

## CONTEMPORARY ISSUES

# Reconsidering the contribution of Canadian poultry production to anthropogenic greenhouse gas emissions: returning to an integrated crop–poultry production system paradigm

M. A. Oryschak<sup>\*,1</sup> and E. Beltranena<sup>\*,†</sup>

*\*Alberta Agriculture and Forestry, Government of Alberta, Edmonton, Alberta, Canada T6H 5T6; and †Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, Alberta, Canada*

**ABSTRACT** Public discourse around “greenhouse gases” (GHG) has led to the application of life-cycle assessments to ascertain the “global warming potential” of human activities. Life-cycle assessments applied to agricultural systems typically do not consider positive contributions (i.e., fixation of atmospheric carbon dioxide [CO<sub>2</sub>]) or consider complex interrelationships among commodities within the larger agricultural sector. The purpose of this article is to present an argument for a paradigm shift and that poultry production should be considered as a value-adding activity within modern crop production systems for GHG foot-printing purposes. To this end, a case study based on 2018 production data is presented where poultry production (chicken and eggs) was contextualized as a sub-component of wheat and corn production in the Canadian provinces of Alberta and Ontario, respectively. Total GHG footprint was calculated to be 3.05 and 3.29 million tonnes (MT) of CO<sub>2</sub> equivalent (eq) for Alberta wheat and Ontario corn production, respectively. The GHG footprint of chicken production was calculated to

be 0.39 and 1.38 MT CO<sub>2</sub> eq in Alberta and Ontario, respectively. The GHG footprint of egg production calculated to be 0.12 and 0.47 MT of CO<sub>2</sub> eq in Alberta and Ontario, respectively. When carbon (C) fixation as crop biomass is included in the scenario, the combined crop–poultry system C balance in 2018 favored net fixation of 40.70 and 35.15 MT of CO<sub>2</sub> eq in Alberta and Ontario, respectively. The calculated total GHG footprint of poultry production in Alberta and Ontario corresponded to only 1.2 and 5.5% of the calculated total net CO<sub>2</sub> fixation of their respective cropping systems. This case study demonstrates that by failing to acknowledge real world estimates of C fixation by crop biomass, GHG foot-printing exercises largely misrepresent reality and can thus perpetuate faulty assumptions about the environmental footprint of animal agriculture. The authors propose that the calculations presented herein provide grounds to postulate the hypothesis that modern, integrated crop-livestock agricultural systems in Canada (and elsewhere) act as net sinks for atmospheric CO<sub>2</sub>.

**Key words:** carbon-fixation, chicken, crop, egg, greenhouse gases emissions

2020 Poultry Science 99:3777–3783

<https://doi.org/10.1016/j.psj.2020.05.004>

## INTRODUCTION

The ongoing discussion within society regarding anthropogenic emissions of greenhouse gases (GHG) has led to the broad application of life-cycle assessments (LCA) to ascertain the global warming potential for a range of human activities.

The LCA process models the environmental impact of production systems by subdividing them into their

constituent components or activities and scrutinizing the individual impact of each activity (Horne et al., 2009). Essential components of LCA include establishing the boundaries of the system under consideration, selection of the “functional unit” or unit of production emerging from the system to serve as the basis for the calculated impact, and sourcing robust data pertaining to each stage of the system’s life cycle (International Standards Organization, 2006). Whereas LCA provides a convenient and standardized methodology to estimate environmental impact, they are characterized by the same limitations common to other modeling processes. Notarnicola et al. (2017), for instance, noted that LCA outputs are open to misinterpretation if the defined boundaries around the system are inappropriately selected or if the data used to model the system are

© 2020 Published by Elsevier Inc. on behalf of Poultry Science Association Inc. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Received October 3, 2019.

Accepted May 5, 2020.

<sup>1</sup>Corresponding author: [matt.oryschak@gov.ab.ca](mailto:matt.oryschak@gov.ab.ca)

incomplete or have large uncertainty associated with them. It is important therefore to scrutinize the assumptions and underlying data when evaluating the accuracy, relevance, and outputs of LCA modeling exercises.

Since the early 2000s, there has been a rapid expansion of the use of LCA in the agricultural sector to calculate the environmental impact of a wide range of livestock commodities. Case studies have been completed for a variety of commodities, jurisdictions, and under a wide range of conditions (De Vries And de Boer, 2010). In general, there is heterogeneity in reported GHG outputs from LCAs conducted on the same commodity and using the same functional unit (Lopez-Andres et al., 2018), which likely trace their origin to the aforementioned factors. This discrepancy has led to calls for greater standardization of LCA methodologies applied to livestock (Herrero et al., 2011).

A major notable deficiency of LCA applied to agricultural systems is that they do not generally consider positive contributions (i.e., fixation of atmospheric carbon dioxide [CO<sub>2</sub>]) to GHG fluxes. Agriculture and forestry are distinct from all other large-scale human activities in that both remove large quantities of CO<sub>2</sub> from the atmosphere each year, converted primarily to plant biomass and soil organic carbon (C). For instance, Kurz et al. (2014) estimated that Canada's managed boreal forests are net sinks for atmospheric CO<sub>2</sub> in excess of 100 million tonnes (T) of CO<sub>2</sub> equivalents (eq) per year. Similarly, Fan et al. (2019) proposed that Canadian agricultural acreage has gone from being a net emitter of GHG in 1990 to a net sink for more than 380 million T of CO<sub>2</sub> eq per year. This estimate is equivalent to more than half of Canada's estimated total anthropogenic GHG emissions (Environment and Climate Change Canada, 2019). Consideration of the CO<sub>2</sub> fixation from managed landscapes therefore should feature prominently into any balanced discussions of GHG emissions from agriculture and/or forestry.

A characteristic common to most LCA of agricultural systems is that the boundaries do not take into consideration the complex interrelationships among commodities within the larger agricultural sector (van Hal et al., 2019). The specialization of farms into either crop or livestock commodities that has occurred over the past several decades (Statistics Canada, 2019a) obscures the indisputable reality that crop and livestock production are still highly interdependent, though more commonly at a regional rather than farm level.

The economics of crop production are dependent on the existence of local feed markets to absorb and utilize crop tonnage that would be of insufficient quality for human food and or export. In Canada, for example, the domestic feed market absorbs approximately 4 million T of non-human food grade wheat annually (Statistics Canada, 2019b). Livestock feed markets also support domestic processing activity by absorbing high value co-product tonnage. For instance, Canadian domestic canola crushing activity generates more than 5 million T of co-product meal, of which domestic livestock

production utilizes 606,000 T and foreign feed markets absorb much of the remainder (Canola Council of Canada, 2019).

The economics and sustainability of specialized poultry (and swine) sectors are, in turn, heavily dependent on the availability of local feed-grade grains and processing co-products. Feed represents the single greatest cost of production (Lachapelle, 2014), and the availability of cropland acreage near intensive livestock operations is of paramount importance for sustainable manure management (Sauer et al., 2000). Regions and or countries that are net importers of feedstuffs to sustain domestic livestock production are susceptible to net accumulations of nitrogen and phosphorus in agricultural soils (Wang et al., 2018) and therefore incur the accompanying environmental risks. In consideration of these realities, it is reasonable to posit that GHG emissions from poultry production should be viewed in the context of regionalized, integrated crop-poultry production systems.

The purpose of this article therefore is to present an argument for a paradigm shift in how GHG emissions from poultry production should be considered. Specifically, poultry production in this article will be contextualized as a value-adding activity integrated within modern crop production systems, rather than as an activity conducted in isolation. In support of this argument, the authors present a crude but empirically-based estimate of the net C balance of integrated grain crop-poultry production systems in 2 representative Canadian jurisdictions. These calculations differ from conventional LCA processes as they take into account both estimated LCA-based GHG emissions as well as estimates of atmospheric CO<sub>2</sub> fixation.

## METHODS AND MATERIALS

### Data Sources

All data sources utilized in this study are in the public domain and are fully available for verification purposes.

Data pertaining to production tonnage of corn grain (*Zea mays*) in the province of Ontario and of wheat (*Triticum aestivum*) in Alberta, both for the 2018 crop year, were drawn from the agricultural statistics database maintained by the Government of Canada (Statistics Canada, 2019c). Production of both crops is expressed in metric T of grain (Table 1).

Data regarding chicken and egg production in both Alberta and Ontario for the 2018 calendar year were obtained from Agriculture and Agri-Food Canada (2019) and Statistics Canada (2019d), with supporting information from the Chicken Farmers of Canada (2019) and the Egg Farmers of Canada (2019); (Table 1). Chicken production is expressed in kg of liveweight, whereas egg production is expressed in dozens of eggs, as these are the respective bases on which producers in Canada are compensated.

Egg production was further adjusted using the weight grade statistics from each province and

**Table 1.** Production of major feedstock crops (metric T grain), chicken (kg liveweight), and eggs (large dozen) in Alberta and Ontario (Canada) in 2018.

Province	Commodity	Production (2018)	% of Canadian production (2018)	Provincial rank (2018)
Alberta				
	Crop products <sup>1</sup>			
	Wheat, T grain	8,771,600	36.6	Second
	Livestock products			
	Chicken <sup>2</sup> , kg liveweight	161,083,352	9.4	Fourth
	Chicken, # head	71,369,009		
	Chicken, avg. wt per bird (kg)	2.257		
	Eggs <sup>3</sup> , dozen large eggs	66,155,309	9.2	Fifth
Ontario				
	Crop products <sup>1</sup>			
	Corn, T grain	8,767,900	63.1	First
	Poultry products			
	Chicken <sup>2</sup> , kg liveweight	576,690,494	33.8	First
	Chicken, # head	235,729,323		
	Chicken, avg. wt per bird (kg)	2.446		
	Eggs <sup>3</sup> , dozen large eggs	268,860,409	37.4	First

<sup>1</sup>Source: [Statistics Canada, 2019b](#).

<sup>2</sup>Source: [Agriculture and Agri-Food Canada, 2019](#).

<sup>3</sup>Source: [Statistics Canada, 2019d](#) and [Egg Farmers of Canada, 2019](#). Count was adjusted by distribution of eggs in Grade A weight categories to be expressed as dozens of large (59.5 g/egg) eggs.

Canadian weight grading standards ([Egg Farmers of Canada, 2019](#)). The weight grade distribution among the Grade A categories resulted in total egg production in Alberta and Ontario being multiplied by correction factors of 0.99 and 1.00, respectively, to express production in dozens of large eggs (average weight of 59.5 g/egg or 714 g/dozen).

### LCA-Based Estimates of GHG-Emissions of Crops and Poultry Products

Carbon footprints (kg of CO<sub>2</sub> eq/T grain production) for corn and wheat grain crops were taken from a recent report by the [Canadian Roundtable for Sustainable Crops \(2019\)](#); ([Table 2](#)). Estimates of the GHG footprint of direct energy, fertilizer manufacturing, seed and pesticide, and nitrous oxide (N<sub>2</sub>O) contributions were averaged for sites in Alberta (3) and Ontario (2). Estimates of net soil organic C loss/deposition were also drawn from the same report. Because of the lack of high-resolution data concerning soil organic C fluxes in situations where there is net accumulation of soil organic C over decadal or multidecadal bases, gains in

soil organic C reported in [Canadian Roundtable for Sustainable Crops \(2019\)](#) were not credited against total GHG footprint for wheat grain. Losses in soil organic C reported for corn grain, however, were added to the other GHG footprint components to yield its total GHG-footprint ([Table 2](#)).

The LCA-based estimate for chicken production used for balance calculations was that reported by the Chicken Farmers of Canada of 2.4 kg of CO<sub>2</sub> eq/kg of liveweight chicken ([Courchesne and Jamaron, 2014](#); [Chicken Farmers of Canada, 2019](#)). The value assumed for eggs was 1.73 kg CO<sub>2</sub> eq/dozen eggs, which is derived from the value reported for the Canadian national average across all housing types by [Pelletier \(2017\)](#).

### Stated Assumptions

To complete the balance calculations, it was necessary to make several assumptions regarding C contained in the crops and residues. As per [Bolinder et al. \(2007\)](#), it was assumed that all crop biomass is 45% C on an as-is basis (~90% dry matter). This assumption is supported by extensive published data for a wide range of

**Table 2.** Total greenhouse gas (GHG) footprint (kg CO<sub>2</sub> eq/T grain production) of major feedstock crops in Alberta and Ontario (Canada), partitioned into major components.

Crop	Region	GHG footprint components <sup>1</sup> , kg CO <sub>2</sub> eq/T grain production					Total GHG footprint <sup>3</sup>
		Direct energy use	Fertilizer manufacturing	Seeds & fertilizer	N <sub>2</sub> O emissions	Soil organic carbon loss <sup>2</sup>	
Wheat	Northern Alberta	30.8	100.6	16.8	209.0	-137.9	357.2
Wheat	Central Alberta	37.8	92.4	13.4	166.1	-153.5	309.7
Wheat	Southern Alberta	27.7	108.6	19.9	218.8	-105.6	375.0
Wheat	Provincial mean	32.1	100.5	16.7	198.0	-132.3	347.3
Corn	Southern Ontario	22.9	57.1	7.3	179.3	79.9	346.5
Corn	Eastern Ontario	25.5	57.1	8.1	181.9	130.4	403.0
Corn	Provincial mean	24.2	57.1	7.7	180.6	105.2	374.8

<sup>1</sup>Source: [Canadian Roundtable on Sustainable Crops, 2019](#).

<sup>2</sup>Negative values indicate a net gain of soil organic carbon, which are not credited against GHG emissions from other components because of uncertainty with regards to steady-state soil organic C fluxes in reduced tillage systems. Positive values indicate loss of soil organic C, which were added to the other components to yield total GHG.

<sup>3</sup>Provincial mean values are those assumed for each crop in each province for subsequent calculations (see [Table 4](#)).

**Table 3.** Estimated carbon fixed as chicken liveweight or egg biomass in Alberta and Ontario (Canada) in 2018.

Province/commodity	Production <sup>1</sup> in 2018, kg	Protein content <sup>2</sup> , g/kg	C content of protein <sup>3</sup> , %	Fat content <sup>2</sup> , g/kg	C content of fat <sup>4</sup> , %	C content fixed as egg/chicken biomass <sup>5</sup> , T CO <sub>2</sub> eq
Alberta						
Chicken	161,083,352	176	45.5	90.0	76.1	87,628
Eggs	47,234,890	105	45.4	89.0	76.2	19,982
Ontario						
Chicken	576,690,494	177	45.5	91.0	76.1	316,411
Eggs	191,966,332	105	45.4	89.0	76.2	81,208

<sup>1</sup>From Table 1. One dozen eggs assumed weight of 714 g.

<sup>2</sup>Derived from Health Canada (2015b,c).

<sup>3</sup>Based on standard amino acid profile (Health Canada, 2015b,c) and proportional C content of constituent amino acids.

<sup>4</sup>Based on standard fatty acid profile (Health Canada, 2015a,c) and proportional C content of constituent fatty acids.

<sup>5</sup>C converted to CO<sub>2</sub> basis by dividing by 0.273 (CO<sub>2</sub> is 27.3% C by weight).

agricultural and nonagricultural biomass such as those reported by Jenkins et al. (1998), Demirbas (2004), Vassilev et al. (2010), Clark and Preto (2011), Parmar (2017), and Ma et al. (2018). The production tonnage of aboveground and belowground, nongrain residue was estimated for each crop based on the yield ratios of each residue type to grain reported for Canadian-grown crops calculated from Thiagarajan et al. (2018).

Because chicken meat and eggs have a relatively short shelf-life and are highly digestible foodstuffs, it was not appropriate to consider chicken or egg biomass as medium- or long-term storage forms of C. The calculated C mass (CO<sub>2</sub> equivalent basis) fixed as chicken liveweight and eggs is therefore reported (Table 2) but is excluded from the overall C balance calculation for the crop–chicken system.

The calculated C content of broiler chicken biomass is based on average market liveweights of 2.25 kg/bird and 2.44 kg/bird in Alberta and Ontario respectively, which were derived from market statistics (Agriculture and Agri-Food Canada, 2019). Values for the amount of protein and fat per chicken marketed in each province were then calculated from empirically derived Gompertz models reported for broiler chickens by Caldas et al. (2019). The estimated protein and fat contents for the assumed market liveweights were 176 g protein/kg BW and 90 g fat/kg BW for Alberta and 177 g protein/kg BW and 91 g fat/kg BW for Ontario (Table 2). The C content of body protein was assumed to be 45.5% C by weight, based on a standard amino acid profile of chicken meat (Health Canada, 2015a) and the relative C content in each constituent amino acid. Likewise, the C content of fat was assumed to be 76.1% by weight, based on a standard fatty acid profile of poultry fat (Health Canada, 2015b) multiplied by the proportional C content in each constituent fatty acid. The resulting calculated C content in each kg of liveweight was 0.549 kg CO<sub>2</sub> eq for Ontario and 0.544 kg CO<sub>2</sub> eq for Alberta.

The C content of egg (0.423 kg CO<sub>2</sub> eq/kg egg mass) was calculated likewise, from the standard protein (105 g/kg egg mass) and fat (89 g/kg egg mass) content reported for a single large egg, corrected for C content of the constituent amino acids and fatty acids according to reported profiles (Health Canada, 2015c).

All C content parameters were converted to a CO<sub>2</sub> equivalency by correcting total C content for the relative contribution of C to the molecular weight of CO<sub>2</sub> (27.3%).

## RESULTS AND DISCUSSION

In 2018, Alberta ranked second among the Canadian provinces in the production of wheat, whereas ranking fourth and fifth (out of 10) for production of chicken meat and eggs, respectively (Table 1). In comparison, Ontario was the largest producer of corn, chicken meat, and eggs in Canada in 2018. The slightly greater average weight (and therefore estimated protein and fat content) of chickens at marketing resulted in the average chicken produced in Ontario containing a slightly greater amount of fixed C compared to chickens from Alberta (Table 3). The distribution of egg weights across Grade A weight classes were nearly identical in each province, resulting in identical C fixed per unit of egg mass.

Despite higher direct energy and fertilizer-associated GHG footprints for Alberta wheat, Ontario corn had a greater GHG-footprint per T of grain produced (Table 2). This finding is largely because of the losses in soil organic C per T of corn grain production, which are not mirrored in Alberta wheat grain production because of widespread adoption of conservation tillage and zero-till management of annual crop acreage in Western Canada (Agriculture and Agri-Food Canada, 2016).

More than 8.7 million T of grain was produced in each province in 2018 (Table 4). The aboveground and belowground residue to grain ratios reported by Thiagarajan et al. (2018) for these crops suggest that in the process, a combined 30 million T of nongrain crop biomass were produced in the 2018 crop year. Annual statistics are not routinely kept for the production of residue biomass, as its local economic value (e.g., straw for bedding) often determines whether producers collect it or simply spread it back onto crop acreage. The range of allocation coefficients for wheat and corn grain in Bolinder et al. (2007) suggests that between 27 and 68 of total crop biomass is returned to the soil, depending on the extent to which residues are harvested or



**Table 4.** Estimated net carbon balance (T of CO<sub>2</sub> eq) of integrated crop–poultry production systems in Alberta and Ontario (Canada) in 2018.

Parameter	Alberta	Ontario
Crop system parameters, 2018	Wheat	Corn
Production <sup>1</sup> , T grain	8,771,600	8,767,900
Aboveground residue:grain yield <sup>2</sup>	1.48	1.05
Belowground residue:grain yield <sup>2</sup>	0.58	0.51
Aboveground residue biomass production <sup>3</sup> , T	12,981,968	9,206,295
Belowground residue biomass production <sup>3</sup> , T	5,087,528	4,471,629
Carbon fixed <sup>4</sup> , T CO <sub>2</sub> eq		
As grain	14,458,681	14,452,582
As aboveground residues	21,398,848	15,175,212
As belowground residues	8,386,035	7,370,817
Total crop biomass fixation	44,243,564	36,998,611
GHG emissions		
GHG footprint <sup>5</sup> , T CO <sub>2</sub> eq/T grain	0.3473	0.3748
Total GHG footprint, T CO <sub>2</sub> eq	−3,046,377	−3,286,209
Net crop system C balance <sup>6</sup> , T CO <sub>2</sub> eq	41,197,187	33,712,402
Poultry system parameters, 2018		
Chicken		
Production <sup>1</sup> , kg liveweight	161,083,352	576,690,494
GHG footprint <sup>7</sup> , kg CO <sub>2</sub> eq/kg liveweight	2.40	2.40
Net chicken system GHG footprint <sup>6</sup> , T CO <sub>2</sub> eq	−386,600	−1,384,057
Eggs		
Production <sup>1</sup> , dozen L eggs	66,155,309	268,860,409
GHG footprint <sup>7</sup> , kg CO <sub>2</sub> eq/dozen L eggs	1.73	1.73
Net egg system GHG footprint <sup>6</sup> , T CO <sub>2</sub> eq	−114,449	−465,129
Net poultry system C balance <sup>8</sup> , T CO <sub>2</sub> eq	−501,049	−1,849,186
Overall crop–poultry system C balance <sup>9</sup> , T CO <sub>2</sub> eq	40,696,138	35,149,425

Abbreviations: GHG, greenhouse gases.

<sup>1</sup>From Table 1.

<sup>2</sup>Source: Table 2 in Thiagarajan et al., 2018.

<sup>3</sup>Estimated residue biomass production = grain production × residue:grain yield ratio.

<sup>4</sup>Carbon fixed = (Tonnage × 0.45)/0.273.

<sup>5</sup>From Table 2.

<sup>6</sup>Positive value indicates net CO<sub>2</sub> fixation as biomass, negative value indicates net GHG emissions (as CO<sub>2</sub> equivalents).

<sup>7</sup>Sources: Chicken Farmers of Canada, 2019, and Pelletier, 2017.

<sup>8</sup>Negative value indicates net emissions of GHG. Sum of total GHG footprint of chicken and egg production.

<sup>9</sup>Sum of net crop system C balance and net poultry system C balance. Positive value indicates net CO<sub>2</sub> fixation by the overall crop–poultry system.

removed. In the context of determining real-world C fluxes therefore, the inclusion of nongrain residues in calculations is integral, as they accounted for nearly two-thirds of crop biomass produced in 2018.

Assuming that biomass contains 45% C, the calculations summarized in Table 4 reveal that for each T of GHG (in CO<sub>2</sub> equivalents) emitted in the production of these 2 crops in 2018, 14.5 and 11.3 T of CO<sub>2</sub> was fixed from the atmosphere as Alberta wheat and Ontario corn biomass, respectively. When the net GHG footprint of poultry production is included to form the integrated crop–poultry system in each province, the footprint of total poultry production is offset by the net CO<sub>2</sub> fixation of the respective crops by factors of 82.2 and 18.2 in Alberta and Ontario, respectively. Put differently, the calculated total GHG footprint of poultry production in Alberta and Ontario corresponds to only 1.2 and 5.5% of the calculated total net CO<sub>2</sub> fixation of their respective cropping systems.

An obvious critique of the calculations herein is that a substantial portion of the calculated mass of CO<sub>2</sub> removed from the atmosphere by crops in 1 yr would return thereto within a 12-month period by way of consumption and subsequent decomposition. It would be more appropriate therefore to view the calculated net

CO<sub>2</sub> fixed as crop biomass as the initial condition for these integrated systems rather than the final balance. The natural decomposition rate of aboveground residues, if left unincorporated on the soil surface (as in reduced tillage systems), would however be expected to be very low, as the C:nitrogen (N) ratio therein is much higher than is regarded as optimal for decomposer organisms (Aulakh et al., 1991; Hadas et al., 2004). A portion of the C in consumed grain too would persist postconsumption in the form of digestion-resistant fiber in manure and sewage sludge, whose postapplication decomposition rate in the field would be affected by several factors, including C:N ratio (NRCS, 2011), temperature (Pratt et al., 2002), moisture conditions (Murwira et al., 1990), and aeration (Kulcu and Yaldiz, 2004). A lack of precise, high-resolution data on the fate and disposition of exported grain and life cycle duration of postharvest grain and residue biomass therefore is the largest source of uncertainty in the real-world C accounting for these exemplar integrated systems.

The authors do not propose that all or even a majority of the CO<sub>2</sub> fixed by the crop component of these systems would persist beyond a 12-month period (beyond the succeeding harvest), therefore serving as a C sink. The calculations herein, however, indicate that only a small

percentage (<6%) of the total C fixed as crop–poultry system biomass would need to persist intact beyond a 12-month period to achieve C neutrality on an annual basis for the integrated crop–poultry systems in both jurisdictions. The current state of knowledge regarding C turnover processes in natural and managed ecosystems (Brady and Weil, 2017), along with what is known about farm-level management practices and grain supply and disposition, suggests that total biomass carryover beyond 12-months in excess of 6% is highly probably. What is more certain is that the presumption of no net CO<sub>2</sub> fixation in the form of grain or crop residue (i.e., all fixed CO<sub>2</sub> is returned to the atmosphere annually), implicit in most LCA models of conventional crop production, is a statistical impossibility. The authors propose that the burden of proving otherwise lies with proponents of the latter assumption rather than the former, particularly in light of the findings in Fan et al. (2019).

The relative contribution of feed to the overall GHG footprint of poultry production reported in the literature varies widely. Feed has been reported to constitute anywhere from 32% (Courchesne and Jamaron, 2014) to 93.7% (Skunca et al., 2015) of the total GHG footprint of chicken meat. Relevant estimates for egg production are somewhat less variable, with values ranging from 65% (Courchesne et al., 2014) to 70% (Pelletier, 2017), though few other LCA described in the literature report the relative contribution of feed to total GHG footprint of eggs. Where most LCA studies agree is that more than 90% of the GHG footprint of feed is directly attributable to the GHG footprint of the principal feed ingredients, with only minor contributions from processing and transport. For a proper accounting of C flux in the crop–poultry system, the contribution of crop-derived feedstuffs to the overall GHG footprint of chicken live-weight and eggs should therefore be removed, as the GHG footprint of the feed crops is already counted in the net balance calculation for the cropping component of the integrated system. Because of the wide range of estimates for the relative contribution of feed along with uncertainty over actual usage of wheat and corn in poultry diets, the authors chose to not correct for the contribution of feed to the overall GHG footprint for chicken liveweight and eggs used in the calculations. Owing to the large margin between CO<sub>2</sub> fixation and GHG emissions (widely favoring the former) in the integrated crop–poultry system however, this correction or lack thereof would have had little effect on the ultimate outcome of these calculations.

## CONCLUSION

In conclusion, the current public concern around GHG emissions mitigation has placed increased scrutiny on all large-scale human activities and their impact on the environment. The boundaries that have been used by LCA models of agricultural commodities appear to be at odds with the symbiotic co-existence and complementarity characteristic of modern livestock and crop

production. Further, by failing to acknowledge real world estimates of C fixation by crop biomass, GHG foot-printing exercises run the risk of misrepresenting reality. Because GHG foot-printing is increasingly finding its way into public discourse around climate change policy, exclusion of C fixation perpetuates a faulty assumption that agriculture (and more specifically, animal agriculture) is a net contributor to the problem of GHG emissions, rather than part of a combined solution.

While the calculations presented herein are relatively simplistic, the authors propose that they provide sufficient grounds to postulate the hypothesis that modern, integrated crop–livestock agricultural systems in Canada (and elsewhere) act as net sinks for atmospheric CO<sub>2</sub>. The authors encourage further discussion and research into this specific question and a more vigorous, balanced, and holistic assessment of the net environmental impact of poultry and livestock production as they pertain to ongoing climate change policy discussions.

## ACKNOWLEDGMENTS

The authors would like to thank our colleagues at Alberta Agriculture and Forestry who reviewed our calculations, assumptions, and provided input to improve this manuscript.

Conflict of Interest Statement: The authors did not provide a conflict of interest statement.

## REFERENCES

- Agriculture and Agri-Food Canada. 2016. Soil organic matter indicator. Accessed Sept. 2019. <http://www.agr.gc.ca/eng/science-and-innovation/agricultural-practices/soil-and-land/soil-organic-matter-indicator/?id=1462905651688>.
- Agriculture and Agri-Food Canada. 2019. Poultry production by month/year (Report 036). Accessed Sept. 2019. <http://www.agr.gc.ca/eng/industry-markets-and-trade/canadian-agri-food-sector-intelligence/poultry-and-eggs/poultry-and-egg-market-information/production/?id1384971854421#poultry>.
- Aulakh, M. S., D. T. Walters, J. W. Doran, D. D. Francis, and A. R. Mosier. 1991. Crop residue type and placement effects on denitrification and mineralization. *Soil Sci. Soc. Am. J.* 55:1020–1025.
- Bolinder, M. A., H. H. Janzen, E. G. Gregorich, D. A. Angers, and A. J. VandenBygaart. 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agr. Ecosyst. Environ.* 118:29–42.
- Brady, N. C., and R. R. Weil. 2017. *The Nature and Properties of Soils*, 15<sup>th</sup> ed. Pearson Education, Columbus, OH, USA.
- Caldas, J. V., N. Boonsinchai, J. Wang, J. A. England, and C. N. Coon. 2019. The dynamics of body composition and body energy content in broilers. *Poult. Sci.* 98:866–877.
- Canadian Roundtable for Sustainable Crops (CRSC). 2019. Carbon Lifecycles for Ten Major Field Crops in Canada, 2017. Data exhibits. Accessed Sept. 2019. <http://metrics.sustainablecrops.ca/home/datacollection/3>.
- Canola Council of Canada. 2019. Canadian canola meal supply and disposition. Accessed Sept. 2019. <https://www.canolacouncil.org/markets-stats/statistics/meal-supply-and-disposition/>.
- Chicken Farmers of Canada. 2019. Sustainability assessment of the Canadian chicken value chain. Accessed Sept. 2019. [https://www.chickenfarmers.ca/wp-content/uploads/2018/08/CFC\\_ENG\\_F\\_Simple.pdf](https://www.chickenfarmers.ca/wp-content/uploads/2018/08/CFC_ENG_F_Simple.pdf).
- Clarke, S., and F. Preto. 2011. Biomass burn characteristics (Agdex 737/120). Ontario Ministry of agriculture, food and Rural Affairs. Accessed Sept. 2019. <http://www.omafra.gov.on.ca/english/engineer/facts/11-033.pdf>.

- Courchesne, A., A. Surveyer, and E. Jamaron. 2014. Life Cycle Assessment of Egg Production in Alberta. Quantis, Canada, p. 152.
- Courchesne, A., and E. Jamaron. 2014. Life Cycle Assessment of Broiler Chicken Production in Alberta. Quantis, Canada, p. 141.
- De Vries, M., and I. J. M. de Boer. 2010. Comparing environmental impacts for livestock products: a review of life cycle assessments. *Livest. Sci.* 128:1–11.
- Demirbas, A. 2004. Combustion characteristics of different biomass fuels. *Progress in Energy, Combust* 30:219–230.
- Egg farmers of Canada. 2019. Canadian egg production. Accessed Sept. 2019. <https://www.eggfarmers.ca/market-information-tables/#tableau-3>.
- Environment and Climate Change Canada. 2019. National inventory report 1990-2017: greenhouse gas sources and sinks: executive summary. Accessed Sept. 2019. [http://publications.gc.ca/collections/collection\\_2019/eccc/En81-4-1-2017-eng.pdf](http://publications.gc.ca/collections/collection_2019/eccc/En81-4-1-2017-eng.pdf).
- Fan, J., B. G. McConkey, B. C. Liang, D. A. Angers, H. H. Janzen, R. Kröbel, D. D. Cerkowski, and W. N. Smith. 2019. Increasing crop yields and root input make Canadian farmland a large carbon sink. *Geoderma*. 336:49–58.
- Hadas, A., L. Kautsky, M. Goek, and E. E. Kara. 2004. Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover. *Soil Biol. Biochem.* 36:255–266.
- Health Canada. 2015a. The Canadian Nutrient File - animal fat, chicken (food code: 445). Accessed Sept. 2019. <https://food-nutrition.canada.ca/cnf-fce/serving-portion.do?id=445>.
- Health Canada. 2015b. The Canadian Nutrient File - Skinless boneless chicken breast (food code: 841). Accessed Sept. 2019. <https://food-nutrition.canada.ca/cnf-fce/serving-portion.do?id=841>.
- Health Canada. 2015c. The Canadian Nutrient File - Whole chicken egg (food code: 125). Accessed Sept. 2019. <https://food-nutrition.canada.ca/cnf-fce/serving-portion.do?id=125>.
- Herrero, M., P. Gerber, T. Vellinga, T. Garnett, A. Leip, C. Opio, H. J. Westhoek, P. K. Thornton, J. Olesen, N. Hutchings, H. Montgomery, J.-F. Soussana, H. Steinfeld, and T. A. McAllister. 2011. Livestock and greenhouse gas emissions: the importance of getting the numbers right. *Anim. Feed. Sci. Tech.* 166–167:779–782.
- Horne, R., T. Grant, and K. Verghese. 2009. Life Cycle Assessment: Origins, Principles and Context. CSIRO Publishing, Collingwood, Australia.
- International Standards Organization. 2006. Environmental management – life cycle assessment – principles and framework. Pages 20 in ISO Standard 14040:2006. Accessed Sept. 2019. <https://www.iso.org/standard/37456.html>.
- Jenkins, B. M., L. L. Baxter, T.R. Miles, Jr, and T. R. Miles. 1998. Combustion properties of biomass. *Fuel Process. Technol.* 54:17–46.
- Kulcu, R., and O. Yaldiz. 2004. Determination of aeration rate and kinetics of composting some agricultural wastes. *Bioresour. Technol.* 93:49–57.
- Kurz, W. A., C. H. Shaw, C. Boisvenue, G. Stinson, J. Metsaranta, D. Leckie, A. Dyk, C. Smyth, and E. T. Neilson. 2014. Carbon in Canada's boreal forest – a synthesis. *Environ. Rev.* 21:260–292.
- Lachapelle, J. M. 2014. Overview of livestock farm operating expenses. Statistics Canada - Catalogue no. 96-325-X. Accessed Sept. 2019. <https://www150.statcan.gc.ca/n1/en/pub/96-325-x/2014001/article/14084-eng.pdf?st=VdKdwwdG>.
- Lopez-Andres, J. J., A. A. Aguilar-Lasserre, L. F. Morales-Mendoza, C. Azzaro-Pantel, J. R. Perez-Gallardo, and J. O. Rico-Contreras. 2018. Environmental impact assessment of chicken meat production via an integrated methodology based on LCA, simulation and genetic algorithms. *J. Clean. Prod.* 174:477–491.
- Ma, S., F. He, D. Tian, D. Zou, Z. Yan, Y. Yang, T. Zhou, K. Huang, H. Shen, and J. Fang. 2018. Variations and determinants of carbon content in plants: a global synthesis. *Biogeosciences* 15:693–702.
- Murwira, H. K., H. Kirchmann, and M. J. Swift. 1990. The effect of moisture on the decomposition rate of cattle manure. *Plant Soil* 122:197–199.
- Natural Resources Conservation Service (NRCS). 2011. Carbon to nitrogen ratios in cropping systems. Accessed Sept. 2019. [https://www.nrcs.usda.gov/Internet/FSE\\_DOCUMENTS/nrcseprd331820.pdf](https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd331820.pdf).
- Notarnicola, B., S. Sala, A. Anton, S. J. McLaren, E. Saouter, and U. Sonesson. 2017. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. *J. Clean. Prod.* 140:399–409.
- Parnar, K. 2017. Biomass: an overview on composition characteristics and properties. *Ira-int. J. Appl. Sci.* 7:42–51.
- Pelletier, N. 2017. Life cycle assessment of Canadian egg products, with differentiation by hen housing system type. *J. Clean. Prod.* 152:167–180.
- Pratt, E. V., S. P. Rose, and A. A. Keeling. 2002. Effect of ambient temperature on losses of volatile nitrogen compounds from stored laying hen manure. *Bioresour. Technol.* 84:203–205.
- Sauer, T. J., K. VanDevender, C. V. Maxwell, M. B. Daniels, A. N. Sharpley, S. E. Watkins, J. L. Hatfield, C. P. West, and K. P. Coffey. 2000. Phosphorus balance model to predict land base requirements for sustainable broiler feeding operations. Pages 401–407 in *Animal, Agricultural and Food Processing Wastes*. Proceedings of the Eighth International Symposium, Des Moines, J. A. Moore ed. Iowa, USA, 9-11 October, 2000.
- Skunca, D., I. Tomasevic, and I. Djekic. 2015. Environmental performance of the poultry meat chain – LCA approach. *Proced. Food Sci.* 5:258–261.
- Statistics Canada. 2019a. Farms classified by farm type, historical data (Table 32-10-0166-01). Accessed Sept. 2019. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210016601>.
- Statistics Canada. 2019b. Supply and disposition of grains in Canada (Table 32-10-0013-01). Accessed Sept. 2019. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210001301>.
- Statistics Canada. 2019c. Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units (Table 32-10-0359-01). Accessed Sept. 2019. <https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210035901>.
- Statistics Canada. 2019d. Production and disposition of eggs, annual (Table 32-10-0119-01). Accessed Sept. 2019. <https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210011901>.
- Thiagarajan, A., J. Fan, B. G. McConkey, H. H. Janzen, and C. A. Campbell. 2018. Dry matter partitioning and residue N content for 11 major field crops in Canada adjusted for rooting depth and yield. *Can. J. Soil Sci.* 98:574–579.
- van Hal, O., A. A. A. Weijenberg, I. J. M. de Boer, and H. H. E. van Zanten. 2019. Accounting for feed-food competition in environmental impact assessment: towards a resource efficient food-system. *J. Clean. Prod.* 240:118241.
- Vassilev, S. V., D. Baxter, L. K. Andersen, and C. G. Vassileva. 2010. An overview of the chemical composition of biomass. *Fuel* 89:913–933.
- Wang, J., Q. Liu, Y. Hou, W. Qin, J. P. Lesschen, F. Zhang, and O. Oenema. 2018. International trade of animal feed: its relationships with livestock density and N and P balances at country level. *Nutr. Cycl. Agroecosy.* 110:197–211.