Highlights of Sustainability

Short Note

The GHG Protein Ratio: An Indicator Whose Time Has Come

James A. Dyer [1,†,*] and **Raymond L. Desjardins** [2,†]

[1] Ag-environmental Consultant, 122 Hexam Street, Cambridge, ON N3H 3Z9, Canada; E-Mail: jamesdyer@sympatico.ca

[2] Science and Technology Branch, Agriculture and Agri-Food Canada, 960 Carling Avenue, Ottawa, ON K1A 0C6, Canada; E-Mail: ray.desjardins@agr.gc.ca

† These authors contributed equally to this work.

* For correspondence.

Abstract The Carbon Footprint (CF) of agriculture must be substantially reduced to help avoid catastrophic climate change. This paper examines the ratio of Greenhouse Gas (GHG) emissions to protein as an indicator of the CF of the major Canadian livestock commodities using previously published results. The GHG emissions for these commodities were estimated with a spreadsheet model that accounted for all three GHGs, the complete life cycles of each livestock type and the livestock interactions with the agricultural land base. The indicator results reviewed here included the responses to livestock types and diets, livestock versus plant protein sources, spatial scales and geographic differences. The sensitivity of the results shown suggest that GHG-protein ratios could provide valuable guidance for producers and consumers to reduce their GHG emissions. For example, diverting feed grains from beef feedlots to hog production would substantially reduce the CF of red meat, although still not as low as the CF of poultry products. The complete proteins derived from pulses have much lower CF values than all livestock products.

Keywords protein; red meat; beef; pork; broilers; pulses; carbon footprints; greenhouse gas; land use

1. Introduction

This paper proposes that the ratio of Greenhouse Gas (GHG) emissions per unit of protein is a highly suitable indicator to assess the Carbon Footprint (CF) of livestock production. The need for animal-equivalent (complete) protein in the human diet [1,2] is the most important reason for livestock agriculture. Population growth and rising per capita consumption will increase the global demand for livestock products [3–5]. However, avoiding catastrophic climate change will require a major reduction of the CF of all sectors, including agriculture [6].

Protein has been used as a basis for assessing the livestock CF in many countries [7–11], including Canada [3]. This indicator only concerns complete protein. It does not consider the possibility that over-dependence on plant protein sources may not provide adequate concentrations of micronutrients compared to meat, or that some animals may be a better source of these micronutrients than others. The growing public awareness that livestock products are a major GHG source [5,12,13] is an added incentive to apply this indicator. The goal of this paper is to provide examples of how this indicator can reflect the variability associated with livestock production and land use.

While exploring livestock CF estimates was not the goal of this paper, appreciable differences in these estimates can be seen in the range of reported GHG-protein ratios [6–10]. This diversity is largely due to the need to adapt IPCC methodology to specific regional or country conditions. Therefore, differences in GHG emission intensities for the same livestock types should be expected. Most GHG emission estimates, however, share a common set of parameters to quantify all three livestock GHGs. They attribute CH_4 emissions to manure management and enteric emissions from ruminants; N_2O to both fertilizer application and manure storage; and CO_2 emissions to the sector's reliance on fossil fuels and soil-atmosphere exchanges.

In 2017, Canada produced 2.5 Mt of beef, 2.8 Mt of pork and 1.3 Mt of chicken (broilers), whereas Canadians consumed 1.5, 1.0 and 1.7 Mt of those three commodities in 2017 [14]. Due to the sheep industry in Canada being less than 4% of the size of the Canadian beef industry, the

Open Access

Received: 16 February 2022
Accepted: 30 May 2022
Published: 2 June 2022

Academic Editor
Carlos Parra-López, Institute of Agricultural and Fisheries Research and Training (IFAPA), Spain

sheep industry was ignored in the livestock comparisons shown in this paper. Goat production is even smaller in Canada. However, the GHG emission intensity of lamb is much higher than that of beef [9,15]. Canadian farmers produced 15.5 Mt of pulses in 2016, of which 6.6 Mt were soybeans and 4.8 Mt were dry peas [16]. Apart from soy oil, there are no Canadian data to suggest that either crop is used for anything but livestock feed. A precise figure for domestic consumption of edible pulses was not available.

2. Materials and Methods

The examples used to satisfy the goal of this paper were extracted from published Canadian applications of the GHG-protein indicator. Details of the development and application of the indicator, and the conclusions reached are described in the papers from which these results were extracted [3,14–21].

2.1. Protein as a Unifying CF Metric

The original intent of this work was to compare the CF of Canadian livestock industries [3] and plant products capable of providing animal equivalent proteins (i.e., pulses) [18]. While pulse crops can provide complete protein, not all commercial products derived from those crops will contain the required quantities of all the essential amino acids [22]. This early work demonstrated that the GHG-protein indicator was the most objective way to compare carcass to non-carcass (milk and eggs) livestock products [3]. As well, protein was shown to be a better measure of the value of meat to the human diet than live weight [21], and an important sustainability metric [17,20,21]. Because they provide complete protein, livestock products are not comparable to other food products solely on the basis of their bulk weight. The minimum human requirement for complete protein has proven to be an important boundary condition for optimizing livestock production to minimize GHG emissions [14,20].

2.2. Livestock GHG Emissions

In Canada, the GHG-protein indicator used livestock GHG emission estimates from Vergé et al. [23–26], which were obtained by using the Unified Livestock Industry and Crop Emissions Estimation System (ULICEES) [27]. Coupled with these published estimates, the GHG-protein indicator has a broad scientific basis, with all three GHGs and the complete life cycles of each livestock type being accounted for. Because ULICEES was designed to apply a common GHG emissions assessment methodology to all of Canada's major livestock types [23–27], it was also used to quantify the effect of livestock interactions on the agricultural land base [15,27,28] and allowed the trade-offs between annual and perennial feed crops to be factored into ruminant versus non-ruminant comparisons [28]. The GHG-protein indicator can be calculated by the ratio of all GHG emissions associated with the production of a product over the weight of protein derived from that product. These calculations used commonly available crop and livestock statistics and were applied to a range of spatial scales, and are sensitive to a wide range of farm input and management decisions within the farm gate [19,27]. Protein contents for plant and animal products were summarized by Dyer and Vergé [18].

2.3. GHG-protein Indicator Applications

The inter-commodity comparisons with this indicator have already shown promise to strengthen Canadian agricultural policy decisions related to mitigating GHG emissions. The indicator has also shown the potential role that consumers can play in lowering the CF of Canadian agriculture if they embrace the advice derived from the 2019 Canada Food Guide to diversify protein sources [14,17–21,29].

Including the soil carbon storage differences between perennial and annual crops [30] provided a more complete accounting of the respective CF of ruminant and non-ruminant livestock [17]. The most recent version of the GHG-protein indicator, which includes the upgrade for soil carbon sequestration, still leaves beef with a higher CF than pork [17]. This indicator application demonstrated that most of the land credited with sequestering soil carbon due to beef production would not be required to produce the same amount of protein from the pork industry [17,20]. While not needing any perennial forage, Dyer et al. [17] showed that hogs required roughly the same areas of land to grow their feed grains, thus freeing harvestable forage areas for other uses, or to be rewilded (taken out of production). These results stem from hogs being a more efficient protein source than beef cattle [3,17].

Largely due to enteric methane emissions, beef production has been singled out by environmentalists as not being sustainable [31,32]. Due to its extensive need for arable land [14], beef production is not capable of the expansion needed to meet the growing global demand for protein, although it will continue to play an important role in lower quality land use [17,33] because ruminants are the only way to convert cellulose into protein for humans [33]. As policy makers look beyond warm-blooded animals as a means of protein supply [30,34], the GHG-protein indicator should provide critical guidance. For example, including pulses in the inter-commodity comparisons resulted in a GHG-protein ratio for edible protein that was far lower than the GHG-protein ratio of livestock products alone [15]. The GHG-protein ratio for pulses is considerably lower than for broilers whose GHG-protein ratio was the lowest of any of the common Canadian livestock products [3].

3. Results and Discussion

A selection of results from the application of the GHG-protein indicator in Canada is provided here to demonstrate the range and sensitivity of this indicator. Dyer et al. [3] showed that the GHG-protein indicator was applicable to non-carcass products such as milk and egg production as long as their protein contents can be defined. But because carcass commodities (beef, pork and broilers) compete to be the main ingredient of the main meal of the day, they interact in a zero-sum game for consumer preference in a way the milk and eggs do not. Consequently, the carcass commodities provided the most effective demonstration of this indicator [14].

These results included the indicator responses to livestock types, ruminant versus non-ruminant livestock, spatial units and scales, livestock versus plant protein, and protein as a boundary condition. The discussion of these sample results is not intended to provide the same level of policy guidance as the conclusions described in the source papers. Nonetheless, these results illustrate that considerable progress has already been achieved in Canada in applying the GHG-protein indicator.

3.1. GHG-protein Ratio Comparisons

The GHG-protein ratios from other counties [7–10] along with the ratios for Canada are shown in Table 1 for beef, pork and chicken (broilers). Regardless of their regional differences, all livestock CFs shown in Table 1 rated the GHG emission intensity of intensively produced beef as roughly three to four times as high as that of pork, and the GHG emission intensity of chicken as slightly more than half that of pork. Nijdam et al. [9] also demonstrated that differences in production intensity result in a wide CF range for beef. The diversity of ratios that Nijdam et al. [9] reported from other literature sources are represented as a separate pair of range values in Table 1 for intensive and extensive beef production systems. The low ratios in Table 1 for Canadian pork and broilers (chicken) reflect their intensive production in Canada compared to many other countries. While the GHG estimates in Table 1 vary in magnitude, the applicability of the GHG-protein ratios is essentially the same as demonstrated in this paper.

Table 1. Ratios of GHG emissions to protein from Canada and other global regions and literature sources for four livestock types.

Literature Sources	**Beef Intensive** [1]	**Beef Extensive** [1]	**Pork**	**Chicken** [3]
	kg CO_2e/kg protein			
De Vries and de Boer, 2010 [7]	133	–	38	21
González et al, 2011 [8]	141	–	40	26
Nijdam et al, 2012 [9] [2]	125	300	37	20
Vauterin et al, 2021 [10]	–	–	–	19
Dyer and Desjardins, 2021 [17]	126	152	22	14
Upper range [2] +	66%	80%	49%	50%
Lower range [2] −	64%	82%	46%	50%

[1] Separate ratios for intensive and extensive beef reported by two sources.

[2] Included range values of ratios extracted from the literature.

[3] Chickens raised for meat are called broilers in Canada.

3.2. Sample Output from GHG-protein Indicator in Canada

The GHG-protein indicator results in Table 2 show the differences among livestock types in Canada [3,14,17]. The estimates for beef were separated by the two diets of the animals destined for market: that is Business as Usual (BAU) and Grass Fed (GF). In contrast to GF beef, BAU in Canada refers to finishing cattle for market that have spent their first year on pasture with the breeding herd [24]. The finishing is done in large concentrated feedlots where their diets include high rations of feed grains for rapid weight gain. For both GF and BAU the breeding cows and the replacement heifers are kept on ranches on a diet based on grazing and hay.

The GF cattle in this analysis were considered to be the slaughter cattle fed a diet similar to the replacement heifers for breeding cattle [14], which is almost entirely grazing and hay [17]. Without hay, a GF diet is not possible, due to Canada's cold winters. The Canadian GF diet is roughly equivalent to the lower values presented by Nijdam et al. [9] for extensive production systems for beef, although the latter values [9] include a wide range of land use, animal husbandry practices and cattle genetics. Although smaller than the beef diet difference reported by Nijdam et al. [9] in Table 1, the 21% increase in the GHG emissions per unit of protein due to the GF beef diet over BAU beef was consistent with the range in feed conversion ratios reported for Canada by Byrne [17,35]. The indicator estimates for BAU and GF beef were four and five times as high, respectively, as for dairy. The next two highest emitting protein sources were pork and poultry, with broilers as the lowest.

Table 2. The GHG-protein indicator differences among livestock types, beef diets, and carcass and non-carcass products for Canada.

Livestock Type	**Beef BAU**	**Beef GF**	**Dairy**	**Pork**	**Poultry Broilers**	**Poultry Eggs**
	tCO_2e/t(protein)					
GHG/protein	126	152	32	22	14	22
Extracted from	[a]	[a]	[b]	[a]	[a]	[b]
Year of estimate	2006	2006	2001	2006	2006	2001

BAU = business as usual for finishing slaughter cattle.
GF = grass fed slaughter cattle.
Sources: a = Table 2, Dyer and Desjardins [17]; b = Table 3, Dyer et al. [3].

Table 3 shows the differences in the GHG-protein indicator among provinces [15]. This application required that all sources of complete (animal equivalent) proteins be integrated into one indicator estimate per province. This included integrating the GHG emissions from all livestock protein sources (beef, dairy, sheep, pork, layers and broilers) and Canada's major pulse crops (Dry peas, Soybeans, Lentils, Chickpeas, White beans and Coloured beans), and dividing the total GHG emissions by the total protein derived from all those products in each province. With Alberta being the home for half of Canada's beef industry, its indicator estimate was almost twice as high as the indicator estimates for the coastal provinces, Atlantic and BC. Ontario had the lowest indicator estimate. This application also demonstrated the importance of protein as a common denominator for a wide range of agricultural commodities [3].

Table 3. Demonstrating the GHG-protein indicator differences among provinces where protein is the sum of all livestock and pulse proteins for Canada in 2006.

Provinces	**AP**	**QC**	**ON**	**MN**	**SA**	**AB**	**BC**
	tCO_2e/t(protein)						
GHG/protein	40.4	28.6	10.5	35.2	27.9	77.6	40.3

Extracted from Table 4, Dyer and Vergé [15].
Atlantic Provinces (AP) treated as one province, QC = Quebec,
ON = Ontario, MN = Manitoba, SA = Saskatchewan, AB = Alberta,
BC = British Columbia.

Table 4 illustrates the sensitivity of the GHG-protein indicator to the spatial scale at which it is calculated [19]. After separately calculating the GHG emissions and aggregating protein at both the ecodistrict and provincial scales, the GHG-protein ratios were determined on an east-west basis. Livestock were grouped as either ruminants (Rum) or non-ruminants (Non-r). With western ruminants being dominated by beef cattle over dairy cattle, compared to the relative parity between beef and dairy cattle in the east, and the CF of beef being greater than dairy, the western Rum values had the highest emission intensities at both scales of calculation. However, the western estimates showed greater differences between the two calculation scales than did those in the east, although the scale differences were small relative to the east-west and livestock type differences.

Table 4. Comparison of the GHG-protein indicator for ruminant and non-ruminant sources of complete protein at two scales of calculation for Canada in 2006.

Ecodistricts				**Provinces**			
East		West		East		West	
Rum	Non-r	Rum	Non-r	Rum	Non-r	Rum	Non-r
tCO_2e/t(protein)							
60	18	99	19	58	19	110	22

Extracted from Table 4, Dyer et al. [18].
Rum = Ruminants, Non-r = Non-ruminants.

Table 5 compares animal and plant (pulse) protein sources [18]. As with Table 4, livestock are grouped as either ruminants or non-ruminants and the results are presented on an east-west basis. Because of their higher protein contents [18] and their use as livestock feed, Soybeans are considered separately from the other five pulses. The farm animal results in Table 5 are (after round-off) the same as the provincial estimates in Table 4. The GHG-protein ratios for pulses are one to two orders of magnitude lower than the ratios for farm animals. Also, the ratios for Soybeans are almost an order of magnitude lower than for the other pulses, which reflects their higher protein content.

The extreme difference between plant and animal protein sources is not surprising. Only a small fraction of the feed consumed by farm animals is converted to food for humans, the rest being lost to the metabolic energy needs of those warm-blooded animals. Even though plants are less protein dense sources than lean meat [3,18], they can convert a much greater share of their nutrient energy to edible tissue, including proteins. Additionally, pulses have a lower CF than other crops because they can fix nitrogen, thus eliminating most fertilizer requirements [6]. The low emission intensities for soybeans compared to other pulses is a result of the higher protein content of this crop.

Table 5. Comparison of the GHG-protein indicator for ruminant and non-ruminant livestock with two groups of plant sources of complete protein (pulses) for Canada in 2006.

Farm Animals				**Pulses**			
East		West		East		West	
Rum	Non-r	Rum	Non-r	Soybeans	Other	Soybeans	Other
tCO_2e/t(protein)							
57.77	18.79	109.83	21.97	0.28	1.98	0.42	2.46

Extracted from Table 3, Dyer and Vergé [15].
Other = other edible pulses.

3.3. Statistical Data Sources

The results shown in Tables 2–5 were, except for dairy in Table 2, all generated from 2006 inputs. Being a census year in Canada (every 5th year), 2006 (and 2001) provided population data on livestock life stages that were essential to the initial livestock GHG emissions modelling [23–27]. Since many of these population parameters were not recorded in later census years nor in the survey data gathered in the intervening years, the 2006 estimates were the latest results for this analysis. Although total breeding herd population records allow the early estimates to be extrapolated forward, such extrapolations are not as reliable as the estimates from the early census years. Also, it was useful to cite published results whose rationale and validity readers can check in those publications. However, although livestock populations ebb and flow, there is no evidence that the feed conversion efficiency of any one livestock type in Canada would have shown significantly more improvement than the efficiency of any other type of livestock [17,35]. Therefore, differences in GHG emission intensities would not have changed enough among the livestock types since 2006 to significantly affect commodity comparisons.

3.4. Protein as a Boundary Condition

Table 6 shows the total GHG emissions from meat production under four consumption scenarios. This scenario analysis [14,17,18] assessed the potential impact of reducing Red Meat (RM) consumption in Canada on the GHG budget of the Canadian meat industry. Beef, pork and broilers were used to represent carcass-based food commodities. This analysis used protein as a boundary condition, rather than as a basis for emission intensity. It assumed that any drop in RM consumption (beef and pork) would be replaced with enough broilers to maintain the 0.39 Mt of protein consumed in Canada of the Canadian production of these three commodities in 2017.

The four scenarios resulted from the interaction of two pairs of production conditions for RM. The first pair was the BAU and GF slaughter cattle diets as defined for Table 2. The second pair was two combinations of the quantities of domestically produced and consumed beef and pork. In one combination RM demand was met with equal shares of beef and pork (50/50). In the second combination RM demand was met by 25% beef and 75% pork (25/75). Dyer and Desjardins [17,21] described these interactions with a 2 by 2 matrix (not shown here) in which the two beef diets defined the columns and the two beef-to-pork ratios for RM defined the rows. Each of the four quadrants of this matrix (numbered clockwise from the upper-left) then defined a Production Scenario (PS).

Table 6. Total GHG emissions from production and consumption, and four production scenarios of beef, pork and broiler combinations for Canada in 2017.

Scenarios	**P**	**C**	**PS-1**	**PS-2**	**PS-3**	**PS-4**
Red Meat Mix	**{%beef/%pork}**		**50/50**	**50/50**	**25/75**	**25/75**
Beef diet			BAU	GF	GF	BAU
Total GHG	GHG Emissions (Tg CO$_2$e)					
	33.5	20.6	16.7	19.1	12.9	11.7
GHG decrease as % of P			%{(C-X)/P}			
			12	4	23	27

P = Production
C = Consumption (domestic)
PS = Production Scenario
X = PS-n, where n = 1 to 4
BAU = Business as Usual
GF = Grass Fed
Extracted from Tables 1 and 2, Dyer et al. [18].

Table 6 also shows the total GHG emissions from the 2017 Canadian Production (P) and Consumption (C) of the P of those three commodities. The relationships among P, C and the four scenarios are best explained by the first scenario (PS-1), which assumed a decrease in annual RM consumption in Canada to 23.7 kg Boneless Weight (BW) per person, with equal quantities of BW apportioned to beef and pork [14,17]. Canadian production of RM in 2017 was 2.59 Tg BW, of which Canadians consumed 1.16 Tg BW, or 45%. Under PS-1, RM consumption dropped to 0.87 Tg BW; that is by 25% of Canadian RM consumption, but by only 11% of Canadian RM production. This difference highlights the limited influence that a change in domestic consumption can have on the Canadian livestock industry.

The second scenario (PS-2) assumed GF beef, rather than the BAU diet. The GF-BAU diet difference assumed in this scenario analysis was similar to, but not as large as, the separation of beef industries into the range of intensive and extensive systems described by Nijdam et al. [9] (Table 1). Scenarios three (PS-3) and four (PS-4) changed RM consumption from a 50:50 BW split between beef and pork to a 25:75 beef-pork split, with a GF beef diet for PS-3 and a BAU diet for PS-4. However, PS-2, -3 and -4 all provided the same BW quantity of RM as PS-1.

The 12% drop in GHG emissions from P (Line 2) between C and PS-1 was close to the 11% drop in RM production due to PS-1. This small difference was because a bit more than half of the 25% decrease in RM consumption called for by PS-1 came from beef. Because of the higher GHG emissions from GF beef, PS-2 only decreased the GHG-protein ratio of P by 4%. PS-3 and PS-4 reduced the GHG emissions of P by 23% and 27%, respectively, due to the shift from beef to pork.

4. Summary and Conclusions

There are several general policy-relevant conclusions that can be drawn from these results. The diverse results shown in Tables 1–5 suggest that GHG-protein ratios are responsive to a wide range of factors that determine agricultural GHG emission budgets. Tables 2,4 and 5 suggest that diverting feed grains from beef feedlots to hog production would appreciably reduce the GHG emissions from RM. Table 5 showed that a plant-based diet that relies on pulses as its protein source would have a dramatically lower CF than a conventional meat-based diet. The response of Table 3 to Canada's wide range of agricultural environments demonstrates the potential value of this indicator for evaluating regional protein sources in Canada or abroad. The use of protein as a boundary condition in Table 6 facilitated the comparison of integrated livestock systems, including the role of consumers, rather than just single livestock type assessments.

One caution, however, is that the only historical trends to which the GHG-protein ratio would be applicable are of multi-livestock or multi-commodity systems, not individual livestock types. Conversely, this stability over time provided confidence in the reliance of this methodology on GHG emission intensities from 2006.

The margins by which the GHG-protein ratios of pulses, and even broilers, were exceeded by the ratios for both beef and pork highlighted the need to explore alternative protein sources that have minimal GHG emission intensities and are affordable to low-income consumers. The fact that pulse production in Canada is so small and mostly grown as animal feed or export [16] illustrates an opportunity for Canadian consumers to influence Canadian agricultural land towards more low CF crops simply by eating more beans and peas grown in Canada.

While the two terms of the GHG-protein ratio are determined by bio-physical factors, this indicator also has economic implications. Protein's essential role in human health makes the indicator relevant to the economics of poverty. Except for pastoralists, beef and dairy consumption is mostly a privilege of richer countries. At the other extreme, except for vegetarians, the populations that must satisfy most of their protein requirements from pulses live mainly in the poorest countries. Beef cattle consume land resources that could grow the grains needed for food aid and famine relief [17] or simply be rewilded. Furthermore, their disproportionate GHG emissions drive the changes in climate that have increased the risk of severe drought and famine in those poorest nations. Not only would a beef-to-pork (or to any other low-CF protein source) shift be a contribution to reducing Canada's GHG emissions budget, it would strengthen Canada's ability to contribute to global famine relief.

Funding

This research was partly funded by the Sustainability Metric project of Agriculture and Agri-Food Canada.

Data Availability

All of the data supporting the results reported in this paper were accessed from the references cited in/for each table presented in this paper.

Acknowledgments

The authors acknowledge Daniel MacDonald, Agriculture and Agri-Food Canada, Ottawa, for policy guidance and encouragement to prepare this paper.

Author Contributions

Conceptualization: J.A.D. and R.L.D.; Methodology: J.A.D.; Formal Analysis: J.A.D.; Resources, R.L.D.; Writing—original draft preparation: J.A.D.; Writing—review and editing: R.L.D.; Funding acquisition: R.L.D.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Capper, J.L.; Bauman, D.E. The role of productivity in improving the environmental sustainability of ruminant production systems. *Annu. Rev. Anim. Biosci.* **2013**, *1*, 469–489. https://doi.org/10.1146/annurev-animal-031412-103727
2. Gunnars, K. Protein Intake How Much Protein Should You Eat per Day? *Healthline Newsletter*, 1 October 2020. Available online: https://www.healthline.com/nutrition/how-much-protein-per-day (accessed 4 December 2021).
3. Dyer, J.A.; Vergé, X.P.C.; Desjardins, R.L.; Worth, D.E. The protein-based GHG emission intensity for livestock products in Canada. *J. Sustain. Agric.* **2010**, *34*, 618–629. https://doi.org/10.1080/10440046.2010.493376
4. Nardone, A.; Ronchi, B.; Lacetera, N.; Ranieri, M.S.; Bernabucci, U. Effects of climate changes on animal production and sustainability of livestock systems. *Livest. Sci.* **2010**, *130*, 57–69. https://doi.org/10.1016/j.livsci.2010.02.011
5. Willard, B. Colouring outside the lines: symbolic legitimacy for Americans. In Meatsplaining: The Animal Industry and the Rhetoric of Denial; Hannan, J., Ed.; Sydney University Press: Sydney, Australia, 2020; Chapter 5, pp. 135–161.
6. Poore, J.; Nemecek, T. Reducing food's environmental impacts through producers and consumer. *Science* **2018**, *360*, 987–992. https://doi.org/10.1126/science.aaq0216
7. De Vries, M.; de Boer, I.J.M. Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livest. Sci.* **2010**, *128*, 1–11. https://doi.org/10.1016/j.livsci.2009.11.007

8. González, A.D.; Frostell, B.; Carlsson-Kanyama, A. Protein efficiency per unit energy and per unit greenhouse gas emissions: Potential contribution of diet choices to climate change mitigation. *Food Policy* **2011**, *36*, 562–570. https://doi.org/10.1016/j.foodpol.2011.07.003
9. Nijdam, D.; Rood, T.; Westhoek, H. The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Policy* **2012**, *37*, 760–770. https://doi.org/10.1016/j.foodpol.2012.08.002
10. Vauterin, A.; Steiner, B.; Sillman, J.; Kahiluoto, H. The potential of insect protein to reduce food-based carbon footprints in Europe: the case of broiler meat production. *J. Clea. Prod.* **2021**, *320*, 128799. https://doi.org/10.1016/j.jclepro.2021.128799
11. MacLeod, M.J.; Vellinga, T.; Opio, C.; Falcucci, A.; Tempio, G.; Henderson, B.; Makkar, H.; Mottet, A.; Robinson, T.; Steinfeld, H.; et al. Invited review: A position on the Global Livestock Environmental Assessment Model (GLEAM). *Animal* **2018**, *12*, 383–397. https://doi.org/10.1017/S1751731117001847
12. Hedenus, F.; Wirsenius, S.; Johansson, D.J.A. The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Clim. Chang.* **2014**, *124*, 79–91. https://doi.org/10.1007/s10584-014-1104-5
13. Mayer, A. Meat and the Environment: Do Canadians Know What's at Stake? what on Earth? *CBC News*, 19 April 2019. Available online: https://www.cbc.ca/news/technology/what-on-earthnewsletter-e-waste-elizabeth-may-1.5104341 (accessed 4 December 2021).
14. Dyer, J.A.; Worth, D.E.; Vergé, X.P.C.; Desjardins, R.L. Impact of recommended red meat consumption in Canada on the carbon footprint of Canadian livestock production. *J. Clean. Prod.* **2020**, *266*, 121785. https://doi.org/10.1016/j.jclepro.2020.121785
15. Dyer, J.A.; Vergé, X.P.C.; Desjardins, R.L.; Worth, D.E. A comparison of the greenhouse gas emissions from the sheep industry with beef production in Canada. *Sustain. Agric. Resh.* **2014**, *3*, 65–75. https://doi.org/10.5539/sar.v3n3p65
16. Table 32-10-0359-01 Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units. Statistics Canada: Ottawa, Canada, 6 May 2022. https://doi.org/10.25318/3210035901-eng
17. Dyer, J.A.; Desjardins, R.L. Reconciling reduced red meat consumption in Canada with regenerative grazing: implications for GHG emissions, protein supply and land use. *Atmosphere* **2021**, *12*, 945. https://doi.org/10.3390/atmos12080945
18. Dyer, J.A.; Vergé, X.P. The Role of Canadian Agriculture in Meeting Increased Global Protein Demand with Low Carbon Emitting Production. *Agronomy* **2015**, *5*, 569–586. https://doi.org/10.3390/agronomy5040569
19. Dyer, J.A.; Vergé, X.P.C.; Desjardins, R.L.; Worth, D.E. District scale GHG emission indicators for Canadian field crop and livestock production. *Agronomy* **2018**, *8*, 190. https://doi.org/10.3390/agronomy8090190
20. Dyer, J.A.; Desjardins, R.L.; Worth, D.E.; Vergé, X.P.C. Potential role for consumers to reduce Canadian agricultural GHG emissions by diversifying animal protein sources. *Sustainability* **2020**, *12*, 5466. https://doi.org/10.3390/su12135466
21. Dyer, J.; Desjardins, R. Protein as a unifying metric for carbon footprinting livestock. *Research Outreach publication (Earth & Environment)*. Issue 118: 142–145. https://researchoutreach.org/publication/ (accessed 4 December 2021).
22. University of Reading. Human gut unable to unlock majority of protein from many plant 'milks'. Available online: https://www.reading.ac.uk/news-and-events/releases/PR853912.aspx (accessed 15 February 2022).
23. Vergé, X.P.C.; Dyer, J.A.; Desjardins, R.L.; Worth, D. Greenhouse gas emissions from the Canadian dairy industry during 2001. *Agric. Syst.* **2007**, *94*, 683–693. https://doi.org/10.1016/j.agsy.2007.02.008
24. Vergé, X.P.C.; Dyer, J.A.; Desjardins, R.L.; Worth, D. Greenhouse gas emissions from the Canadian beef industry. *Agric. Syst.* **2008**, *98*, 126–134. https://doi.org/10.1016/j.agsy.2008.05.003
25. Vergé, X.P.C.; Dyer, J.A.; Desjardins, R.L.; Worth, D. Greenhouse gas emissions from the Canadian pork industry. *Livest. Sci.* **2009**, *121*, 92–101. https://doi.org/10.1016/j.livsci.2008.05.022
26. Vergé, X.P.C.; Dyer, J.A.; Desjardins, R.L.; Worth, D. Long Term trends in greenhouse gas emissions from the Canadian poultry industry. *J. Appl. Poult. Res.* **2009**, *18*, 210–222. https://doi.org/10.3382/japr.2008-00091
27. Vergé, X.P.C.; Dyer, J.A.; Worth, D.; Smith, W.N.; Desjardins, R.L.; McConkey, B.G. A greenhouse gas and soil carbon model for estimating the carbon footprint of livestock production in Canada. *Animals* **2012**, *2*, 437–454. https://doi.org/10.3390/ani2030437
28. Dyer, J.A.; Vergé, X.P.C.; Desjardins, R.L.; Worth, D.E. An assessment of greenhouse gas emissions from co-grazing sheep and beef in Western Canadian rangeland. In Agricultural Management for Climate Change; Lac, S., Kulshreshtha, S., McHenry, M., Eds.; Nova Science Publishers Inc.: New Nork, NY, USA, 2015; Chapter 2, pp. 13–29.
29. Flanagan, R., What's on your plate? Inside the changes to Canada's Food Guide. *CTV.News*, 23 January 2019. Available online: https://www.ctvnews.ca/health/what-s-on-your-plate-inside-the-changes-to-canada-s-food-guide-1.4265399 (accessed 29 November 2021).
30. VandenBygaart, A.J.; McConkey, B.G.; Angers, A.D.; Smith, W.; De Gooijer, H.; Bentham, M.; Martin, T. Soil carbon change factors for the Canadian agriculture national greenhouse gas inventory. *Can. J. Soil Sci.* **2008**, *88*, 671–680. http://doi.org/10.4141/CJSS07015
31. Capper, J.L. The sustainability and 'carbon footprints' of conventional and alternative beef production systems. In Ensuring Safety and Quality in the Production of Beef, Volume 2. Burleigh Dodds Science Publishing Limited: Cambridge, UK, 2017; pp. 1–27. https://doi.org/10.4324/9781351114172
32. Carrington, D. Giving up beef will reduce carbon footprint more than cars. *The Guardian*, 21 July 2014. Available online: https://www.theguardian.com/environment/2014/jul/21/giving-up-beef-reduce-carbon-footprint-more-than-cars (accessed 1 December 2021).
33. Desjardins, R.L.; Worth, D.E.; Vergé, X.P.C.; Maxime, D.; Dyer, J.; Cerkowniak, D. Carbon footprint of beef cattle. *Sustainability* **2012**, *4*, 3279–3301. https://doi.org/10.3390/su4123279
34. Kramer, L. The future of meat is shifting to Plant-Based Products. *U of T news*, 17 June 2019. Available online: https://www.utoronto.ca/news/future-meat-shifting-plant-based-products-u-t-expert (accessed 4 December 2020).
35. Byrne, J. Feed Efficiency in Feedlot Production. *OMAFRA*, 28 February 2018. Available online: http://www.omafra.gov.on.ca/english/livestock/beef/news/vbn0218a2.htm (accessed 1 June 2022).