

Importance of LCA for the Environmental Management

LCA is an analytical method used to evaluate the resource consumption and environmental burden associated with production or a specific product activity [4]. LCA provides a systems-based accounting of material and energy inputs and outputs at all stages of the life cycle of grain products including the acquisition of raw materials, production, processing, packaging, use and retirement. The Life Cycle Inventory Analysis deals with the collection and synthesis of information on the major physical materials utilised and can provide an environmental profile of the total 'production system' from 'cradle to grave'.

LCA of a product varies with functional unit and system boundary. The functional unit determines whether it should be the environmental performance, for example, one tonne of grain production or product (e.g. one loaf of bread production), while the system boundary depends on the functional objective and contains the number of stages of the life cycle to determine the functional objective. Figure 1 provides an example of the system boundary of one tonne of wheat transported to port, which consists of pre-farm, on-farm and post-farm stages. It should be noted that the LCA with a functional unit of 'one loaf of bread production' has a bigger system boundary (paddock to bread) or consists of more stages than the LCA with a functional unit of 'one tonne of wheat transported to port' (i.e. paddock to port).

The grain supply chain or system boundary includes many stages with associated emissions. The pre-farm stage includes GHG emissions from agricultural machinery, fertilizer and pesticide production. The on-farm stage includes GHG emissions from diesel use for on-farm transport or farm machinery operations (e.g. ploughing, seedling, top dressing, swathing, etc.), liming and nitrous oxide (N_2O) emissions from N fertilizer applications. The post-farm stage includes grain storage, flour milling, transportation, starch production and starch end-use. LCA can adopt a 'cradle-to-grave' approach, which involves analysing all inputs and (non-) product outputs that are extracted from the environment or disposed of to the environment across all stages of the grain supply chain. Also, LCA can assist in a more comprehensive and inclusive calculation of GHG emissions from the agricultural supply chain resulting in the identification of 'hot spots' including point and non-point sources[1] and those stages resulting in high levels of GHG emissions.

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[1] The example for a point source is the emission from a chimney, while N_2O emission from paddock is the emission from non-point source.

Cleaner Production Benefits From Life Cycle Assessment

Once the environmental hot spots in the supply chain are identified, appropriate cleaner production techniques can be applied across these areas, in order to improve the environmental performance of the grain supply chain. Cleaner production initiatives involve the continuous application of an integrated preventative strategy to processes, products and services to increase efficiency and reduce risks to humans and the environment [5]. van Berkel [5] suggests that the prevention practices include:

- Good housekeeping – to improve operation, maintenance and management procedures.
- Input substitution – the use of environmentally preferred and 'fit-for-purpose' process inputs.
- Technology modification – improving the production facility.
- Product modification – changing product features to reduce its life-cycle environmental impacts.
- Reuse and recycling – on-site recovery and reuse of materials, energy and water.

These strategies can potentially be implemented across the grain supply chain.

Review of Text

LCA of Grain Products in Australia

Barley

Narayanaswamy *et al.* [6] carried out an LCA of barley, where the functional unit was to assess the environmental impact associated with production of 1 HL of beer from barley. The stages, which were considered in this LCA were pre-farm, on-farm, storage, mulching and brewing. The ecological footprints were 135 kg CO_2 equivalent (equ-) for global warming, 0.58 kg SO_2 equ- for acidification, 0.18 kg $(PO_4)^{-3}$ equ- for eutrophication and 1300 MJ for resource scarcity caused by production of 1 HL[2] of beer.

This LCA analysis showed that the post-farm activities, including storage and processing, accounted for more than 70% of the total global warming, acidification and resource energy impacts in producing beer from barley. Application of cleaner strategies in the storage and processing stage can reduce these impacts significantly. Recycling and good housekeeping strategies can be applied in the processing of beer in order to reduce the life-cycle ecological footprints. For examples, research by EPA [7] at a South Australian Brewery highlighted the cleaner production technology improvement benefits of better calibration of the reduction of filling losses, standard operating practices and statistical process control, recovery extraction and improved pipe layout in avoiding unnecessary beer losses equivalent to 540 000 stubbies[3] per year and therein reducing GHGs by 273[4] tonne of CO_2 equ-. The payback period of these strategies was only 1.5 years. A recycling strategy that recycles the beer bottles and boxes can further reduce energy use for the mining and production of these materials in order to reduce the global warming impact.

The pre-farm and farming stage of beer production contributed to eutrophication impacts significantly (i.e. >90%). Input substitution strategy, which replaces the need for chemical fertilizer with legume rotation system, could reduce this impact.

This LCA study considered IPCC values for gaseous emissions from the farming activities in order to determine the life-cycle ecological footprints. The research did not separate pre-farm and on-farm stages and therefore it is not possible to determine the environmental implications of these stages separately.

Canola

Narayanaswamy *et al.* [6] also carried out an LCA on canola to canola oil production, where the functional objective was to assess the environmental impacts of the production of 1 litre of canola oil from canola seeds. The stages of this LCA analysis were pre-farm and on-farm, storage and processing, and retail and consumption. The ecological footprints were 7 kg of CO_2 equ- for global warming, 0.022 kg SO_2 equ- for acidification, 0.13 kg $(PO_4)^{-3}$ equ- for eutrophication and 220 MJ of resource scarcity as a result of production of 1 litre of canola oil. However, this research did not separate pre-farm and farming or on-farm stages and, therefore, it was not possible to determine the relative environmental implications at each stage of production.

It was found from this LCA analysis that pre-farm and farming activities accounted for a significant portion (45–100%) of global warming, acidification and eutrophication impacts. Good housekeeping strategies that include precision farming and crop rotation systems can mitigate these impacts by reducing energy and chemical consumption during the pre-farm and farming stages. For example, wheat yields are often higher in wheat-lupin and wheat-subterranean clover rotations than in continuous wheat cropping systems, and this is attributed to improved nitrogen availability after the legume crop, as well

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[2] HL=Hectolitre=100 litre.

[3] A short glass bottle for beer, between 330 and 375 millilitre, is generally called a stubby.

[4] 0.375 litre/stubby × 540 000 stubbies × 1.35 kg CO_2 equ-/litre of beer production=273 400 kg of CO_2 equ- ≈273 tonne of CO_2 equ-.

as lower disease and weed pressure [8]. In a 12-year study of energy use, energy output and energy-use efficiency in conventional and organic crop rotations and crop production systems in Canada, Hoeppner and others [9] found that energy use was 50% lower with organic compared to conventional management systems. An accurate machinery guidance system is also an example for technological modification strategy, where the amount of inputs (fuel, pesticides and fertilizers) can be reduced by using accurate auto-steer systems [10].

Other canola-based LCA studies have included the environmental implications of the conversion of canola oil to biodiesel. Canola and cottonseed are the major oilseed crops (accounting for 57 and 36% of total oilseed production, respectively), with soybeans and sunflower accounting for a smaller proportion (3 and 4%, respectively) [11]. An LCA of alternative fuel for Australian heavy vehicles that used biodiesel from the above mentioned crops found that pure biodiesel produces 41–51% less GHG emissions than the petroleum diesel [11]. However, these studies did not take into account local on-farm (e.g. N_2O) emission factors in the calculation of total associated GHG emissions.

Biswas *et al.* [12] carried out an LCA on 1000 litres of biodiesel production from canola oil in Western Australia (WA) that used locally measured GHG emissions. The life-cycle GHG emission during the production of 1000 litre of biodiesel was 567 kg of CO_2, which was about 2.6 times lower than the value calculated when using the IPCC emission factor for N_2O. This LCA analysis was carried out for three major stages: pre-farm, on farm and canola seeds to biodiesel production. The on-farm stage has been found to contribute the largest portion (72%) of total GHG emissions for canola biodiesel production. However, a UK-based study found that N_2O emissions can account for around 70% of the farm gate carbon footprint for rapeseed oil [13].

In addition, Biswas *et al.* [12] found that CO_2 emissions from the hydrolysis of urea accounted for the largest proportion (60%) of life-cycle GHG emissions, followed by fertilizer production, and N_2O emissions from the soil. An input substitution strategy that substitutes chemical fertilizers with organic N fertilizers could be considered in this case. For example, it had been suggested that $\sim$80% of CO_2-equivalent emissions could be mitigated from the on-farm stage by substituting chemical fertilizer for organic fertilizer [14]. However, the substituting of synthetic N fertilizer with organic fertilizer requires further research in Australian application as extrapolation of findings from other parts of the world may not be appropriate because of differences in soil types, climate and production systems. While applying organic fertilizer, it needs to be ensured that the resources for organic fertilizer are sufficient at a national level to replace chemical fertilizers for the same yield. Using data from Lal [15], it can be estimated that the per unit N_2O-N emissions from farm yard manure and synthetic N are broadly similar (incorporating both 'production' and N_2O-N emissions [15, 16]).

The aforementioned studies have only carried out LCAs of global warming potential of biodiesel production. However, other environmental impacts, which result from the production of biodiesel, warrants investigation. For example, other environmental impact categories need to be considered when assessing the use of biodiesel, as De Nocker *et al.* [17] found biodiesel use impacted more on soil and water acidification, eutrophication and radioactive waste type (i.e. other environmental impact categories) than use of diesel.

Maize

Grant and Beer [18] performed the LCA of a multi-institutional project in order to determine the life-cycle global warming potential of snack food corn chips produced from maize. The functional unit was to determine the global warming potential of the production of one 400-g packet of corn chips. This LCA analysis considered three production stages, pre-farm, on-farm and post-farm activities, involved in the use of maize for the manufacture of corn chips. In this LCA analysis, the post-farm stage includes all activities required to process maize into corn chips, its packaging and then disposal of the packet.

Grant and Beer [18] found that the corn chip production chain emitted total net GHG emissions of 0.53 kg CO_2 equ- per 400 g packet of corn chips reaching the domestic market. Pre-farm, on-farm and post-farm stages contributed 6, 36 and 58% of the total GHG emissions, respectively. The single largest source of greenhouse emissions was the on-farm emission of nitrous oxide associated with the application of N fertilizer and stubble burning (0.126 kg CO_2 equ- per packet, 25%). Other emission sources were electricity from chip production (17%), transport of chips to market (8%), production of the box for transporting the corn chips (8%), water pumping (7%), natural gas for chip processing (6%) and the corn-chip packet (4%).

Good housekeeping within cleaner production strategies includes farm management techniques that can be used to increase soil carbon and reduce GHG emissions. If farms that currently burn stubble were to implement stubble incorporation then, in the absence of other changes to the supply chain, they will achieve a 30% reduction in emissions from 'cradle to farm gate' [18]. Also the same research found that pumping irrigation water from deep bores currently produces GHG emissions that are almost three times those from irrigation using surface waters.

Other than the complete LCA analysis, other research had been carried out to estimate the gases emitted from significant GHG-producing sources during the life cycle of maize production. Fertilizer application and stubble burning during the on-farm stage have usually found to be the predominant sources of N_2O emissions, which has a global warming potential of 310 kg CO_2 equ-/kg N_2O

Table 1 Comparative global warming performance of grain products on a per unit basis

Grains	Functional unit	Global warming impacts (kg CO_2 equ-)	References
Barley	1 litre of beer production	1.35	[6][1]
Canola	1 litre of canola oil production	7	[6][1]
	1 litre of biodiesel production	5.67	[12]
Maize	1 packet of corn chips (400 g)	0.53	[18][1]
Wheat	1 loaf of bread production	2.3	[6][1]
	1 kg of wheat transported to port	0.3	[22]

[1] These research projects used IPCC default value of N_2O-N for determining the global warming impact.

[19, 20]. Galbally *et al.* [21] found that the N_2O emission factor decreased by 45% by avoiding stubble burning and stubble retention. The emission factors are 2.8 and 1.6% for stubble burning and retention, respectively.

Wheat

Narayanaswamy *et al.* [6] carried out an LCA of wheat, where the functional objective was to assess the environmental impacts of the production of one loaf of bread. The stages of this LCA analysis were pre-farm and on-farm, storage, processing, retail and consumption.[5] The associated ecological footprints were global warming for 2.3 kg equivalent of CO_2 equ-, acidification of 0.01 kg SO_2 equ-, eutrophication of 0.0083 kg $(PO_4)^{-3}$ equ- and resource scarcity of 74 MJ from the production of one loaf of bread. It was found in this LCA analysis that the retail and consumption stage contributed 55% of the total GHGs in the bread supply chain. However, this LCA study did not consider local values for N_2O emission factors. The variation on local versus IPCC N_2O values could significantly affect the outcome of any LCA analysis, given the high GHG value associated with N_2O.

Biswas *et al.* [22] estimated the global warming impact of 1 tonne of wheat transported to port. This LCA analysis showed that GHG emissions decreased from 487 to 304 kg CO_2 equivalents when Western Australian data for N_2O-N emissions was used instead of the IPCC default value for the application of synthetic N fertilizers to land (1.0%). The emission factor of N_2O-N in WA is extremely low (0.02%) [23] and is approximately 50 times less than the default value suggested by the IPCC for calculating N_2O emissions from cropped soils [19, 16]. The proportion of N fertilizer lost from cropped soils in semi-arid environments is likely to be significantly lower than the global average [23]. Like Barton *et al.* [23], Barker-Reid *et al.* [24] suggests that that the proportion of fertilizer N lost from cropped soils in arable environments is likely to be significantly lower than the global average. Given that globally, and across a variety of climatic regions, a range of annual N_2O losses (0.3–16.8 kg N_2O-N/ha/yr) have been reported for cropped mineral soils [25], it is recommended that analysis includes regional-specific data to accurately assess GHG emissions from wheat production.

Fertilizer production in the pre-farm stage contributed significantly (35%) to GHG, followed by on-farm CO_2 emissions (27%) and the emissions from transportation of inputs to paddock and the wheat to port (12%). Nitrous oxide emissions from the paddock represented 9% of the total GHG emitted. Similarly, a European study found that 40–80% of CO_2-equivalent emissions could be mitigated from the on-farm stage by substituting chemical fertilizer for organic fertilizer [14, 26].

As can be seen, the LCA outcomes change when the functional objective is the environmental impact assessment of one loaf of bread instead of 1 tonne of wheat.

A reduction in GHG emissions from synthetic N fertilizer production might be achieved by introducing a cleaner production technological modification strategy in the urea production process, and by considering plant capacity utilization, type of feedstock, technology employed and age of the plant [27] in the production process.

Comparative environmental performance of different grain products

Since all studies, other than Narayanaswamy *et al.* [6], used LCA analysis to determine the global warming impact only, a comparative global warming performance of aforementioned grain products has been carried out. Table 1 shows the comparative global warming performance of one unit of product, produced from different grains. As can be seen from Table 1, global warming impact for grain products vary from 0.3 to 7 kg of CO_2 equivalent. The emission figures for 1 litre of canola oil is higher than that for the 1 litre of biodiesel production from canola oil, as Narayanaswamy *et al.* [6] used the IPCC default value for N_2O-N, which is 50 times lower than the local value.

Future Work

A number of methodological issues still need further evaluation and assessment in order to more fully account for the environmental impacts from agricultural (grain)

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[5] Retail and consumption stage includes retail operations, storage at retailer and consumer, and consumption, regarding discarding the packaging.

production including the carry over between crops (nutrient cycling), human and eco-toxicity and land-use environmental impacts [28]. For example, the impacts of dryland salinity on GHG have not been found in the existing LCA frameworks and software databases. Therefore, an additional impact category for salinity effects (i.e. increased fertilizer application and land use change) would be beneficial in taking account of the GHG production associated with salinity management and broadacre grain production in Australia.

Furthermore, none of the aforementioned LCAs was carried out on genetically modified grain products, even though the use of genetically engineered plants may not only increase crop yields, but may also reduce pesticide application [29].

Research also highlighted the benefits from utilizing regionally specific LCI boundary data (e.g. N_2O emissions), rather than IPCC international default values, when assessing GHG for agricultural production systems in Australia. Further research therefore is needed in providing locally/regionally specific data for major LCI variables.

In addition, no local LCA analysis has been carried out for lupin and rice, while these crops are extensively produced for fodder and food purposes in Australia.

Finally, in addition to the LCA of GHG emissions, the full economic, social and environmental impacts (i.e. soil condition, air pollution, water quality) need to be taken into account in order to assess the sustainability of grain industries in Australia, and the remediation potential of proposed GHG mitigation strategies.

Conclusions

The functional unit of an LCA analysis has a large bearing on the conclusions drawn. Recently, more attention has been given to the review of grain supply chains in order to more fully understand the environmental implications of agricultural production and consumption. LCA is an environmental management tool that provides a framework for analysing and evaluating environmental impacts in the different stages of the life cycle of grain products. The LCA also provides an opportunity for utilising cleaner production strategies in the management of the grain production ecological footprint. Through this reviewing process, it appears that measures to reduce emissions from N-fertilizers or find alternative N-fertilizers should be a priority in the grain supply chain management both locally and globally.

The substantial contribution by agriculture (including grain production) to environmental emission warrants an investigation of cleaner production strategies to assist farmers and industry to both reduce ecological footprints and improve grain production efficiency. In addition, there is potential for improvement in the existing LCA research in the areas of data quality, system boundary and interdisciplinary impact category aspects to help further elucidate the benefits of GHG management of grain production.

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